OUR WORLD OCEAN: UNDERSTANDING THE MOST IMPORTANT ECOSYSTEM ON EARTH



W. Sean Chamberlin, Nicki Shaw, and Martha Rich
Fullerton College

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Our World Ocean: Understanding the Most Important Ecosystem on Earth, Essentials Edition

W. Sean Chamberlin, Nicki Shaw, and Martha Rich

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TABLE OF CONTENTS

Licensing

About the Book

About the Authors

Foreword

Preface

Voyage I Ocean Science

- 1: The World Ocean System
  - 1.1: A World Ocean Perspective
  - 1.2: An Interdisciplinary Science
  - 1.3: An Earth Systems View
  - 1.4: Earth's Seven Spheres
  - 1.5: The World Ocean System
  - 1.6: Keeping an Eye on Climate Change
  - 1.7: Ocean Literacy
  - 1.8: Your Mission
  - 1.9: Chapter References
- 2: Team Oceanography
  - 2.1: Channel Your Inner Scientist
  - 2.2: Investigate the Natural World
  - 2.3: Ask a Good Question
  - 2.4: Propose an Idea or Model
  - 2.5: Test Your Hypotheses
  - 2.6: Conduct an Investigation
  - 2.7: Analyze Your Results
  - 2.8: Form Your Conclusions
  - 2.9: Communicate Your Science
  - 2.10: Chapter References
- 3: Science Aboard Ships
  - 3.1: The Birth of Oceanography
  - 3.2: Sampling over Space
  - 3.3: Sampling over Time
  - 3.4: The Challenge of Pressure
  - 3.5: The Undersampling Problem
  - 3.6: Modern Oceanographic Vessels
  - 3.7: Beneath the Surface
  - 3.8: Chapter References
- 4: Robots, Satellites, and Observatories
  - 4.1: Bottles, Drifters, and Floats
  - 4.2: Gliders
  - 4.3: Towfish

- 4.4: Remotely Operated Vehicles
- 4.5: Autonomous Underwater Vehicles
- 4.6: Hybrid Platforms
- 4.7: Benthic Landers
- 4.8: Mini-Autonomous Underwater Explorers
- 4.9: Ocean Moorings
- 4.10: Uncrewed Aerial Platforms
- 4.11: Satellite Oceanography
- 4.12: Ocean Observatories
- 4.13: Chapter References

Voyage II Ocean Geology and Chemistry

- 5: The Beach
  - 5.1: What Is a Beach?
  - 5.2: Anatomy of a Beach
  - 5.3: The Origins of Beach Sand
  - 5.4: From the Mountains to the Sea
  - 5.5: Wave-Driven Sediment Transport
  - 5.6: The Littoral Cell
  - 5.7: Human Impacts on Beaches
  - 5.8: The Last Beach?
  - 5.9: Chapter References
- 6: The Seafloor
  - 6.1: Planet Earth vs. Planet Ocean
  - 6.2: A Few Words About “Seafloor”
  - 6.3: Marine Geomorphometry
  - 6.4: Seafloor Provinces
  - 6.5: Deep-Sea Mining
  - 6.6: Chapter References
- 7: Seawater and Its Elements
  - 7.1: Anatomy of a Molecule
  - 7.2: The Periodic Table of the Elements
  - 7.3: The Name’s Bond, Chemical Bond
  - 7.4: Chemical Formulas
  - 7.5: The Water Molecule
  - 7.6: What Are Salts?
  - 7.7: Seawater Constituents
  - 7.8: Chapter References
- 8: The Water Cycle and Ocean Salinity
  - 8.1: A Useful and Simple Model
  - 8.2: The Global Water Cycle
  - 8.3: The Three States of Water
  - 8.4: Water, the Dissolver of Rocks
  - 8.5: Salinity over Long Timescales
  - 8.6: Salinity over Short Timescales
  - 8.7: Airborne Sources of Salts
  - 8.8: Biological Sources and Sinks
  - 8.9: Residence Time

- 8.10: Measuring Salinity
- 8.11: The Global Water Crisis
- 8.12: Chapter References

Voyage III Ocean Physics

- 9: The Sun and the Earth
  - 9.1: Interesting Facts About the Sun
  - 9.2: Electromagnetic Radiation
  - 9.3: How the Sun Warms the Earth
  - 9.4: Earth's Energy Imbalance
  - 9.5: Chapter References
- 10: The Surface Circulation
  - 10.1: Main Features
  - 10.2: Boundary Currents
  - 10.3: West Wind Drift Currents
  - 10.4: Polar Ocean Currents
  - 10.5: Understanding Ocean Motions
  - 10.6: Ocean Currents Up Close
  - 10.7: Monsoonal Circulation
  - 10.8: Final Thoughts
  - 10.9: Chapter References
- 11: The Seasons of the Sea
  - 11.1: Sunrise, Sunset
  - 11.2: Why Do Seasons Occur?
  - 11.3: How Does Earth's Tilt Affect Surface Warming?
  - 11.4: The Ocean Layer Cake
  - 11.5: Measuring the Ocean's Layers
  - 11.6: Visualizing Layers- The XZ Graph
  - 11.7: The Seasons and the Thermoclines
  - 11.8: The Importance of the Ocean's Seasonal Cycle
  - 11.9: Chapter References
- 12: Atmospheric Circulation
  - 12.1: Earth's Atmosphere
  - 12.2: What Causes Winds?
  - 12.3: Local and Regional Winds
  - 12.4: Global Atmospheric Circulation
  - 12.5: Final Thoughts
  - 12.6: Chapter References
- 13: Ocean Waves
  - 13.1: Energy in Motion
  - 13.2: The Source of a Wave's Energy
  - 13.3: The Geometry of Waves
  - 13.4: Types of Waves
  - 13.5: The Timing of Waves
  - 13.6: The Speed of Waves
  - 13.7: Wave Orbitals
  - 13.8: Wind Stress- A Transfer of Energy
  - 13.9: The Wind-Stressed Sea Surface

- 13.10: Factors Affecting Wave “Size”
- 13.11: The Beaufort Wind Force Scale
- 13.12: Dispersion of Waves
- 13.13: Deep- and Shallow-Water Waves
- 13.14: The Making of Surf
- 13.15: Chapter References

- 14: Ocean Tides and Sea Level Rise
  - 14.1: The Tide-Causing Forces
  - 14.2: The Tides Follow the Moon
  - 14.3: Measuring and Predicting Tides
  - 14.4: Classification of Tides
  - 14.5: Tidal Height
  - 14.6: Spring and Neap Tides
  - 14.7: Practical Applications of Tide Knowledge
  - 14.8: An Ever-Changing Sea Level
  - 14.9: How Do We Measure Sea Level?
  - 14.10: What Causes Sea Level Change
  - 14.11: What Have We Learned About Global Sea Level Rise?
  - 14.12: What Have We Learned About Local Sea Level Rise?
  - 14.13: It’s Not Just Sea Level Rise
  - 14.14: Chapter References

Voyage IV Ocean Biology

- 15: The Living Sea
  - 15.1: Systems of Classification
  - 15.2: A Quick Lesson in Classification
  - 15.3: Two or Three Domains?
  - 15.4: A Brief History of Life on Earth
  - 15.5: Life and Earth as One?
  - 15.6: Chapter References
- 16: Ocean Depth Zones
  - 16.1: Defining an Organism’s Habitat
  - 16.2: Marine Biogeography
  - 16.3: Oceanic Environments
  - 16.4: Pelagic Depth Zones
  - 16.5: Benthic Depth Zones
  - 16.6: Ocean Depth Zoning Out
  - 16.7: Chapter References

Appendices

- 17: Appendix A—Common Abbreviations
- 18: Appendix B- Ocean Science Abbreviations
- 19: Appendix C—Abbreviations for Ocean Currents*
- 20: Appendix D—Metric Prefixes
- 21: Appendix E—Useful Formulas
- 22: Appendix F—Estimating Water Pressure
- 23: In the Periscope- Tiny Treasures by Colleen Chamberlin

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Glossary

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About the Book

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W. Sean Chamberlin, PhD is an American oceanographer, professor, and author. He holds bachelor's degrees in English and Oceanography from the University of Washington, and a PhD in Biology from the University of Southern California. Since 1996 he has taught oceanography, meteorology, and climate science at Fullerton College in Fullerton, California (a few short miles from Disneyland). Chamberlin has traveled four of the five major oceans (sorry, Indian Ocean) and carried out studies aboard Jacques Cousteau's Calypso. He co-authored Exploring the World Ocean (Chamberlin and Dickey 2008) and has published numerous papers in ocean science and online education. When not teaching or writing, he cares for three cats and spends much-treasured time with his beloved partner of 22+ years. Professor Sean's website

Nicole Shaw

Nicole Shaw is an American cartoonist, writer, business analyst, and mother to four kids. She holds a BS in Bioengineering from UC San Diego. In 2017, she started @nickisdoodles, an Instagram feed featuring fun science facts and puppy comics. She currently works as a senior business analyst for a medical IT company in Durham, North Carolina. When not doodling or making computers behave, she helps her husband run their specialty coffee business, Olilu Coffee. Nicki's website

Martha Rich

Martha Rich is an American artist, illustrator, and professor. She is a graduate of (and has taught classes at) the Art Center College of Design in Pasadena, California, and holds an MFA from the University of Pennsylvania. She has also taught at Tyler School of Art and Architecture and the Fashion Institute of Technology. In 2019, Chronicle Books published her book, The Furious Notebook, Release Your Rage, Use Your Anger for Good and Chill the Heck Out. Her work has appeared in music videos, books, magazines, murals and in various products sold worldwide. In 2023, a collection of her work appeared at the Hey There Projects gallery in Joshua Tree, California. Martha's website

Foreword

by Dr. Bridget Salzameda, Dean, Natural Sciences, Fullerton College

From the ground, a family sees my body clinging to the side of a mountain, about two-thirds of the way to the top. My arms are feeling weak as I grip two rocks wedged into the caked dirt. Thankfully my legs are firmly planted on two more wedged rocks. But I'm worried about my newly painted, bright red nails. OMG! What's wrong with me? Focus, Bridget. How did I get here, and what's my plan now?

I was forty-three years old and free solo climbing a mountain—really a shallow hill—with my climbing partner just a few feet across from me. I looked over, and he was gone. I looked down. He wasn't there. I called for him and heard no response. I assumed he was around the curve. He was, and climbed back down. I thought about returning to the bottom but badly wanted to reach the top because I was so close. I was tired, my arms were weakening, and I convinced myself to finish because I had witnessed a ten-year-old climb to the top an hour earlier. This made the task possible. If I hadn't seen it, I might not have continued. Civil and children's rights activist Marian Edelman's words bombarded my mind: "You can't be what you can't see." I made it to the top. I was out of breath, but content. Now I understood those words.

The first time I fell in love I was about eleven years old. I fell in love with my at-home chemistry kit. I was enamored by the brightly colored solutions evolving into different-looking substances in a thin, delicate test tube. My parents, who emigrated from Sri Lanka, gave me this toy, not realizing that it would help guide the trajectory of my career from student to chemistry professor to dean of natural sciences.

My wonder grew in my high school chemistry class in Mission Viejo, California. I was mesmerized by chemical reactions and reliable math problems and solutions. As a chemistry major at the University of San Diego, my uncomfortably direct academic advisor, Dr. Pat Traylor, called Our World Ocean: Understanding the Most Important Ecosystem on Earth me into her office and told me I must get a PhD in chemistry. I had no idea what a PhD was, but I was certain I would get one, because Dr. Traylor said I must. It was an important lesson in believing in others so they may believe in themselves. I worked hard in college and was accepted into several PhD programs, but I chose to earn my degree in biochemistry, not chemistry. Perhaps it was the rebel in me.

In graduate school, I met my muse. Dr. Christine Cremo, Department of Pharmacology, was my research advisor and a professor at the University of Nevada School of Medicine. She possessed the most important qualities that I wanted—the ability to produce and expect high-quality work, set high standards for herself and others, and demand rigor and intelligence in her research laboratory. She was organized, analytical, and direct. I was productive in the laboratory and blossomed as a research scientist, authoring scientific publications and making new discoveries to advance science. I earned my PhD and obtained the title of mother along the way. Others believed I would continue my research career and lead my own lab, but I had an internal calling to follow another path—to teach college chemistry (which I did for close to fifteen years).

Most would assume that the biggest challenge of being a mother and a professor is balancing work and family life. This is far from the truth. I have marvelous children, a supportive spouse, intelligent colleagues, and strong friendships. All of these, combined with efficient planning, allowed me to feel present in all I did at work and at home. This combination of skills, passion, and support is reflected in my most recent recognitions, receiving an Inspirational Professor Award and being a finalist for the Faculty of the Year award at our college.

But new challenges faced me in the last five years. Because my children were older, I took on more responsibilities at work, and as an administrator, I had time to pay attention. I was less naïve and less immune to blunt racism and microaggressions. I noticed my colleagues and friends experiencing it daily and began recognizing it from my past interactions. I am wholeheartedly thankful that I was naïve for my own emotional and mental protection—I had the luxury of focusing on science, not realizing there was anything standing in my way. As I work with students who are more aware of these topics, I am learning about the difficulties that underrepresented minorities experience. It's challenging to navigate my leadership role to ensure that all colleagues and students feel seen and heard. I understand the importance of surrounding myself with people who think differently so I can maintain a balanced perspective.

Representation is also important. All people deserve to see themselves in all areas of success, and science is no different. The outcome of my climb might have been different if I hadn't seen that ten-yearold completing it. This textbook will reach you differently because it incorporates lessons from a group of diverse scientists. The author followed his inner voice—probably the

rebel in him—to thoughtfully communicate with students. It's not a boring textbook. It's fun, magical, and will allow you to learn and grow. You may find yourself smiling and smirking while reading this book, all while growing intellectually. Have fun falling in love!

Dr. Bridget Salzameda

Dean, Natural Sciences

Fullerton College August 22, 2022

Preface

Aloha! If you're reading this, you're one of those rare people who read front matter. Perhaps you want to know what you're in for on this voyage of the sea. (An exhilarating one!) Maybe you want to know if we're your kind of people. (We hope so!) Possibly you're looking for the answer to a test question. (Keep reading.) Whatever your reason, we thank you. We hope you'll continue reading and enjoy your reading. After all, we can't protect what we don't understand.

When we set out to write this book (more than 12 years ago), Chamberlin had just finished publishing his first book, Exploring the World Ocean, with co-author and oceanographer extraordinaire Tommy Dickey (Chamberlin and Dickey 2008*). That book, published by McGraw-Hill, took the form of a traditional textbook. But there was a nagging feeling that, like so many textbooks, that textbook presented its subjects like bags of old bones. The meats and flavors were missing. Oceanography, like all science, is alive. It's alive! So Chamberlin set out to write a non-traditional, student-centered, scienceinfused book that inspired people to fall in love with the ocean and the people who have dedicated their lives to understanding how it works.

This book offers an alternative to the traditional, dry-as-bones, hohum approach of the standard textbook. Sure, it covers all the topics you'll find in a traditional oceanography textbook. But that's just the tip of the iceberg. We go broader and deeper. We write the way people talk— conversationally. We encourage folks to interact with the text, to click through to full-size images, to view video and hear audio, and to quickly access the reference materials on which the presented facts and ideas are based. A future edition of the book will include an audio glossary (so you can hear the proper pronunciation of terms). It features cartoons that *Chamberlin, W. Sean, and Tommy Dickey. 2008. Exploring the World Ocean. Dubuque: McGraw-Hill Higher Education. Our World Ocean: Understanding the Most Important Ecosystem on Earth tickle the funny bones and imagery that makes you feel and think. The design makes it easy to read, gives ample space for posting notes, and numbered headings and subheadings make topics easier to find and make it easier for teachers to assign parts of chapters.

To our way of thinking, books do their best work when they stimulate action from the reader. As teachers well know, the strongest foundation for learning comes from attention to three domains: the affective (i.e., emotional), cognitive (i.e., intellectual), and psychomotor (i.e., physical). The structure, design, writing, artwork, and interactive elements of this book strive to engage those domains.

We also believe that science achieves its greatest success when it's built on the interdisciplinary and multiperspective works of diverse scientists. The problems of the world are best solved by giving everyone a voice in their solution. Scientific progress relies on the diverse knowledge, experience, and perspectives of scientists from all walks of life. That's why you'll find references with scientists' names throughout the text. We want readers to identify with names they recognize and develop curiosity about ones they don't. This approach builds a stronger appreciation for the contributions from scientists all over the world. We also make visible the dates of publication. Modern science is built on the shoulders of scientists spanning centuries of discovery. Making obvious the dates of publications connects readers to the history of science.

Of course, none of this matters if we bore our readers. We unapologetically use humor and irreverant analogies wherever possible to make our points. We've made every effort to make the text easy to read, the images engaging to look at, and the evidence for our statements simple to find. That doesn't mean we don't present difficult concepts and uncertainties in scientific knowledge. Readers deserve the "full monty" of science. How can the public develop an appreciation for the complex problems facing humanity if we treat them like dummies?

If you like what you read, please tell someone and share a copy. It's 100 percent free to distribute or copy to your website (as long as you give appropriate credit and don't violate copyrights or creative commons licenses). If you don't like what you read here, please tell us. We aim to do better.

May the ocean be with you. May a giant yellow sponge wipe away your tears when you're sad. May a thousand dolphins sing at your next big event. In the spirit with which this was written, aloha!

Sean, Nicki, and Martha

PS: The answer to the test question is C

SECTION OVERVIEW

Voyage I Ocean Science

1: The World Ocean System

1.1: A World Ocean Perspective
1.2: An Interdisciplinary Science
1.3: An Earth Systems View
1.4: Earth's Seven Spheres
1.5: The World Ocean System
1.6: Keeping an Eye on Climate Change
1.7: Ocean Literacy
1.8: Your Mission
1.9: Chapter References

2: Team Oceanography

2.1: Channel Your Inner Scientist
2.2: Investigate the Natural World
2.3: Ask a Good Question
2.4: Propose an Idea or Model
2.5: Test Your Hypotheses
2.6: Conduct an Investigation
2.7: Analyze Your Results
2.8: Form Your Conclusions
2.9: Communicate Your Science
2.10: Chapter References

3: Science Aboard Ships

3.1: The Birth of Oceanography
3.2: Sampling over Space
3.3: Sampling over Time
3.4: The Challenge of Pressure
3.5: The Undersampling Problem
3.6: Modern Oceanographic Vessels
3.7: Beneath the Surface
3.8: Chapter References

4: Robots, Satellites, and Observatories

4.1: Bottles, Drifters, and Floats
4.2: Gliders
4.3: Towfish
4.4: Remotely Operated Vehicles
4.5: Autonomous Underwater Vehicles
4.6: Hybrid Platforms

4.7: Benthic Landers
4.8: Mini-Autonomous Underwater Explorers
4.9: Ocean Moorings
4.10: Uncrewed Aerial Platforms
4.11: Satellite Oceanography
4.12: Ocean Observatories
4.13: Chapter References

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CHAPTER OVERVIEW

1: The World Ocean System

Imagine you are a cosmic explorer on a long, interstellar voyage between your solar system and its closest neighbor. Your trusty and comfortable spaceship has carried you billions and billions of miles from home, yet for most of that trip, you've seen very little. Sure, that asteroid almost hit you, and your onboard computer developed a split personality half a parsec back, but other than that, your trip through interstellar space has been one of the most boring experiences of your thousand-year life.

Then, out of the corner of your telescopic viewscreen, a solar system with a strange blue dot appears. You do a systems check. All systems normal. Suddenly the dot increases to two pixels. And then more. Switching to ultrasupercalifragilistic high definition, you realize that the dot is a real object. It's real! And it's BLUE. Could there be something, a water-rich object, in this ghastly stretch of nameless space? Phone home, explorer. You just found a water planet!

Viewed from the far reaches of space, Earth, our home, looks like a tiny blue speck immersed in a sea of black. We know Earth looks this way because in 1990 a small spacecraft, *Voyager 1*, going where no manmade object had ever gone before, turned its camera back toward Earth and snapped a picture. In doing so, *Voyager 1* captured a moment that has come to define what it means to be human. Deeply moved by this image, Carl Sagan (1934–1996), astronomer, author, and host of the original 1980 TV miniseries *Cosmos*, offered these words:

> *That's here. That's home. That's us. On it, everyone you ever heard of, every human being who ever lived, lived out their lives. The aggregate of all our joys and sufferings, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilizations, every king and peasant, every young couple in love, every hopeful child, every mother and father, every inventor and explorer, every teacher of morals, every corrupt politician, every superstar, every supreme leader, every saint and sinner in the history of our species, lived there—on a mote of dust, suspended in a sunbeam. (Sagan and Druyan 1994)*

The **pale blue dot**, as Sagan called it, is Earth, our home, the only known place in the universe where humans exist. Though small compared to the infinity of space, Earth remains our lone island, our singular port of call, a solitary outpost inhabited by the most fascinating and enigmatic species in the known universe, *Homo sapiens*. Earth is also the only known planet with liquid water covering most of its surface. Its pale blue color, visible from millions of miles away, comes from that water, the ocean—our world ocean.

1.1: A World Ocean Perspective
1.2: An Interdisciplinary Science
1.3: An Earth Systems View
1.4: Earth's Seven Spheres
1.5: The World Ocean System
1.6: Keeping an Eye on Climate Change
1.7: Ocean Literacy
1.8: Your Mission
1.9: Chapter References

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1.1: A World Ocean Perspective

The **world ocean** covers 71 percent of the surface of our planet to an average depth of 2.3 miles (3.7 km). It includes all of the waters contained by the ocean basins—which cover 64.7 percent of Earth's surface—and the waters that cover the edges of the continents—about 6.3 percent of the globe (e.g., Harris et al. 2014) . Myriad terms describe various parts of the ocean (seas and gulfs, straits and passages, bights and bays, harbors and sounds, banks and fjords), but **oceanographers**, the people, animals, and robots who study the world ocean, recognize only one ocean, the world ocean.

For convenience oceanographers call the three major ocean basins by their geographic names—the Atlantic, Pacific, and Indian Oceans. They also recognize two smaller oceans: the Arctic Ocean, an ocean basin surrounded by continents at the North Pole, and the Southern Ocean, a doughnut-shaped ocean defined by cold waters surrounding the Antarctic landmass. Of course, there are many geographic regions within the oceans: the Mediterranean Sea, the Gulf of Mexico, the Caribbean Sea, the Coral Sea, the Arabian Sea, the Red Sea, the Barents Sea, and numerous others. But these geographic designations disguise an important characteristic of Earth's waters: they don't stay in the same place for long. They don't even stay in the same ocean basin. Water at one geographic location eventually—over timescales of hundreds of years—finds itself in another geographic location and even back where it began. The waters of the five major oceans flow between the basins and mix to form one ocean—the world ocean.

The idea of a world ocean, as opposed to several independent oceans, occurred to oceanographers at least a century ago, and likely much earlier. Scientific publications expressing the idea of a world ocean are difficult to find prior to 1917, but British author Agnes Giberne (1845–1939), who wrote novels and nonfiction (mostly with Christian themes), clearly states in 1902 her understanding of a world ocean:

> *In these days, we know the Ocean as one vast whole. . . . Minor oceans do exist, certainly. We have the Atlantic, North and South; the Pacific, North and South; the Arctic, the Antarctic, and the Indian. Yet for us there is but one great world-wide Ocean, encircling the Earth, every part being in connection with every other part. (Giberne 1902)*

Giberne's proclamation notwithstanding, various sources give credit for the term "world ocean" to Russian oceanographer Yuli Shokalsky (1856–1940), who used it in his 1917 monograph *Oceanography*. For English readers, Scottish oceanographer James Johnstone (1870–1932) used "World-Ocean" as the title of the first chapter in *An Introduction to Oceanography*, one of the earliest textbooks on the subject (Johnstone 1923). Johnstone mentions "the great Southern Ocean" and the "three Oceanic 'Gulfs' open out from the Southern Ocean." The idea of the Southern Ocean at the "center" of the three major basins anticipates a modern view of the Southern Ocean as a kind of "steering wheel" for the world ocean circulation (Alfred Wegener Institute 2020).

World ocean thinking appears firmly embedded in oceanographic thinking by the 1930s. American oceanographer Thomas Wayland Vaughn (1870–1952) wrote in *International Aspects of Oceanography* (1937):

> *Just when the concept of the unity of all oceans originated is not easy to ascertain. As soon as it was recognized that the cold water in the depths of the oceans had come from Polar regions and that the renewal of the supply of water in those regions had come from other latitudes, the idea of a world ocean was born, and research was directed toward both the circulation within and the exchange of water between the different ocean basins.*

South African American oceanographer Athelstan Spilhaus (1911–1998) put it even more succinctly in a paper titled "Maps of the Whole World Ocean" (1942):

> *Because it covers more than two-thirds of the earth's surface, a map of the world ocean is essentially a world map. On ordinary world maps, the interruption forming the edges of the map are often placed in the oceans to show the continents to best advantage. If, on the other hand, oceanographic conditions as a whole are to be shown, it is desirable to have the map interrupted within the land masses and the world ocean shown as a unit.*

By the 1960s, various authors had published books with “world ocean” in their titles or chapter headings, suggesting common usage of the term by this time (e.g., Carrington 1960; Cromie 1962; Pizer 1967). The first textbook to use the term in its title, *The World Ocean: An Introduction to Oceanography* (Anikouchine and Sternberg 1973), was the one I used in my freshman year at the University of Washington in 1974. The authors introduce the interconnectivity of the world ocean’s waters as the **principle of unity**. And they argue that a focus on memorizing the “names and placements of the continents and ocean . . . is slightly misleading because it suggests that the oceans are separated geographically. From an oceanographer’s point of view, the emphasis should be on a world ocean that is completely intercommunicating.” Of course, once the idea of a single world ocean is firmly embedded in your thinking, it doesn’t hurt to know the names and locations of at least some of the geographic oceans. How else will you know where to go when someone invites you to the Caribbean?

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1.2: An Interdisciplinary Science

The scientific study of the world ocean, a field of science called **oceanography**, involves several different scientific disciplines. Generally, oceanographers identify with one of four major subdisciplines:

- **geological oceanography**, the study of geologic processes in the ocean
- **chemical oceanography**, the study of chemical processes in the ocean
- **physical oceanography**, the study of physical processes in the ocean
- **biological oceanography**, the study of biological processes in the ocean

Oceanography also borrows from astronomy, geophysics, meteorology, physiology, ecology, and environmental sciences, to name a few. The integration of many different fields of science into one makes oceanography an **interdisciplinary science**, one that shares and integrates the tools and knowledge of many sciences. Though oceanographers tend to specialize in one discipline, their work requires them to be conversant in other sciences as well. They tend to dabble in multiple subjects, which is why an oceanography course can be so much fun—you learn a little of everything!

Oceanography also involves a host of non-scientist professionals, too, from technicians and programmers to a ship's crew. Technicians provide an onboard repair shop for finicky instruments, programmers maintain the software that communicates with ocean sensors, and the crew navigate the ship, help deploy gear, and cook your meals. (A good rule to follow on board an oceanographic vessel? Be nice to the cook.) Without these support personnel, oceanography would be next to impossible.

From a practical standpoint, oceanographers seek to understand the ways that the ocean serves humanity, how it provides what are called **ecosystem services**. Costanza et al. (1997) define ecosystem services as "the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being." The ocean, for example, provides food, water, materials, waste purification, and a stable climate, among other things. Oceanographers want to know how human activities interfere with the services the ocean provides—how our actions affect the ocean's ability to function properly and provide services to humanity. With more global-scale environmental and social challenges facing us than ever before, the stakes for understanding the ocean have never been higher.

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1.3: An Earth Systems View

Humans exist in the web of a vast life support system controlled largely by the ocean. Much of the air that we breathe, the water that we drink, the food that we eat, and the climate in which we live originates from processes that operate within the ocean. While geologic forces ultimately contribute to slow changes in Earth's climate, the ocean—in concert with other systems—dominates processes that affect climate on human timescales (e.g., decades to centuries). Together the various interdependent, interconnected systems that collectively regulate conditions on Earth have come to be known as the **Earth system**.

Loosely defined, a **system** consists of an assemblage of parts and processes working together. System parts include physical components—things composed of matter—while system processes refer to events or activities that result in some outcome. "Working together" implies interactions among those parts and processes—exchanges of energy and matter—and interdependency, meaning the parts and processes depend on each other. Systems may be simple or complex. Like molecules, they may exhibit **emergent properties**, characteristics and behaviors that cannot be observed by studying the individual parts separately. The properties of a water molecule differ markedly from the individual properties of hydrogen (a highly flammable gas) and oxygen (necessary for combustion). With emergent properties, the whole is greater than the sum of its parts.

A great number of systems surround and support you in your daily life. For example, a coffee maker is a fairly simple manmade system. It has parts (stand, filter, heater, etc.), the parts work together (coffee goes in the filter, the filter goes in the filter holder, water pours through the filter), there are regulatory processes for temperature and water flow (adjustable on pricier models), and the system produces a great-tasting end product: a cup of coffee. Yet it would be difficult to describe the taste of a cup of coffee simply by studying the parts of a coffee maker.

Similarly, the human body consists of lots of subsystems: circulatory, nervous, musculoskeletal, urinary, reproductive, and more. But do these individual subsystems really describe you? Of course not. Each of you maintain your own beautiful self, despite the similarities of our bodily systems.

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1.4: Earth's Seven Spheres

Though highly complex, the Earth system operates in much the same way as other systems with which we might be familiar. Within the Earth system, we can identify seven major subsystems, sometimes referred to as spheres (a reference to their names as well as the concept of their operation in a volume of Earth):

- the **heliosphere**, the Sun and solar system
- the **atmosphere**, the gases surrounding Earth
- the **geosphere**, the solid Earth
- the **cryosphere**, the frozen parts of Earth
- the **biosphere**, Earth's living systems
- the **hydrosphere**, Earth's waters
- the **anthroposphere**, the human system

The hydrosphere includes the world ocean and all other waters upon or within Earth's surface, including groundwater. The geosphere shapes the ocean basins and controls exchanges of energy and matter between Earth's crust and the ocean. The atmosphere exchanges energy and matter between the atmosphere and ocean. In the frozen regions of the ocean, the cryosphere, when present, acts as a lid blocking the exchange of energy and matter between the ocean and the atmosphere. All subsystems interact with the Sun, part of the heliosphere, which supplies energy to Earth. Life on Earth constitutes what's known as the biosphere, found from the uppermost reaches of the atmosphere to deep within Earth's crust. One part of the biosphere, humans, have so radically changed our planet that scientists now consider human activities as a separate subsystem, the anthroposphere.

The description of the Earth system as a collective of seven spheres or subsystems is a useful model for understanding complex systems. Scientists call this a **conceptual model**, a sort of mental picture of how we think something works. Conceptual models guide our thinking and promote insights that can be tested by observation or experimentation. Our model of Earth as a system helps us appreciate the interconnectedness of its geological, chemical, physical, biological, and human processes. Perhaps most importantly, it helps us understand our utter dependency on this system for our survival. As so eloquently put in one of my favorite short documentaries, *The Living Sea*, "We live because the sea lives" (MacGillivray 1995). Conditions established by interactions among the seven spheres make Earth habitable for all living things.

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1.5: The World Ocean System

The world ocean may also be viewed as its own system, the world ocean system. The geology, chemistry, physics, and biology of the ocean interact over nearly all scales of space and time. They're all connected! In fact, the study of the world ocean as a system of interdependent parts and processes is what distinguishes oceanography from related disciplines, such as marine biology. Fundamentally, oceanographers aim to understand how the ocean works as a system. That's why it behooves oceanographers to be familiar with other subdisciplines. Oceanographic research works best as an interdisciplinary science. We'll visit this idea of an interconnected ocean system throughout the book. Indeed, it's the book's central theme.

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1.6: Keeping an Eye on Climate Change

Earth's warming temperatures—**global warming**—and the consequences of that warming for Earth's weather should concern every one of us. Nearly 100 percent of all climate scientists agree that humans are the cause of global warming. Yes, climate varies naturally. But human activities, especially the burning of fossil fuels and the chopping down of forests (i.e., deforestation), have sent Earth's climate beyond its natural variations. Well beyond. Because we're the cause, we have the capacity to be the solution.

As you might expect, the ocean plays an enormous role in regulating the severity of the changes ahead. But before we go much further in our journey, it's helpful to distinguish what scientists mean when they are talking about weather or climate.

Every day of our lives, we experience the changing conditions of the atmosphere, or what we call **weather**, the instantaneous state of the atmosphere in a particular location. Weather is happening right here, right now. Weather includes several different variables, such as temperature, humidity, clouds, precipitation, and wind. The ocean influences these variables.

As we grow older, we notice patterns in the weather; seasons change, some years feel hotter or colder, some seem wetter or drier. Seasonal, annual, decadal, and even longer timescale patterns in weather define what scientists call **climate**, the long-term statistics of weather conditions at a given location or globally. Climate represents the probability of a particular type of weather at a given time and place. For example, in California we normally expect hot, dry summers followed by cool, wet winters. Of course, any given day may be hot or cold in any season. But climate includes more than just the statistical average of weather conditions (e.g., average temperature or amount of precipitation). It also includes the type of weather event, its frequency and duration, and its intensity (Environmental Protection Agency 2021). Heatwaves, cold snaps, extreme floods, and droughts exhibit patterns over time that make up the statistics of climate.

A sports analogy can help us differentiate between weather and climate. A baseball player may get a hit or strike out in any given at bat. How they perform over a series of at bats defines their batting average. Hitters with a high batting average hit the ball more frequently. They may still strike out, but on average, they're going to hit the ball more times than players with lower batting averages. Climate is like a batting average: it's the weather we expect on average. Weather, however, like a given at bat, is what we get on any given day. A cold day in summer doesn't mean winter has come. It's just the weather for that day.

What worries scientists is that since the mid-1800s, Earth's global climate has been changing faster than normal. Scientists refer to this as **global climate change**—changes in the statistics of weather conditions for the entire planet. Now, climate has been changing throughout Earth's history. During the ice ages, much of North America and Europe was covered in glaciers. At other times, Earth has been so hot that the polar ice caps were completely melted. But the changes that brought these "icehouse" and "hothouse" conditions to Earth happened slowly, over the course of millions of years. The pace of change over the past several decades has no natural counterpart in Earth's past. We hold the key to our climate future. And it begins with our appreciation and understanding of the Earth system.

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1.7: Ocean Literacy

In 2004, a group of more than 100 scientists, educators, policymakers, and ocean advocates met to discuss the most important ideas about the ocean. Based on those discussions, they published *Ocean Literacy: The Essential Principles of Ocean Sciences* (Ocean Literacy Network 2006) and later *The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages* (NOAA 2021). This document outlines seven major principles of ocean literacy, defined as "an understanding of the ocean's influence on people and people's influence on the ocean." *The Essential Principles of Ocean Sciences* provides a road map for understanding our relationship with the ocean. The principles state:

1. The Earth has one big ocean with many features.
2. The ocean and life in the ocean shape the features of the Earth.
3. The ocean is a major influence on weather and climate.
4. The ocean makes Earth habitable.
5. The ocean supports a great diversity of life and ecosystems.
6. The ocean and humans are inextricably interconnected.
7. The ocean is largely unexplored.

This book adopts these principles and aims to develop in you an understanding of them. Like all science education, this effort is part of a global effort to improve **science literacy**, defined by the National Academy of Sciences as "the knowledge and understanding of scientific concepts and processes required for personal decision-making, participation in civic and cultural affairs, and economic productivity" (National Research Council 1996, 2013). Through a study of the ocean, you become not only an ocean-literate person but a science-literate one too. Your ability to "speak science" serves not only your interests but also the interests of the world. An ocean- and science-literate person uses their scientific knowledge and understanding to advocate sustainable use of the world ocean for the benefit of future generations.

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1.8: Your Mission

Your mission, ocean explorer, if you decide to accept it, is to develop an understanding of our world ocean, the most important ecosystem on Earth. Through this understanding, I hope that you will dedicate yourself to becoming an ocean-literate person. In traveling these pages, I hope you will see how your life and the world ocean are intimately connected. Ultimately, I hope that what you learn here will inspire you to teach others about the world ocean. Together we can make our planet a more sustainable home for all beings, human and otherwise. As Sengalese conservationist Baba Dioum (*b*. 1937) so eloquently put it, “In the end, we will conserve only what we love; we will love only what we understand and we will understand only what we are taught” (Dioum 1968, as cited by Lotze 2020).

I hope you’ll join me. Full speed ahead!

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1.9: Chapter References

Anikouchine, William A., and Richard W. Sternbeg. 1973. *The World Ocean: An Introduction to Oceanography*. Englewood Cliffs, NJ: Prentice Hall. https://archive.org/details/worldoceanintrod00anik

Carrington, Richard. 1960. *A Biography of the Sea*: *The Story of the World Ocean, Its Life, and Its Influence on Human History*. New York: Basic Books. https://archive.org/details/biographyofseat00carr

Costanza, Robert, Ralph d'Arge, Rudolf de Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, Shahid Naeem, Robert V. O'Neill, Jose Paruelo, Robert G. Raskin, Paul Sutton, and Marjan van den Belt. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387: 253–260. https://doi.org/10.1038/387253a0

Cromie, William. 1962. *Exploring the Secrets of the Sea*. Englewood Cliffs, NJ: Prentice Hall. https://archive.org/details/exploringsecrets0000crom_i1o3/page/n7/mode/2up

Environmental Protection Agency. 2021. "Climate Change Indicators: Weather and Climate." Updated May 12, 2021. https://www.epa.gov/climate-indicators/weather-climate

Giberne, Agnes. 1902. *The Mighty Deep and What We Know of It*. London: C. Arthur Pearson. https://doi.org/10.5962/bhl.title.18276

Harris, P. T., M. Macmillan-Lawler, J. Rupp, and E. K. Baker. 2014. "Geomorphology of the Oceans." *Marine Geology* 352: 4–24. https://doi.org/10.1016/j.margeo.2014.01.011

Johnstone, James. 1923. *An Introduction to Oceanography*. Boston: Small, Maynard, and Company; Liverpool: The University Press of Liverpool.https://doi.org/10.5962/bhl.title.25450

Lotze, Heiki K. 2020. "Combining Love and Knowledge to Heal the Ocean." *Ethics in Science and Environmental Politics* 20: 33–39. https://doi.org/10.3354/esep00193

MacGillivray, Greg, director. 1995. *The Living Sea*. Laguna Beach, CA: MacGillivray Freeman Films. Film, 40 minutes. https://www.imdb.com/title/tt0113676/

NASA. 2018. "Earthrise 1: Historic Image Remastered." NASA Science, December 24, 2018. https://science.nasa.gov/earthrise-1-historic-image-remastered

National Research Council. 1996. *National Science Education Standards*. Washington, DC: The National Academies Press. https://doi.org/10.17226/4962

———. 2013. *Next Generation Science Standards: For States, by States*. Washington, DC: The National Academies Press. https://doi.org/10.17226/18290

NOAA. 2021. *Ocean Literacy: The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages*. Washington, DC: NOAA. https://www.marine-ed.org/ocean-literacy/overview

Ocean Literacy Network. 2006. *Ocean Literacy: The Essential Principles of Ocean Sciences, K–12*. Washington, DC: The National Geographic Society. https://www.aquariumofpacific.org/downloads/ed_SevenEssentialPrinciples.pdf

Pizer, Vernon. 1967. *The World Ocean: Man's Last Frontier*. Cleveland and New York: World Publishing. https://www.google.com/books/edition/The_World_Ocean/O74z2lnoMZwC

Rather, Dan. 2017. *What Unites Us: Reflections on Patriotism*. Chapel Hill: Algonquin Books. https://www.workman.com/products/what-unites-us/paperback

Sagan, Carl, and Ann Druyan. 2011. *Pale Blue Dot: A Vision of the Human Future in Space*. New York: Ballantine Books. https://www.penguinrandomhouse.com/books/159735/pale-blue-dot-by-carl-sagan/

Shokalsky, Yu. 1917. *Oceanography*. Petrograd.

Spilhaus, Athelstan F. 1942. "Maps of the Whole World Ocean." *Geographical Review* 32(3): 431. https://doi.org/10.2307/210385.

Vaughan, Thomas Wayland. 1937. *International Aspects of Oceanography: Oceanographic Data and Provisions for Oceanographic Research*. Washington, DC: National Academy of Sciences. https://doi.org/10.5962/bhl.title.16994

Wikipedia. 2023. “List of Seas.” Wikipedia, March 4, 2023. https://en.Wikipedia.org/wiki/List_of_seas

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CHAPTER OVERVIEW

2: Team Oceanography

Our understanding of how the world ocean works as a system emerges from the **scientific method**, the systematic and self-correcting set of practices that scientists use to discover knowledge about the natural world. But while textbooks often present the scientific method as a set of rigid rules that scientists must follow, I'm here to tell you that science is messy—occasionally very messy—with twists and turns as dramatic and spine-tingling as an Agatha Christie novel. As you'll see, the scientific "method" is more of a scientific "process," a back-and-forth, collaborative, social—and did I say messy?—web of activities carried out by a community of scientists on a quest to understand how nature works.

The Hollywood model of the scientific method goes something like this: A scientist—usually a man in a white lab coat working in a dark basement filled with bubbling test tubes—poses a question, creates a hypothesis, tests the hypothesis, gets a result, forms a conclusion, communicates the results, and wins a Nobel Prize. The crowd roars. But science rarely, if ever, works this way.

Scientific research proceeds in fits and starts, maybe even two steps forward, one backward, and a couple sideways. The standard sequence may be taken out of order. An initial approach may prove to be a dead end. Early results may be shared to get feedback. Methods may be refined. Hypotheses may be revised, and revised again, as new observations and measurements lead to a deeper understanding of a problem. All kinds of things, theoretical, methodological, statistical, and conceptual, may interrupt the smooth sequence of textbook science. Instead, scientists multitask and work with other scientists and skillfully jump between different activities to ensure that by the end of a particular study, the data they collect, the methods they use, and the interpretations they offer meet rigorous standards and pass muster with their fellow scientists, a key step called peer review.

This modern approach has been called the **activity model of the scientific method** (Harwood 2004). The activity model emphasizes the social character of science, which proceeds in small, careful steps with numerous refinements and do-overs. Preliminary results are scrutinized to refine methods and make adjustments prior to full-scale implementation. Scientists may share data in the cloud or an online database to gain feedback from other scientists for improving their approach or to support scientists working on similar problems. An exchange of ideas and new findings happens via telephone, email, social media, and at any of the regular gatherings of professional organizations, scientific conferences, or virtual meetings. In this way, science in the 21st century takes on many of the aspects of a thriving, dynamic, and exciting entrepreneurial enterprise.

Oceanography, perhaps more than any other discipline, embodies the activity model of the scientific method. If you're looking for a scientific career that brings you into contact with people from all walks of life, you'll likely enjoy working in ocean science. We call it team oceanography. Come join us!

2.1: Channel Your Inner Scientist
2.2: Investigate the Natural World
2.3: Ask a Good Question
2.4: Propose an Idea or Model
2.5: Test Your Hypotheses
2.6: Conduct an Investigation
2.7: Analyze Your Results
2.8: Form Your Conclusions
2.9: Communicate Your Science
2.10: Chapter References

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2.1: Channel Your Inner Scientist

To understand the scientific process, it's helpful to learn how to think like a scientist—a real scientist, not the fact-quoting one you learned about in secondary school or the nerdy one on TV (although I do love Sheldon). In fact, your natural "inner child" instincts are those of a scientist.

Anyone who spends time with young children appreciates their innate curiosity, their desire to know. Not long after children learn to speak, they learn to ask "what" and "why." "What's that?" they may say, pointing to a squirrel in a tree. "Why did the cat bite me?" they might cry, learning to never again pull the cat by its tail. "Why do stars fall down from the sky?" as they point to the trail of a shooting star.

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2.2: Investigate the Natural World

Science starts with curiosity. To see the world as scientists do requires a childlike wonder to see and hear and smell and touch and taste the world in high definition. In the lab or in the field, a scientist's senses are on alert. Every detail matters. Like the Bene Gesserit of the 1965 novel *Dune*—written by Frank Herbert (1920–1986) and considered the best-selling science fiction novel of all time—scientists are "trained in the minutiae of observation." Only through repeated observations of the same organism, behavior, event, or occurrence can scientists establish a set of facts upon which experiments or further observations can be based.

Phenomena that can be observed and measured consistently and repeatedly lend themselves to **scientific inquiry**, the multifaceted process of investigating the natural world. Things that cannot be observed or measured, or that occur once or rarely, do not lend themselves to scientific inquiry. Such phenomena fall outside the domain of science. Scientific inquiry encompasses a diverse set of tools and approaches. To the extent that the researchers carrying out the inquiry report their methods and results truthfully, and as long as they remain willing to modify their conclusions based on their results, then these efforts may be considered legitimate science.

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2.3: Ask a Good Question

Science aims to ask questions about the universe and everything in it, including us. In my classroom and online teaching experience, it's a rare student who asks a question about a topic or concept being covered in the course. Perhaps students fear that they will appear unknowledgeable and their instructor or their classmates will judge them. Maybe it's because nobody likes a smarty-pants (e.g., Rentzsch and Schröder-Abé 2014). Or maybe students just aren't curious about the topics on the syllabus—the saddest of all possibilities.

Whatever the reason, I like to think that many students don't realize that asking questions is a good thing. Journalists and scientists learn very early in their careers that asking great questions reaps great benefits. Experienced journalists and scientists can ask questions that other folks never think of. Just like surfing Bonzai Pipeline takes practice (and a bit of nerve), asking good questions takes practice (and a bit of confidence). Like the big wave that got away, an unasked question is an opportunity missed.

In science, however, we differentiate between scientific and nonscientific questions. A **scientific question** concerns the natural and observable world. As outlined by the National Research Council (NRC 2002), a scientific question is one that "can be investigated empirically," that is, by using our senses to gather evidence. Questions like why is the ocean blue, why do waves break at the shore, and how do sperm whales hold their breath so long can be answered using science. Questions about if God exists or whether humans have untapped mental powers aren't scientific. They don't lend themselves to observation (at least not at this time).

A scientific question typically builds upon previous research and scientific theory; it "links research to relevant theory" (NRC 2002). A newly posed scientific question contributes to a **chain of reasoning**, a logical extension of previous work. It's not enough to simply work on a question in a field of study in which others are working. A scientist's work requires an intimate knowledge of what has been published in that field and what questions remain unanswered. A scientist's questions pick up where others left off or take the next step in a series designed to figure something out. A 12th-century quote popularized by Sir Isaac Newton (1643–1727) sums it up nicely: "If I have seen further, it is by standing on the shoulders of giants" (Newton 1675). The discoveries of modern science owe their existence to the discoveries of scientists in previous times.

Scientific questions must be general enough to apply in different settings. A study that focuses on one event in one place at one time will be difficult to replicate and generalize. Research on human behavior in social sciences and education often faces problems of replicability and generalization. Replicability stands at the heart of scientific progress. If a scientist's results cannot be replicated, then those results will be questioned and potentially dismissed.

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2.4: Propose an Idea or Model

Collecting observations and forming questions naturally lead to consideration of possible answers. Humans relish in coming up with ideas about why something happened. Because of the way our brains work, we try to fit observations into mental frameworks of what we already know. These frameworks become conceptual models (introduced in Chapter 1), idealized representations of the world around us.

Conceptual models often take the form of illustrations, diagrams, and even animations. Descriptions and drawings of imaginary things like dragons, mermaids, and extraterrestrials represent someone's conceptual model of these creatures. Ideas also take the form of illustrations or graphics, primarily as a means of refining those ideas and explaining them to others. In fact, most illustrations that you see in textbooks represent conceptual models. An illustration of the major ocean currents and a diagram of the interactions of species in an oceanic food web serve as examples of conceptual models of how a part of the ocean works.

Scientists, like everyone else, employ other kinds of models to help them understand and test hypotheses about the natural world. As a child, you likely played with toys. Toys are a kind of **physical model**, a scaled-down, three-dimensional, semirealistic representation of an object or part of nature. A Matchbox car is a physical model of a real car. A Cabbage Patch doll is a physical model of a human baby. Lincoln Logs represent real logs; Legos represent construction materials. These physical models allow kids to experience through pretend play what it's like to drive a real car, care for a real baby, or build a house. They provide a sense of the excitement and, hopefully, the responsibilities involved with an actual car, baby, or house.

A third kind of model uses mathematics to formulate and test ideas. **Mathematical models** represent simple or complex expressions used to describe or simulate how something works. We usually think of them as **quantitative**—giving numerical results—but they may also be **qualitative**, helping scientists describe properties or relationships between variables (e.g., Dambacher et al. 2015). Mathematical models underpin the stock market, retirement planning, business development, economics, and a whole host of other human activities.

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2.5: Test Your Hypotheses

Models form the cornerstone of human thinking, but a model, any model—conceptual, physical, or mathematical—is only as good as the facts that support it. To determine whether a model accurately describes or predicts a natural event, scientists carry out what may be the most important part of their work: creating testable hypotheses.

A **hypothesis** is a carefully worded, conditional, and testable explanation of how nature works. You'll often hear people call them educated guesses, but there's little guesswork involved. Scientists typically frame hypotheses within the context of known explanations. Because of previous observations and experiments, they often have a pretty good idea of what's happening—or at least they think they do—and so hypotheses represent the next step in a progression of observations and experiments designed to figure something out. They aren't random and they aren't long lists that include every possible explanation. They are focused, narrowly interpreted, tentative statements that can be tested using carefully planned observations and carefully designed experiments. For example, you might state the hypothesis, "Whales jump out of the water to remove barnacles from their skin." You could test this by observing whales.

One often overlooked and misunderstood characteristic of hypotheses is how they are worded. Scientists pose hypotheses in a manner that allows them to be rejected by observations and experiments. It may seem a curious way to go about something, but science generally attempts to disprove possibilities—eliminate hypotheses—rather than prove them. Scientists call this method **falsification**, the process of disproving a hypothesis. While some argue that falsification can be limiting in certain fields, especially branches of modern particle and theoretical physics (e.g., Carroll 2014), most scientists view it as a cornerstone of the scientific method. Our test of the whale-jumping hypothesis would be rejected (i.e., falsified) if we observed whales without barnacles jumping or if the act of jumping had no effect on whale-attached barnacles. See how that works?

The process of eliminating competing hypotheses was developed by Austrian-British science philosopher Karl Popper (1902–1994; Popper 2005). It belongs to a broader approach called **deductive reasoning**. Deduction operates as a kind of top-down logic: If A is true, and B belongs to A, then B is also true. For example, if all mammals breathe air, and a dolphin is a mammal, then dolphins breathe air.

While most scientists use deductive reasoning, the opposite form, **inductive reasoning**, also plays a part in science. Inductive reasoning operates as a bottom-up approach to figuring something out. Specific observations lead to general principles. For example, if dolphins use tools, and sea lions use tools, and both dolphins and sea lions are mammals, then, inductively thinking, all mammals use tools. Induction helps in the process of generating appropriate scientific questions and hypotheses from observations or preliminary experiments. Many scientists consider this the most interesting part of their research because it draws upon the creative mind. Science requires a person to imagine all the possibilities. For that reason, scientists tend to be highly creative people, despite their characterization as boring nerds.

A third form of reasoning, **abductive reasoning**, plays a larger role outside of science, where explanations or conclusions are needed to fix something, make a diagnosis, or render a judgment. Abductive reasoning is best explained as the quickest way to the most logical and usually simplest explanation, even though facts and observations may be incomplete. Car mechanics, doctors, and jurors often use abductive reasoning to complete a task because they are presented with limited data. Scientists often use abductive reasoning to generate hypotheses. It's considered the more creative approach to scientific inquiry.

Hypothesis making through inductive and abductive reasoning and hypothesis falsification through deductive reasoning make up what's known as the **hypothetico-deductive approach**, also known as the hypothetico-deductive model or simply the H-D method. It relies on the process of generating a hypothesis that can be falsified by a set of observations or experiments and then carrying out those observations or experiments to reject or support the hypothesis.

The H-D method remains a mainstay of science because it aspires to objectivity. Scientists go to great lengths to be impartial in their work from beginning to end. They don't always get it right, but the self-correcting nature of science and the willingness of scientists to admit their errors make the H-D method the best thing going. To quote American philosopher and education reformer John Dewey (1859–1952):

> *Science represents the safeguard of the race against . . . natural propensities and the evils that flow from them. It consists of the special appliances and methods which the race has*

> *slowly worked out in order to conduct reflection under conditions whereby its procedures and results are tested. . . . Without initiation into the scientific spirit one is not in possession of the best tools which humanity has so far devised. (Dewey 1916)*

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2.6: Conduct an Investigation

All scientific investigations take time, patience, and funding. But ocean science presents special challenges. At least eight broad and overlapping approaches characterize the discipline of oceanography:

- **laboratory investigation**, usually carried out in a laboratory or special facility outfitted with instrumentation, artificial habitats, and other tools for conducting controlled experiments and observations
- **oceangoing (or field) investigation**, typically carried out in the ocean, including along the shore, using snorkel or scuba, or on a small vessel, large ship, submersible, or other manned vehicle
- **robotic investigation**, using remotely operated vehicles, autonomous vehicles, drifters, gliders, and similar craft
- **time-series investigation**, using instruments deployed on moorings, autonomous seafloor instruments, and cabled ocean observatories
- **animal-tagging investigation**, in which oceanographers attach instrument packages to marine mammals (e.g., elephant seals) or large fishes (e.g., great white sharks)
- **aerial investigation** (confined to Earth's atmosphere), including instruments flown on drones, tethered balloons, and manned aircraft
- **spaceborne investigation**, mostly carried out by instruments aboard satellites but occasionally conducted by instruments and personnel aboard spacecraft and space stations
- **computer modeling investigation**, ranging from studies done on personal computers to those requiring supercomputers

An oceanographic research program may include any or all of the above approaches. Investigations may be carried out by a single investigator or multiple investigators. They may be supported by undergraduate and graduate research assistants, postdoctoral researchers, lab and field technicians, and personnel from private industry. An investigator may work with colleagues at their own institution or collaborate with colleagues, students, technicians from multiple institutions. The largest oceanographic programs involve scientists from across the globe cooperating on different aspects of a scientific problem and sharing the costs of personnel, equipment, travel, and ships. It's not uncommon to find people from different countries spending several weeks at sea together, working through language barriers, getting used to different customs, and attempting to enjoy what are often unfamiliar foods (like fiskeboller). It works (most of the time) because everyone depends on each other for assistance and safety and is focused on a common goal.

As a real-life example, an international expedition involving hundreds of researchers from 19 countries began a yearlong mission aboard the icebreaker *Polarstern* in the Arctic Ocean in September 2019. Dubbed the Multidisciplinary drifting Observatory for the Study of Arctic Climate, or MOSAiC, the expedition froze their ship into the ice to conduct investigations designed to shed new light on climate change. MOSAiC, the largest shipboard polar expedition ever mounted, recalls the historic journey of Norwegian oceanographer Fridtjof Nansen (1861–1930). Nansen froze his round-bottom wooden sailing ship, *Fram*, into the Arctic ice from 1893 to 1896. (He's also the only oceanographer to win a Nobel Prize, albeit for his humanitarian work.) Oceanographers participating in the MOSAiC mission—which ended in October 2020—were able to take measurements and perform experiments at polar latitudes over all four seasons, including Arctic winter. Though larger than most, MOSAiC serves as just one example of dozens of similar oceanographic investigations carried out in coastal waters and across the world ocean annually.

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2.7: Analyze Your Results

Data analysis represents the worst of times and the best of times for scientists. Entering, organizing, reducing, summarizing, tabulating, graphing, and analyzing scientific observations and data—in some cases, millions upon millions of data points—can be time consuming, frustrating, tedious, and a downright pain in the caboose. On the other hand, as the averages emerge, as the trends become clear, as the relationships make themselves known, and as something that no one has previously witnessed or discovered sees the light of day, data analysis can be one of the most exhilarating experiences in a scientist's life. After all, the data tell the story. They refute or confirm the hypotheses and ideas. They tell the scientists whether they're on the right track or whether a particular set of experiments is an utter failure. Data analysis is often the make-or-break moment in a scientific study. Occasionally, a scientist's work results in something so extraordinary that it changes the world. Our modern, industrialized civilization—including the smartphone you're checking as you read this—represents an accumulation of these moments in science.

Without question, the tools, methods, and approaches of data analysis have been transformed by the development of technology, notably computing. Scientists have been using computers since the 1950s, but computers' speed and ease of use have changed dramatically in the past 20 years. As one oceanographer put it, computers did for the 20th century what adoption of Arabic numerals did for the 17th century: they transformed how we think (Warren 2006). Three examples illustrate Warren's point: numerical models, big data, and artificial intelligence.

In recent decades **numerical models**, also known as mathematical or computer models, have evolved alongside theory and observation into what oceanographers call the third element of oceanographic research. Models generate data by solving sets of equations that represent—in the scientist's mind—how a system works. When the model's predictions (or forecasts) are compared to observations from nature, scientists can determine how well they do or don't understand a system. When the model outputs fail to match observations, scientists know that some part of their model needs revision. This stepwise process—generating model predictions, comparing them to real-world observations, and revising the model—helps scientists improve their understanding of the natural world.

Models serve a practical function too. A branch of applied ocean science known as **operational oceanography** serves as a kind of ocean weather forecasting service. Its models produce near-real-time output called **nowcasts**. To create nowcasts, oceanographers use observational data from various near-real-time electronic streams, such as buoys, floats, satellites, and even ships. Operational oceanography serves commercial marine interests (fishing and shipping, for example), the military (which depends on up-to-date knowledge of the ocean to conduct its operations), and recreational interests (like boaters and surfers).

Increasingly, oceanographers are turning to computer scientists for help managing large oceanographic data sets. **Big data** refers to an emerging subdiscipline of computer science that tackles the challenges of analyzing data sets whose size or complexity exceeds the capabilities of traditional software and computers. Hey et al. (2009) refer to this "data-intensive computing" as the **fourth paradigm**, the use of computers to explore and mine big data for information. In a sense, the fourth paradigm emerges from the ability of computers to think. They detect patterns that we cannot. Big data scientists emphasize five key properties of big data: volume (lots of it), variety (many different sources), velocity (coming at you fast), veracity (ensuring the data are real and free of errors), and value (what you can learn; e.g., De Mauro et al. 2016). The terminology has largely developed in response to the proliferation of electronic devices such as smartphones, watches, tablets, virtual assistants, and similar devices. Capable of tracking, storing, and archiving (via the cloud) practically everything you do on your device, the resultant data stream (popularly known as digital exhaust) generates mind-blowing quantities of information.

Oceanographers have long faced the challenges of big data, **marine big data**, as they refer to it (e.g., Huang et al. 2015, 2019). They note that American oceanographer Matthew Maury's (1806–1873) compilation of wind and current data from ships' logs contained 1.2 million data points. Results from the world's first global oceanographic voyage, the *Challenger* expedition (1872–1876), spanned 50 volumes and more than 29,500 pages (Murray 1895). More recently, large, multi-institutional oceanographic expeditions churn out data by the petabyte. That's a thousand times a terabyte, the typical storage capacity of the current generation of desktop computers. A single Earth-observing satellite, the *Aquarius*, logs more data in two months than the first 125 years of ship and buoy data gathering (Huang et al. 2015). Developing the architecture and algorithms to collect, verify, store, process, integrate, and analyze such massive volumes will require new ways of thinking and a new generation of marine data science techies. Perhaps you will be among them.

One possible solution for extracting meaningful information from big data lies in **artificial intelligence**, or AI, a broad category of data science aimed at building computer and software systems that mimic human intention, intelligence, and adaptability (e.g., West and Allen 2018). While application of AI-based data analysis in the marine sciences has been slow to develop, the field holds great promise for extracting greater value from big data. Working side by side, humans and machines engaged in ocean science research may accelerate our knowledge and understanding of the world ocean as never before.

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2.8: Form Your Conclusions

The grand finale of the scientific method—forming your conclusions—proves to be the most challenging for many scientists. This is where the rubber meets the road, so to speak. A scientist must now make sense of their data. They must extract meaning and significance. They must use the evidence of their observations, measurements, and experiments to tell a story. And they must tell that story in a way that other scientists and even the public can understand. Most often, this story forms the basis of a **scientific discussion**, the presentation in oral or written form of the conclusions of a particular scientific study. Though forming conclusions differs depending on the nature of the research, in general, four steps are crucial (e.g., Heard 2016):

1. How do the results shed light on (i.e., answer) your original research questions?
2. What are the strengths and weaknesses of your results in answering your research questions?
3. How do your conclusions build upon, extend, or contradict previous work on this topic?
4. What questions and considerations arise for future research on this topic?

Here's where science most often tests the modesty of a scientist. After all, if you designed and carried out the research, you're naturally (and forgivably) inclined to think it's brilliant! Yet a scientist's interpretation of their results may be subject to **bias**, a less-than-objective, partial, and sometimes distorted view of scientific evidence. Scientific bias almost certainly stems from a worldview formed as a result of years or decades of experience in the field. There's nothing intentional or malevolent about it. Scientists are human, after all, but they must always remain aware of the inherent biases in their work. As Milroy (2016) puts it:

> *Regardless of the strength of your hypothesis or the veracity of your data, as human beings we are always prone to making errors in our analyses. In the context of science, this almost always occurs because we have some preconceived notion of how our experiments should turn out, and if our data seem to support our original hypothesis, it is difficult to step back from all of your hard work and look at the results with a truly cynical eye. Results can be easily misinterpreted unless you are very careful to devise an experiment where the results can only be construed in one way.*

The scientific method embodies a set of checks and balances that guard against this very thing, a system called **peer review**, which may be defined as the feedback on a scientist's work by other scientists or experts. A scientist may meet with or Zoom with a trusted colleague and ask them what they think, or present preliminary conclusions to gain feedback. Scientific papers undergo scrutiny by anonymous reviewers, a formal peer review process that further ensures the validity of the data and the veracity of a scientist's conclusions. Of course, errors, misstatements, and, on rare occasions, deliberate misrepresentation of results may occur. But science rests on the accumulation of evidence from multiple studies and multiple scientists. The self-correcting nature of science is what makes it one of the most valuable tools ever invented by humans. Scientists don't always get it right the first time, but eventually, through the scrutiny of the ages, after decades to centuries, the truth emerges. Truths become well-established scientific theories, and the extent of our knowledge and understanding progresses.

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2.9: Communicate Your Science

In the 21st century, communication of scientific results takes many forms, including:

- peer-reviewed scientific journals
- talks and poster presentations at scientific conferences
- workshop or symposium compilations
- popular magazines (e.g., *National Geographic*, *Scientific American*)
- science books (of all varieties, including textbooks)
- public social media (especially Twitter, but also Facebook and Instagram)
- professional and scientific social media (such as LinkedIn, ResearchGate, Academia)
- videos (e.g., YouTube, Vimeo, TikTok)
- live appearances (e.g., Zoom)
- blogs, podcasts, websites, email, and more!

Unfortunately, most scientists are trained only to present papers and talks. That's fine if you're communicating solely with scientists in your own discipline. But nearly all forms of science these days—and the agencies that fund the work—require communication with people outside the discipline, including scientists in other fields.

In its 2017 report, *Communicating Science Effectively: A Research Agenda*, the National Academy of Sciences, Engineering, and Medicine (NASEM) defines **science communication**, popularly known as SciComm, as "the exchange of information and viewpoints about science to achieve a goal." A science communicator may strive to develop "a greater understanding of science and the scientific method" or to "help people understand the science relevant to a decision." NASEM acknowledges that:

The methods scientists use to understand the world are unlike the ways people typically think on a day-to-day basis. The results of science also can be insufficient, ambiguous, or uncertain, and scientific conclusions can change over time as new findings emerge. These inherent characteristics of science can create barriers to communication and understanding.

You can't really blame the scientists. American biologist and book author Paul Ehrlich (*b*. 1932) famously opined that "If what does is comprehensible to the general public, it means he's not a good scientist. That's what I thought. I was wrong" (from Goodell 1977). Indeed, the importance of communicating science to the public is greater than ever before. Public interest in climate change, vaccines, environmental pollution, genetically modified foods, fracking, and a host of similar socioscientific issues underscores the need to bridge the gap between scientists and the public. As Fischhoff (2013) puts it, "Effective SciComm informs people about the benefits, risks, and other costs of their decisions, thereby allowing them to make sound choices." Increasingly, educators view SciComm training as a priority in the education of future scientists (e.g., Brownell et al. 2013; Montgomery et al. 2022).

Even if you're pursuing a career outside science, you play a role in SciComm. When you tell family or friends about your science courses, you represent something about science. Your experience in a science class (and reading a science textbook!) shapes your opinions, good, bad, or otherwise. And those opinions are expressed every time you post something (hopefully, good) about science.

A common refrain I hear from students is "I'm not good at science." Of course not! You're probably not good at fixing spaceships, either. These things take years of training and experience. But having a sense of where scientists are coming from, learning how to decipher their statements, and understanding that behind every statement is a body of evidence may be more valuable to the world than just knowing a bunch of science facts. If the end result of a science course is that you understand and appreciate how science works—and have a positive feeling about the work that scientists do—then you deserve an A in my book!

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2.10: Chapter References

Alfred Wegener Institute. “MOSAiC.” Accessed May 27, 2022. https://mosaic-expedition.org/

Brownell, Sara E., Jordan V. Price, and Lawrence Steinman. 2013. “Science Communication to the General Public: Why We Need to Teach Undergraduate and Graduate Students This Skill as Part of Their Formal Scientific Training.” *Journal of Undergraduate Neuroscience Education* 12(1): E6–E10. https://pubmed.ncbi.nlm.nih.gov/24319399

Carroll, Sean. 2014. *Falsifiability*. Contribution to *What Scientific Idea Is Ready for Retirement?* Edge.org. https://www.edge.org/response-detail/25322

Dambacher, Jeffrey M., Peter C. Rothlisberg, and Neil R. Loneragan. 2015. “Qualitative Mathematical Models to Support Ecosystem-Based Management of Australia’s Northern Prawn Fishery.” *Ecological Applications* 25(1): 278–298. https://doi.org/10.1890/13-2030.1

De Mauro, Andrea, Marco Greco, and Michele Grimaldi. 2016. “A Formal Definition of Big Data Based on Its Essential Features.” *Library Review* 65(3): 122–135. https://doi.org/10.1108/LR-06-2015-0061

Dewey, J. 1916. *Democracy and Education: An Introduction to the Philosophy of Education*. New York: Macmillan. https://www.google.com/books/edition/Democracy_and_Education/8P0AAAAAYAAJ?hl=en

Fischhoff, Baruch. 2013. “The Sciences of Science Communication.” *Proceedings of the National Academy of Sciences 110*: 14033–14039. https://doi.org/10.1073/pnas.1213273110

Goodell, Rae. 1977. “The Visible Scientists.” *The Sciences* 17(1): 6–9. https://doi.org/10.1002/j.2326-1951.1977.tb01494.x

Harwood, William. 2004. “A New Model for Inquiry: Is the Scientific Method Dead?” *Journal of College Science Teaching* 33(7): 29–33. https://www.jstor.org/stable/10.2307/26491315

Heard, Stephen B. 2016. *The Scientist’s Guide to Writing*. Princeton, NJ: Princeton University Press. https://doi.org/10.2307/j.ctvcmxs67

Herbert, Frank. 1965. *Dune*. New York: Ace Books. https://archive.org/details/dune0000herb_a7n1/mode/2up

Hey, Tony, Stewart Tansley, and Kristin Tolle, eds. 2009. *The Fourth Paradigm: Data-Intensive Scientific Discovery*. Seattle: Microsoft Research. https://www.microsoft.com/en-us/research/publication/fourth-paradigm-data-intensive-scientific-discovery/

Huang, Dongmei, Wei Song, and Guoliang Zou. 2019. *Marine Big Data*. Hackensack: World Scientific. https://doi.org/10.1142/11337

Huang, Dongmei, Danfeng Zhao, Lifei Wei, Zhenhua Wang, and Yanling Du. 2015. “Modeling and Analysis in Marine Big Data: Advances and Challenges.” *Mathematical Problems in Engineering*. https://doi.org/10.1155/2015/384742

Milroy, Scott. 2016. *Field Methods in Marine Science: From Measurements to Models*. New York: Garland Science. https://www.routledge.com/Field-Methods-in-Marine-Science-From-Measurements-to-Models/Milroy/p/book/9780815344766#

Montgomery, Thomas D., Joanne Rae Buchbinder, Ellen S. Gawalt, Robbie J. Iuliucci, Andrew S. Kock, Evangelia Kotsikorou, Patrick E. Lackey, Min Soo Lim, Jeffrey Joseph Rohde, Alexander J. Rupprecht, Matthew N. Srnec, Brandon Vernier, and Jeffrey D. Evanseck. 2022. “The Scientific Method as a Scaffold to Enhance Communication Skills in Chemistry.” *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.2c00113

Murray, John. 1895. *Report on the Scientific Results of the Voyage of the H.M.S. Challenger During the Years 1872–76: A Summary of the Scientific Results, First Part*. Published by Order of Her Majesty’s Government. https://doi.org/10.5962/bhl.title.6513

National Academies of Sciences, Engineering, and Medicine. 2017. *Communicating Science Effectively: A Research Agenda*. Washington, DC: National Academies Press. https://doi.org/10.17226/23674

National Research Council. 2002. *Scientific Research in Education*. Washington, DC: National Academies Press. https://doi.org/10.17226/10236

Newton, Sir Isaac. 1675. “Letter to Robert Hooke.” https://digitallibrary.hsp.org/index.php/Detail/objects/9792

Popper, Karl. *The Logic of Scientific Discovery*. 2nd Ed. Milton Park: Routledge. https://www.routledge.com/The-Logic-of-Scientific-Discovery/Popper/p/book/9780415278447

Rentzsch, Katrin, and Michaela Schröder-Abé. 2014. "Self-Enhancement 2.0: An Integrated Approach to Measuring Dyadic Self-Enhancement at Two Levels." *Social Psychological and Personality Science* 6(3): 251-258. https://doi.org/10.1177%2F1948550614558634

Rudzin, Johna E., Dax C. Soule, Justine Whitaker, Halle Berger, Sophie Clayton, and Kristen E. Fogaren. 2022. "Catalyzing Remote Collaboration During the COVID-19 Pandemic and Beyond: Early Career Oceanographers Adopt Hybrid Open Science Framework." *Frontiers of Marine Science* 9: 1–7. https://doi.org/10.3389/fmars.2022.855192

Warren, Bruce A. 2006. "Historical Introduction: Oceanography of the General Circulation to the Middle of the Twentieth Century." In *Physical Oceanography: Developments Since 1950*. Edited by Jochum Markus and Raghu Murtugudde, 1–14. New York: Springer. https://doi.org/10.1007/0-387-33152-2

West, Darrell M., and John Allen. 2018. "How Artificial Intelligence is Transforming the World." Brookings. April 4, 2018. https://www.brookings.edu/research/how-artificial-intelligence-is-transforming-the-world/

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CHAPTER OVERVIEW

3: Science Aboard Ships

We can never know for sure who was the first person to dive beneath the waves in search of food or artifacts, but we do know that ancient peoples—perhaps as far back as one hundred thousand years ago—collected shells, shellfish, and other valuable undersea resources along the coastline (e.g., Will et al. 2019). As human use of the ocean grew for military, economic, and industrial purposes, so too did the need to know more about the ocean. Studies of marine biology, oceanography, and fisheries emerged as scientific quests to acquire knowledge of the sea for human purposes (e.g., Mills 2012).

In the next three chapters, we explore the approaches and technologies used to carry out ocean science—the methods of an oceanographer. Admittedly, a tour of methods might seem a bit like wandering through a home improvement store. (Indeed, oceanographers often shop at these stores—you can never have enough duct tape on board a rolling ship.) But a brief survey of these technologies will help you appreciate the myriad ways in which oceanographers are probing the world ocean. This appreciation will help you better understand the team approach to ocean science and the interconnectedness of processes in the world ocean.

My friend and colleague University of California (UC) Santa Barbara physical oceanographer Tommy Dickey (*b.* 1945) spent his career pushing the boundaries of ocean science through application of new technology. In his 2020 paper "New Discoveries Enabled by the Emergence of High-Resolution, Long-Term Interdisciplinary Ocean Observations," he wrote:

> *The vastness and inhospitable nature of our oceans has limited our ability to understand oceanic phenomena and to make ocean predictions. Great progress in sampling the vertical and temporal variability of the ocean was made with new sensors and moorings in the period of 1980–2000; however there remain major challenges to adequately sample the full three-dimensional and temporal variability of the interior ocean.*

3.1: The Birth of Oceanography
3.2: Sampling over Space
3.3: Sampling over Time
3.4: The Challenge of Pressure
3.5: The Undersampling Problem
3.6: Modern Oceanographic Vessels
3.7: Beneath the Surface
3.8: Chapter References

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3.1: The Birth of Oceanography

While many important scientific expeditions took place in the 19th century, one above all, the *Challenger* expedition (1872–1876), brought together the interdisciplinary approaches that would characterize the field of oceanography in modern times. Oceanographer and marine biologist Henry Bigelow (1879–1967), who helped found the world-famous Woods Hole Oceanographic Institution (WHOI) in Massachusetts, wrote in his 1931 textbook, *Oceanography*, "Students of the history of science may well date the birth of modern oceanography from December 21, 1872, the date when put to sea from Plymouth, England." Indeed, the *Challenger* expedition was the first devoted entirely to ocean science. A decade after their voyage, Scottish expedition leader Sir Charles Wyville Thomson (1830–1882) and Canadian oceanographer John Murray (1841–1914) wrote:

> *The vast ocean lay scientifically unexplored. All the efforts of the previous decade had been directed to the strips of water round the coast and to enclosed or partially enclosed seas. . . . This consideration led to the conception of the idea of a great exploring expedition which should circumnavigate the globe, find out the most profound abysses of the ocean, and extract from them some sign of what went on at the greatest depths. (Thomson and Murray 1885, p. l)*

The *Challenger* expedition covered 79,277 miles (127,584 km) of ocean and gained fame for its ambitious plan and the magnitude of its accomplishments. Its results filled 50 printed volumes. But perhaps most lasting among its contributions was its influence on the way oceanographers sample the ocean, a sampling approach that remains an integral part of oceanographic research more than 150 years later.

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3.2: Sampling over Space

Since the days of the *Challenger* expedition, shipboard oceanography has used a sampling approach based on grids of points stretched over a region of interest. As Thomson describes it, “At intervals as nearly uniform as possible, we established 362 observing stations” (Thomson 1878, p. xi). Thomson’s observing stations are now known as **hydrographic stations**, or simply stations. Each point on the grid represents a station. The line along which the ship moves from station to station is known as a **transect**. Hydrographic stations mark the spots where geological, chemical, physical, and biological measurements and samples may be taken. Of course, oceanographers may carry out measurements and take samples along the transect while underway, too. The number of stations and length of the transect depend on the number of days allotted to the expedition and the type and amount of work that the expedition team desires to carry out.

The distance between samples of different regions of the ocean—horizontally or vertically—defines the **spatial resolution** of the measurements. As someone living in the 21st century, you have undoubtedly witnessed increases in the spatial resolution of televisions and smartphone cameras. Spatial resolution defines the smallest object or feature that may be resolved or distinguished by the display or sensor in your television or smartphone camera—such as 4K resolution (and soon 8K and 16K). Similarly, for oceanographers, spatial resolution refers to the smallest features that may be distinguished in a particular set of data. At higher spatial resolution, oceanographers can identify an individual underwater mountain versus a blob of mountains. They can discriminate the fine details of different water temperatures (depicted as colors) instead of one blotch of the same temperature. Low spatial resolution occurs when oceanographers have to take samples far apart in distance or when a sensor can only measure broad swaths of the ocean. To obtain higher spatial resolution, oceanographers must take more samples in a given area or build sensors that detect smaller features. But there are limits.

Time, technology, and funding don’t always permit the highest spatial resolution. A compromise has to be made between *where* oceanographers sample and *how much* they sample: more locations with fewer samples at each location or fewer locations and more samples. Taking and processing more samples takes more time. Observing smaller details of the ocean demands better technology. But time and technology require money that is not always available.

An excellent example of the application of grid sampling can be found in the California Cooperative Oceanic Fisheries Investigation (CalCOFI), which has been conducting oceanographic surveys off the coast of California since 1949. The original grid in 1950 included hundreds of stations along the California coastline and parts of Baja. But since 2004 the survey has been limited to between 75 and 109 stations over a smaller area. Today CalCOFI samples an area of 73,184 square miles (189,547 km^2), a considerable expanse but still less than 0.05 percent of the world ocean. Nevertheless, CalCOFI ranks as “the longest-running oceanographic monitoring program on the planet” (e.g., Koch 2019).

Combinations of technology and ships now provide an ability to sample the ocean at spatial scales spanning twelve orders of magnitude—from kilometers down to nanometers (e.g., Dickey 1990; Branson et al. 2016). The challenge for 21st-century oceanographers will be to connect the dots—to find the connections—between processes at each of those scales (e.g., Dickey 1991).

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3.3: Sampling over Time

Ocean properties also vary with time. Similar to spatial resolution, we refer to **temporal resolution** (i.e., time resolution) as the interval of time between samples. A once-a-month sampling program has a temporal resolution of one month. A daily sampling regime has a temporal resolution of a day, and so on. But why is this important?

Imagine that you were tasked with summarizing the details of every movie playing in a 21-screen multiplex, all with different start times. To complete the task, you would have to move from theater to theater and watch only a few minutes of one movie before moving on to the next. You would never be able to see one movie in its entirety. And if you spent more time on one movie, you would sacrifice your knowledge of other movies.

The ocean is like a multiplex in which thousands—if not millions—of movies are playing simultaneously. What's more, the plot of each movie keeps changing as different characters and events arise. When you return to the first theater, there's no guarantee that the original film will still be playing. It's maddening, but somehow, through persistence, repetition, well-honed methods, and careful sampling strategies, oceanographers have begun to make sense of it all.

In the CalCOFI program, oceanographers obtain one set of samples per station approximately every three months. Such sampling permits oceanographers to track changes on seasonal scales, but what about day-to-day or week-to-week changes? Oceanographers simply don't have the tools or manpower to sample the ocean over all relevant scales of space or time. But, as we shall see in the chapters ahead, new technologies are helping to improve ocean sampling at ever-finer spatial and temporal scales.

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3.4: The Challenge of Pressure

Nearly every technology developed for ocean exploration beneath its surface confronts one inevitable question: How deep can it go without being crushed? Many a machine has been lost (some with lives aboard) because of the intense pressure exerted by the ocean. Pressure is the reason why it's easier to explore outer space. A dozen humans went to the Moon half a century ago, traveling a distance of 238,855 miles (384,400 km), but until 2019, only three humans had been to the Challenger Deep, the deepest location in the world ocean, a mere 6.8 miles (10,925 m) deep. Though dozens of people have now descended to the Challenger Deep (see below), extreme water pressure remains a barrier to all but the most specialized technologies.

Physicists define **pressure** as the force exerted by a fluid (a gas or a liquid) on an object immersed within it. In the ocean, every 10 meters of water depth, about 33 feet, increases pressure by about 14.7 pounds per square inch, or 1 atmosphere (atm) at sea level. Earth's atmosphere, on average, extends about 7.5 miles (9.17 km) above us. So the pressure exerted by about 33 feet of water equals the pressure exerted by about 7.5 miles of gases in our (one) atmosphere. For simplicity, oceanographers often express water pressure in units of atmospheres. The calculation is quite simple:

$$P\ (atm) = z\ (m) / 10\ (m/atm) + 1\ (atm)$$

(Eq. 3.1)

where P is water pressure, z is depth, and 1 atm represents the pressure at sea level (from the atmosphere pressing down on the ocean).

The simple math makes it apparent: you don't have to go very deep to experience great pressure. At 800 times the density of air, water exerts a much greater pressure on objects immersed within it. At a depth of a hundred feet (roughly 30 m), a diver experiences three times the pressure they would experience at sea level. Free divers—persons who dive with no scuba gear and rely only on holding their breath—experience even greater pressure. The current no limits freediving record depth of 702 feet (214 m), held since 2007 by Austrian Herbert Nitsch (*b.* 1970), converts to a water pressure 22 times the pressure at sea level (e.g., The Salt Sirens 2021). Imagine a newborn baby elephant (about 300 lbs) balanced on a USB wall charger (about 1 square inch on each side). That's what a free diver experiences at those depths.

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3.5: The Undersampling Problem

The challenges of sampling a difficult environment across multiple scales of space and time have led to what is known as the **undersampling problem** in oceanography. Oceanographers do not yet possess a sufficient number of measurements to develop a complete understanding of ocean processes. Advances in technology—especially satellites and robots—have improved the spatial and temporal resolution of observations. Though some oceanographers contend the physics of the ocean is adequately sampled (e.g., Munk 2000), many parts of the ocean, especially the deep ocean, and many biological processes remain undersampled (e.g., van Haren 2018; Claustre et al. 2020).

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3.6: Modern Oceanographic Vessels

Oceanographic research vessels form the backbone of ocean research in the 21st century. While their ability to provide much-desired spatial and temporal resolution remains limited, ships offer a platform for nearly every other type of technology used to study the ocean. Humans working aboard ships can perform feats no modern robots can come close to. Ships enable diverse teams of oceanographers from all over the world to carry out collaborative research.

Modern oceanographic research vessels—designated by R/V in front of the ship's name—serve several functions. Under the supervision of a trained captain and crew, they provide a safe, comfortable, mobile habitat for dozens of scientists and technicians. Among their many attributes,

- They provide a stable platform for launching and deploying a variety of oceanographic instruments above, below, and on the surface of the ocean.
- They permit scientists to access remote ocean locations, including the central gyres of the major oceans, ice-covered oceans, and remote islands.
- They offer state-of-the-art navigation capabilities, providing precise locations for sampling (underway or on station) and the ability to return to those exact locations in the future.
- They offer state-of-the-art communications and telepresence capabilities, allowing oceanographers and crew to download satellite imagery and stream images to shoreside personnel and the public.
- They provide specialized cranes and winches for deploying oceanographic instruments, such as submersibles and robotic craft.
- They offer ample deck space, such as a **fantail**, a broad platform on the rear of a vessel, where oceanographers can work outside close to the waterline, and where portable vans (or clean rooms) can be installed for carrying out specialized analyses and experiments.
- They provide laboratories with benchtop instruments for at-sea analyses of collected samples, where live organisms may be observed, and where samples may be prepared and stored for shoreside analyses.
- They offer computing capability for storing and analyzing electronic data in real time or on demand.
- They provide mess halls and places to sleep, bathe, and relax (e.g., a lounge with a big-screen TV, a library, a gym, and, on some vessels, a sauna). Some of these spaces can also be used for meetings and conversations with colleagues.

Most oceanographic research vessels operate under the supervision of the University–National Oceanographic Laboratory System, better known as UNOLS. The UNOLS fleet includes five global-class ships, six intermediate-range oceangoing vessels, and seven regional/coastal-class ships. UNOLS also coordinates the use of nearly one hundred small research vessels (35–100 feet in length). UNOLS-approved vessels meet strict standards, including rules aimed at individual conduct, prohibitions on drugs and alcohol, and guidelines on privacy, discrimination, and harassment while on board (UNOLS 2021). Researchers who request use of a UNOLS vessel must adhere to these standards.

Oceanographers also make use of **ships of opportunity**, commercial vessels that regularly cross the ocean, such as freighters, tankers, cruise ships, and ferries. The Ships of Opportunity Program (SOOP) provides reports on weather conditions and deploys expendable profilers that measure properties of the **water column**, an unspecified volume of water from the surface to a particular depth. SOOP, managed by the National Oceanic and Atmospheric Administration (NOAA), currently collects weather and ocean data from more than 1,200 vessels.

It goes without saying that life aboard an oceanographic research vessel brings adventure, excitement, and a sense of camaraderie with fellow scientists. Crew and scientists typically work around the clock in shifts of four hours on and eight hours off or some variation thereof. With multiple teams of scientists carrying out different kinds of investigations, a research cruise may seem a little like a three-ring circus. But in the end, weather and equipment permitting, everyone accomplishes as much as they possibly can in the time allotted. It's a lot of work, and the work can be exhausting, but you won't get any sympathy from the crew. When I once complained on the R/V *Oceanus* about being tired, the galley person responded, "You can sleep when you're dead."

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3.7: Beneath the Surface

Technology that permits humans to travel beneath the surface of the ocean dates back at least to the fourth century BCE. The Greeks apparently figured out they could hoist a large metal pot over their head, walk out into the water, and breathe the air trapped inside. Thus was born the **diving bell**, a dome-shaped, air-filled chamber that permits divers to work at depth, even in modern times. Aristotle (384–322 BCE) mentions diving bells used by sponge divers in the Aegean Sea (Forster 1927). His student, Alexander the Great (356–323 BCE), purportedly used a diving bell to observe a "gigantic creature that took three days to pass by" (Bevan 1999). Of course, had he stayed submerged for such a time, he would have been dead from lack of oxygen. Obviously, you can't believe everything you read in books.

Human desire to reach the deepest depths of the ocean finds a place in the 20th century as well. In the 1930s, two Americans, naturalist William Beebe (1877–1962) and engineer Otis Barton (1899–1992), built the world's first **bathysphere**, a hollow steel sphere with transparent baseball-sized portholes for making observations. Lowered on a cable from a ship, the bathysphere—with the men bolted inside—made a series of successful descents, including one to 3,028 feet (923 m) on August 11, 1934. Beebe's sketches and account of his dives resulted in a best-selling book, *Half Mile Down* (1934), the first work to document the strange and wonderful animals that inhabit the dimly lit waters known as the **mesopelagic zone**.

A few decades later, a similar vehicle, the **bathyscaphe** *Trieste*, enabled two men to reach the Challenger Deep, the first humans ever to do so. A bathyscaphe consists of a hollow steel sphere attached to a giant gasoline-filled "bladder," which provides the necessary buoyancy for returning divers to the surface without a cable. On January 23, 1960, Swiss oceanographer and engineer Jacques Picard (1922–2008) and US Navy lieutenant-oceanographer Don Walsh (*b.* 1931) descended to 35,814 feet (10,916 m), setting a world record for the deepest dive. Their record would stand for 52 years (Walsh 1962).

Scuba

No summary of underwater technology would be complete without mention of the invention that permitted humans to see the undersea world firsthand: the self-contained underwater breathing apparatus, better known as **scuba**. Invented in 1943 by French engineer Émile Gagnan (1900–1979) and French ocean explorer Jacques Cousteau (1910–1997), scuba permits humans to inhabit shallow waters for limited periods of time. Cousteau's television series, *The Undersea World of Jacques Cousteau* (1968–1975), instilled in the public a love for the ocean and inspired the careers of many a marine biologist and oceanographer, including mine (Cousteau and Schiefelbein 2007).

While typically limited to shallow waters (less than 130 ft), **scientific diving**—underwater observations, measurements, and experiments using scuba—provides a means for scientists to carry out direct observations or experimental studies for extended periods of time. In recent years, marine scientists have begun to use advanced scuba tools (i.e., advanced technical diving) to explore **mesophotic coral ecosystems**, deep, light-dependent coral reefs found at depths between 100 and 500 feet (30–250 m; e.g., Loya et al. 2019; Bell et al. 2022).

Scientific divers may also employ a **shark cage** (also invented by Cousteau)—a metal cage that permits safe viewing of sharks and other pelagic ocean species. Divers enter and exit the cage at the surface through an opening in the top. Once divers are inside, the cage descends to an optimal depth for viewing the animals. Though shark-cage diving is popular as a tourist adventure, the cages prove useful for scientific studies where direct observation is required, including estimates of animal length (e.g., May et al. 2019) and studies of feeding behavior (e.g., Becerril-Garcia et al. 2019). I'm told there's nothing like meeting a great white shark face-to-face. Maybe some day you'll get the opportunity.

Atmospheric Diving Suits

The **atmospheric diving suit**, or ADS—also known as an armored diving suit or articulated diving suit—allows divers to explore deeper waters. The ADS resembles a space suit, but it operates more like a submersible (see below). In fact, some authors classify the ADS as a one-person submersible. The ADS maintains sea-level pressure inside the suit—hence its name. This eliminates the need for decompression when the diver comes to the surface.

An early type of ADS, the JIM suit, enabled American marine biologist Sylvia Earle (*b.* 1935) to reach 1,281 feet (381 m) off the coast of Oahu in 1979. The dive lasted two and a half hours and set a record for the deepest dive at the time. During her dive, Earle observed bioluminescence in bamboo corals, a phenomenon not filmed until 2016 (Helgason 2016). The JIM suit—named after a

diver named Jim—was also featured in the James Bond film *For Your Eyes Only* (Glen 1981) and a lesser-known sci-fi film, *DeepStar Six* (Cunningham 1989).

New-generation ADSs can reach depths of 2,000 feet (610 m). They incorporate various types of propulsion units and include LED lights, sonar, HD cameras, real-time atmospheric monitoring, and two-way wired and acoustic communication systems. In 2019, the US Navy teamed up with the National Aeronautics and Space Administration (NASA) to develop a diver-augmented vision device, a heads-up display system for dive helmets. Using the display, the diver can monitor a host of data and receive text messages from topside (such as ROSL, roll on seafloor laughing). The system can even provide augmented-reality displays, useful where visibility is poor (Melnick 2019; Naval Technology 2021).

Submarines

Though predominantly used for military purposes, **submarines**, defined as a vessel capable of propelling itself underwater, also play a role in modern oceanographic research. Since 1993 oceanographers and the US Navy have collaborated on the use of nuclear submarines for oceanographic research, especially in the Arctic. The first mission, named SCientific ICe EXercise 1993, or SCICEX-93, carried five scientists aboard the USS *Pargo*, a Sturgeon-class fast attack submarine named after a fish. The success of SCICEX-93 spurred five more missions from 1995 to 1999. For security reasons the navy instituted scientific accommodation missions, or SCICEX SAMs, in 2000, in which trained navy personnel carried out oceanographic measurements without scientists on board. Scientists may access the data—once it's declassified—through the National Snow and Ice Data Center (SCICEX Science Advisory Committee 2010). As a joint civilian-military program, SCICEX SAMs enable collection of data that would not otherwise be possible to obtain. Observations beneath the ice help verify above-ice satellite observations and further scientific understanding of the role of the Arctic in climate change (Morelo 2010).

Submersibles

Small submarines, better known as **submersibles**, deep submergence vehicles (DSVs), or human-occupied vehicles (HOVs), play a larger role in oceanographic research than submarines, sacrificing speed for depth capability. Unlike submarines, submersibles require a transport ship to carry them to their dive location. And while typical naval submarines carry more than a hundred personnel, most submersibles carry only two or three. Typical modern submarines operate at depths less than 1,500 feet (457 m), but many submersibles can attain depths of 14,763 feet (4,500 m) or more. New generations of submersibles can now reach the deepest locations in the world ocean.

No submersible in the world can match the record of WHOI's HOV *Alvin*—in operation since 1964—the only American scientific research submersible. *Alvin* has enabled the discovery of hydrothermal vents, helped find the RMS *Titanic*, and served countless scientists in pursuit of knowledge about the ocean (e.g., Humphris et al. 2014). As of 2020, the near-60-year-old vessel had logged 5,065 dives, carried 15,186 people, and spent 35,474 hours submerged. But *Alvin*'s most exciting days may lie ahead. In 2022, upgrades to the submersible allowed it to reach a depth of 21,325 feet (6,453 m), the deepest ever for the sub. It may now access some 98 percent of the seafloor. Despite the opinion of some that robots could better serve science at these depths, there's simply no substitute for being there. As one ocean engineer put it, underwater cameras are "still a long way short of what the human eye can do" (Oberhaus 2020).

Still, the very deepest spots remain mostly unreachable. Only two submersibles, the Chinese *Fendouzhe* and the US DSV *Limiting Factor*, can reach the Challenger Deep today. Descending in the *Limiting Factor* in April 2019, American undersea explorer Victor Vescovo became the fourth explorer to reach the Challenger Deep and set a new world record for the deepest dive ever, reaching 35,853 feet (10,928 m). On July 12, 2022, American marine geologist Dawn Wright became the first Black person (and fifth woman) to reach the deepest spot on Earth with a 35,823-foot dive (10,919 m) aboard the *Limiting Factor* (Weinman 2022). More than two dozen people have now reached these depths (Kreier 2022).

Undersea Research Stations

Undersea research stations—semipermanent structures designed for human habitation and scientific research on the seafloor—entered the human imagination long before they became a reality. Historians credit "freethinking" English bishop John Wilkins (1614–1672) as the first person to imagine permanent undersea colonies (Wilkins 1708; Matsen 2009). French writer Jules Verne (1828–1905) imagined a mobile underwater habitat in his epic novel *Twenty Thousand Leagues Under the Sea* (Verne 1870;

translated by Miller and Walter 1993). Captain Nemo's exploits aboard *Nautilus* inspired many an ocean explorer, including Cousteau (Matsen 2009).

In the 1960s Cousteau and his team of divers built three stationary underwater living spaces on the seafloor of the Mediterranean and the Red Sea. The first, the cylindrical Continental Shelf Station Number One, or simply Conshelf I, was established at a depth of 33 feet (10 m) near Marseille, France. At 17 feet long and 8 feet high (about 5.2 × 2.4 m), it served as a kind of underwater tiny house complete with television, radio, and a record player. From September 14 through 21, 1962, French aquanauts Albert Falco (1927–2012) and Claude Wesley (1930–2016) spent a week on Conshelf I, the first humans ever to live underwater for multiple days. According to protocol, the men were required to spend five hours a day outside of the station carrying out observations of marine life and tending an underwater farm. When asked what he would like to do upon his return to the surface a week later, Falco simply replied, "To walk" (Cousteau and Dugan 1963, p. 324).

A year later, the Conshelf II "village" was established in the Red Sea. The starfish-shaped main station, at 33 feet long (10 m), accommodated five men and included a parrot to warn of pressure changes. The undersea village also had a garage for a submersible, an equipment hangar, and a second station 82 feet deeper (25 m). This time, the aquanauts stayed a month. During the last four days of their residency, they were joined by Cousteau's research partner and wife, Simone Cousteau (1919–1990), who became the first woman to live underwater.

The exploration and research in these underwater habitats were captured in the documentary *World without Sun* (Cousteau 1964), which won an Academy Award in 1965 (Cousteau's second in the category). That year the Cousteau team also established a much deeper habitat near Nice, France. Conshelf III, at 336 feet (102 m), housed six aquanauts who remained underwater for three weeks. The idea of people living and working beneath the sea was no longer a fantasy. Cousteau had made it a reality.

Cousteau's success led to construction of similar habitats around the world. Since 1962 at least 70 underwater habitats have been built (Chamberland 2007). But don't let that number fool you—many never made it beyond their first mission. Most no longer exist or have become manmade reefs. And only three ever accommodated aquanauts for longer than 30 days.

The only remaining undersea habitat dedicated to scientific research is Florida International University's Aquarius Reef Base (1986–present), a 400-square-foot, six-person habitat in the Florida Keys. One other operational undersea habitat, the Jules Undersea Lodge (formerly La Chalupa research laboratory), serves as an underwater hotel and occasional classroom in a lagoon in Key Largo Undersea Park in Florida. In 2023, University of South Florida professor Joseph Dituri (*b*. 1968) set a world record for living underwater in the Jules Undersea Lodge (Kim 2023).

In 2020, Cousteau's grandson, French ocean explorer Fabien Cousteau (*b*. 1967), and Swiss designer Yves Béhar (*b*. 1967) announced plans to build an underwater manned research station in 60 feet of water (about 18 m) off the coast of Curaço in the Caribbean. Named PROTEUS™, the planned habitat will accommodate a dozen aquanauts and have a capability to live-stream video in 16K resolution. About the project Cousteau says, "I'm just a crazy person with a dream that sees this as being not only possible—but absolutely necessary—for our future well-being" (Knapp and Jennings 2020). A partnership announced with NOAA in May 2023 may just help that dream come true (NOAA 2023).

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3.8: Chapter References

Becerril-Garciá, Edgar E., Daniela Bernot-Simon, Marcial Arellano-Martínez, Felipe Galván-Magaña, Omar Santana-Morales, and Edgar M. Hoyos-Padilla. 2020. “Evidence of Interactions between White Sharks and Large Squids in Guadalupe Island, Mexico.” *Scientific Reports* 10: 17158. https://doi.org/10.1038/s41598-020-74294-4

Beebe, William. 1934. *Half Mile Down*. New York: Harcourt, Brace, and Company. https://doi.org/10.5962/bhl.title.10166

Bell, James J., Valerio Micaroni, Benjamin Harris, Francesca Strano, Manon Broadribb, and Alice Rogers. 2022. “Global Status, Impacts, and Management of Rocky Temperate Mesophotic Ecosystems.” *Conservation Biology*, e195235. https://doi.org/10.1111/cobi.13945

Bevan, John. 1999. “Diving Bells Through the Centuries.” *South Pacific Underwater Medicine Society Journal* 29(1): 42–50.

Bigelow, Henry B. 1931. *Oceanography: Its Scope, Problems, and Economic Importance*. Boston: Houghton Mifflin. https://hdl.handle.net/1912/219

Branson, Oscar, Elisa A. Bonnin, Daniel E. Perea, Howard J. Spero, Zihua Zhu, Maria Winters, Bärbel Hönisch, Ann D. Russell, Jennifer S. Fehrenbacher, and Alexander C. Gagnon. 2016. “Nanometer-Scale Chemistry of a Calcite Biomineralization Template: Implications for Skeletal Composition and Nucleation.” *Proceedings of the National Academy of Sciences* 113(46): 12934-12939. https://doi.org/10.1073/pnas.1522864113

Chamberland, Dennis. 2007. *Undersea Colonies: The Future of Permanent Undersea Settlements*. Orlando: Quantum Editions.

Claustre, Hervé, Kenneth S. Johnson, and Yuichiro Takeshita. 2020. “Observing the Global Ocean with Biogeochemical-Argo.” *Annual Review of Marine Science* 12: 23–48. https://doi.org/10.1146/annurev-marine-010419-010956

Cousteau, Jacques-Yves. 1964. *World without Sun*. Columbia Pictures. 93 minutes. https://www.imdb.com/title/tt0058364/

Cousteau, Jacques-Yves, and James Dugan. 1963. *The Living Sea*. New York: Harper & Row. https://www.google.com/books/edition/the_living_sea/RH62lplz-2AC

Cousteau, Jacques-Yves, and Susan Schiefelbein. 2007. *The Human, the Orchid, and the Octopus: Exploring and Conserving Our Natural World*. New York: Bloomsbury. https://www.bloomsbury.com/us/human-the-orchid-and-the-octopus-9781596914186/

Cunningham, Sean S., director. 1989. *DeepStar Six*. Carolco Pictures. 99 minutes. https://www.imdb.com/title/tt0097179/

Dickey, Tommy. 1990. “Physical-Optical-Biological Scales Relevant to Recruitment in Large Marine Ecosystems.” In *Large Marine Ecosystems: Patterns, Processes, and Yields*. Edited by Kenneth Sherman, Lewis Alexander, and Barry Gold, 82–98. Washington, DC: American Association for the Advancement of the Sciences. http://www.opl.ucsb.edu/tommy/pubs/Dickeyscales1990.pdf

———. 1991. “The Emergence of Concurrent High-Resolution Physical and Bio-Optical Measurements in the Upper Ocean and Their Applications.” *Reviews of Geophysics* 29(3): 383–413. https://doi.org/10.1029/91RG00578

———. 2020. “New Discoveries Enabled by the Emergence of High-Resolution, Long-Term Interdisciplinary Ocean Observations.” *Perspectives of Earth and Space Scientists* 1(1): 1–10. https://doi.org/10.1029/2020CN000129

Forster, E. S. 1927. *The Works of Aristotle. Volume VII: Problemata*. Edited by W. D. Ross. Oxford: Clarendon Press.

Glen, John, director. 1981. *For Your Eyes Only*. United Artists. 127 minutes. https://www.imdb.com/title/tt0082398/

Hegalson, Nicole. 2016. “First Video of Coral Bioluminescence in the Deep Sea.” Reef Builders. August 10, 2016. https://reefbuilders.com/2016/08/10/first-documentation-of-bioluminescence-in-the-deep-sea/

Humphris, S. E., C. R. German, and J. P. Hickey. 2014. “Fifty Years of Deep Ocean Exploration with the DSV Alvin.” *EOS*. June 3, 2014. https://eos.org/features/in-june-2014-the-deep-submergence-vehicle-dsv-alvin-the-worlds-first-deep-diving-sub-marine-dedicated-to-scientific-research-in-the-united-states-celebrated-its-50th-anniversary

Kim, Juliana. 2023. “76 Days and Counting Underwater, Florida Professor Breaks World Record, for Science.” *NPR*. May 16, 2023. https://www.npr.org/2023/05/16/1176131967/underwater-florida-professor-breaks-world-record

Knapp, Alex, and Katie Jennings. 2020. “Fabien Cousteau Is Raising $135 Million to Build the International Space Station of the Deep Sea.” *Forbes*. July 22, 2020. https://www.forbes.com/sites/katiejennings/2020/07/22/fabien-cousteau-is-raising-135-million-to-build-the-international-space-station-of-the-deep-sea/?sh=41846a010132

Koch, Kristen. 2019. “California Ecosystem Surveys Give Insight on Ocean Changes to Come.” NOAA Fisheries. December 30, 2019. https://www.fisheries.noaa.gov/leadership-message/california-ecosystem-surveys-give-insight-ocean-changes-come

Kreier, Freda. 2022. “Historic Dive Aims to Map Earth’s Deepest Point Like Never Before.” *Nature*. July 13, 2022. https://doi.org/10.1038/d41586-022-01916-4

Loya, Yossi, Kimberly A. Puglise, Tom C. L. Bridge, eds. 2019. *Mesophotic Coral Ecosystems*. Vol. 12 in *Coral Reefs of the World*. Cham: Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-92735-0

Matsen, Brad. 2009. *Jacques Cousteau: The Sea King*. New York: Pantheon Press. https://www.penguinrandomhouse.com/books/109161/jacques-cousteau-by-brad-matsen/

May, Cameron, Lauren Meyer, Sasha Whitmarsh, and Charlie Huveneers. 2019. “Eyes on the Size: Accuracy of Visual Length Estimates of White Sharks, *Carcharodon carcharias*.” *Royal Society Open Science* 6: 190456. http://dx.doi.org/10.1098/rsos.190456

Melnick, Kyle. 2019. “NASA Partners with US Navy to Develop AR Displays for Spacesuits.” VRScout. July 21, 2019. https://vrscout.com/news/nasa-us-navy-ar-heads-up-display/

Melville, Herman. 1851. *Moby-Dick*. New York: Harper & Brothers.

Mills, Eric. 2012. *Biological Oceanography: An Early History. 1870–1960*. University of Toronto Press. https://utorontopress.com/9781442613720/biological-oceanography/

Morelo, Lauren. 2010. “Reenlisting Submarines to Study Global Warming in the Arctic.” *Scientific American*, reprinted from Climatewire with permission from Environment & Energy Publishing. July 20, 2010. https://www.scientificamerican.com/article/re-enlisting-submarines-t0-study-global-warming-in-the-arctic/

Munk, Walter. 2000. “Achievements in Physical Oceanography.” In *50 Years of Ocean Discovery: National Science Foundation 1950–2000*. Washington DC: National Academy Press: 44–50. https://doi.org/10.17226/9702

Naval Technology. 2021. “NAVSEA and NASA Partner to Test Generation 2 DAVD System.” Naval Technology. March 2, 2021. https://www.naval-technology.com/news/navsea-and-nasa-partner-to-test-generation-2-davd-system/

NOAA. 2023. “NOAA, Proteus Ocean Group to Explore Uses of Groundbreaking Underwater Lab.” NOAA website, accessed June 12, 2023. https://www.noaa.gov/news-release/noaa-proteus-ocean-group-to-explore-uses-of-groundbreaking-underwater-lab

Oberhaus, Daniel. 2020. “The Oldest Crewed Deep Sea Submarine Just Got a Big Makeover.” *Wired*. December 22, 2020. https://www.wired.com/story/the-oldest-crewed-deep-sea-submarine-just-got-a-big-makeover/

Oreskes, Naomi. 2020. *Science on a Mission: How Military Funding Shaped What We Do and Don’t Know about the Ocean*. Chicago: University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/S/bo59258933.html

The Salt Sirens. 2022. “Current List of Freediving Records (2022).” April 27, 2022. https://thesaltsirens.com/current-freediving-records/

SCICEX Science Advisory Committee. *2010 SCICEX Phase II Science Plan, Part I: Technical Guidance for Planning Science Accommodation Missions*. Arlington, VA: US Arctic Research Commission. https://www.arctic.gov/uploads/assets/scicex_plan.pdf

Thomson, Sir C. Wyville. 1878. *The Voyage of the “Challenger,” the Atlantic: A Preliminary Account of the General Results of the Exploring Voyage of the H.M.S. “Challenger” During the Year 1873 and the Early Part of the Year 1876*. New York: Harper and Brothers.

Thomson, Sir C. Wyville, and John Murray. 1885. *Report on the Scientific Results of the Voyage of the H.M.S. Challenger During the Years 1873–76*. Narrative Volume I: First Part. Published by Order of Her Majesty’s Government. https://doi.org/10.5962/bhl.title.6513

University-National Oceanographic Labratory System. 2021. *Research Vessel Safety Standards*. 11th ed. Seattle: UNOLS Office. https://www.unols.org/document/research-vessel-safety-standards-rvss

van Haren, Hans. 2018. "Abyssal Plain Hills and Internal Wave Turbulence." *Biogeosciences* 15: 4387–4403. https://doi.org/10.5194/bg-15-4387-2018

Verne, Jules. (1870) 1993. *Twenty Thousand Leagues Under the Sea*. Translated by Walter James Miller and Frederick Paul Walter. Annapolis: Naval Institute Press. https://www.usni.org/press/books/20000-leagues-under-sea

Walsh, Don. 1962. *The Bathyscaph Trieste: Technological and Operational Aspects, 1958–1961*. Report 1096. San Diego: U.S. Navy Electronics Laboratory. https://apps.dtic.mil/sti/pdfs/AD0616288.pdf

Weinman, Steve. 2022. "Deep-Sea Mapper Can't Get Much Deeper!" Divernet. July 15, 2022. https://divernet.com/world-dives/deep-sea-mapper-cant-get-much-deeper/

Wilkins, John. 1708. *The Mathematical and Philosophical works of the Right Reverend John Wilkins, Late Lord Bishop of Chester*. London: Printed for J. Nicholson, A. Bell, B. Tooke, and R. Smith.

Will, Manuel, Andrew W. Kandel, and Nicholas J. Conard. 2019. "Midden or Molehill: The Role of Coastal Adaptations in Human Evolution and Dispersal." *Journal of World Prehistory* 32: 33–72. https://doi.org/10.1007/s10963-018-09127-4

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CHAPTER OVERVIEW

4: Robots, Satellites, and Observatories

In Douglas Adams's five-part trilogy *The Hitchhiker's Guide to the Galaxy* (1995), earthling Arthur Dent narrowly escapes Earth's destruction thanks to an extraterrestrial Good Samaritan who is field-testing a not-so-dependable computerized guide to the galaxy. Their adventures, full of strange technological inventions, bear modest similarities to the technology-enhanced lives of oceanographers.

The application of electronic sensors for observing, measuring, and adventuring into the world ocean has provided a view of the ocean as never before (minus the leaps through hyperspace). These sensors—attached to ships, subs, satellites, robots, and even animals—have dramatically changed our ability to investigate and understand the ocean. Our 21st-century view of the ocean feels like a trip to a galaxy far, far away.

The ever-expanding fleet of sensor-outfitted platforms that fly above, glide on top, or dive below the surface of the ocean belongs to a broad category of tools known as **ocean observing systems**. Here we include any platform or sensor that permits observations and measurements at a distance. Independent and self-navigating platforms, such as satellites and autonomous underwater vehicles (AUVs), fit the definition to a tee. Tools as simple as drifters and as complex as seafloor observatories may also fall into this category. Some oceanographers might include conductivity-temperature-depth instruments, or CTDs, in this category (covered in Chapter 13). Most importantly, the tools of ocean observing systems share a common goal: to expand the reach of human senses over broad scales of space and time (e.g., Lee et al. 2017).

As oceanographers increase their ability to observe all parts of the ocean and connect measurements across space and time, a new and vital understanding of Earth and its ocean system will emerge. Our ability to survive in the coming centuries may well depend on the robotic eyes and ears of the sea. Like Arthur Dent, we may return to a restored Earth thanks in part to these platforms. That day, when it comes, may bring new meaning to "thanks for all the fish."

4.1: Bottles, Drifters, and Floats
4.2: Gliders
4.3: Towfish
4.4: Remotely Operated Vehicles
4.5: Autonomous Underwater Vehicles
4.6: Hybrid Platforms
4.7: Benthic Landers
4.8: Mini-Autonomous Underwater Explorers
4.9: Ocean Moorings
4.10: Uncrewed Aerial Platforms
4.11: Satellite Oceanography
4.12: Ocean Observatories
4.13: Chapter References

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4.1: Bottles, Drifters, and Floats

If you've ever seen a plastic bottle adrift on the surface of a lake or the ocean, then you have a pretty good understanding of one of the earliest tools for tracking ocean currents. The **drift bottle method** relies on a return-to-sender card sealed inside a buoyant container—traditionally a glass bottle—that is tossed from a ship or shore. The card requests that the finder return the card with information on the date and location where the bottle was found. By comparing the starting point to the final destination, the path of the drift bottle may be inferred. Drift bottles have served as indicators of surface current speed and direction since at least 1802 and remain in use today (e.g., Stommel 1965; Storch et al. 2020). At Woods Hole Oceanographic Institute (WHOI), oceanographer Dean "Bump" Bumpus (1912–2002) oversaw the release of hundreds of thousands of drift bottles during his 40-year career (Lipsett 2014; Woods Hole 2021).

While drift bottles are not autonomous, their use inspired two types of passive float technologies in use today: drifters and floats. **Drifters** (a.k.a. surface drifting buoys) provide information on surface currents, and **floats** track currents at deeper depths. As WHOI physical oceanographer Bruce Warren (1937–2010) puts it, "Drifters float and floats sink" (e.g., Lumpkin et al. 2017). Drifters and floats represent what are known as **Lagrangian platforms**—devices that move with the currents—named after Italian mathematician Joseph-Louis Lagrange (1736–1813), who developed the mathematics of fluid flows (e.g., Knauss and Garfield 2017).

In the 1950s English oceanographer John Swallow (1923–1994) developed a float that could maintain a constant depth and transmit an acoustic signal so that it could be tracked by a ship or a receiving station (Swallow 1955). These acoustically transmitting floats —known as **Swallow floats**—provided some of the first hints at the complex, eddy-like nature of the ocean (e.g., Crease 1962).

In 1979 the National Oceanic and Atmospheric Administration (NOAA), along with the World Meteorological Organization and Intergovernmental Oceanographic Commission, established the Global Drifter Program (GDP; Niiler 2001). The most common drifter in use today, the Surface Velocity Program (SVP) drifter, consists of a small, spherical surface float attached to a nearly 23-foot-long (7 m) cloth cylinder with holes in it (to reduce drag), the so-called **holey sock drogue**. As of August 2022, some 1,244 drifters have been deployed by 26 countries. Each transmits position and temperature data to a satellite for upload to NOAA's GDP database and website.

Swallow floats and SVP drifters set the stage for development of **autonomous profiling floats**, underwater robots that collect, store, and report data via satellite. The crown jewel of autonomous profiling floats is the Array for Real-Time Geostrophic Oceanography, known simply as Argo.

Put into service in 1999, the Argo floats take their name from the legendary ship *Argo*. Commanded by the Greek hero Jason, *Argo*, with his heroic crew, the Argonauts, set sail to find the Golden Fleece, the fur of a winged golden ram, as told in Greek mythology (Colavito 2014). The Argo floats have been hailed as "one of the scientific triumphs of our age" (Gillis 2014). Fittingly, the Argo floats serve under the watchful eye of the ocean-observing Jason satellites, named for the Greek mythological hero first mentioned by Homer in 800 BCE (Colavito 2014). Together they provide simultaneous ocean measurements above and below the surface.

An individual Argo float resembles a tall and skinny version of R2-D2, the feisty robot in the Star Wars movies. They move up and down in the water column by regulating their **buoyancy**, the balance between rising or sinking in the water column (see Chapter 13). As anyone who has used a floatie knows, your ability to float on the surface depends on the volume of air inside the floatie. Let the air out and you sink. Fill the float with air and you float. An Argo float works in a similar fashion, except instead of air, the float uses oil in an internal reservoir. When pumped into a flexible bladder at the bottom of the float, the oil occupies a greater volume and makes the float more buoyant. When the oil is removed, the bladder shrinks and the float sinks. By carefully controlling the bladder, the float can sink, rise, or stay at a constant depth.

Argo floats can measure, store, and transmit observations on a number of physical, chemical, and biological properties, including temperature, salinity, pH, oxygen, and nitrate. As of August 2022, a flotilla of 3,930 floats report data from the surface to depths of 6,562 feet (2,000 m) across the entire world ocean, including the Southern and Arctic Oceans. Over the span of their more-than-two-decade lifetime, the Argo floats have generated more than two million profiles of the upper ocean, nearly four times the number of profiles available prior to their implementation. More than 2,000 scientific papers have used Argo data to support their findings (e.g., Jayne et al. 2017).

In recent years a new generation of Argo floats—Deep Argo—are being deployed to obtain data over the entirety of the world ocean. Argo floats with nicknames such as Deep SOLO and Deep APEX developed in the United States will reach depths up to 19,685 feet (6,000 m). Deep NINJA and Deep ARVOR, under development by Japan and France, respectively, will operate at depths to 13,123 feet (4,000 m; Jayne et al. 2017). Oceanographers have also developed a new suite of sensors for measurements of optical and biogeochemical properties, a fleet of floats called Biogeochemical Argo (e.g., D'Ortenzio et al. 2020). These new Argo floats promise to shed light on the role of the deep ocean in climate change and improve our understanding of its physics, chemistry, and biology (Roemmich et al. 2019).

While all the above drifters and floats are traditionally deployed from ships, aircraft can launch floats too. The Air-Launched Autonomous Micro-Observer (ALAMO) can profile the ocean to depths of more than 3,900 feet (1,200 m). ALAMO floats were developed in response to a need for obtaining observations in places difficult to reach, such as ice-covered waters and the interior of hurricanes (e.g., Jayne and Bogue 2017; Goni et al. 2017). Deployments of ALAMO floats during the 2017 and 2018 Atlantic hurricane seasons yielded new insights into the response of the upper ocean to the passage of a hurricane and provided ground-truth data for hurricane forecast models (Sanabia and Jayne 2020). Ultimately, the better our understanding of factors that influence hurricane intensity, the more likely hurricane forecasts can provide accurate warnings and save property and human lives.

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4.2: Gliders

Torpedo-shaped, with wings and a tail rudder, **gliders** "fly" through the water column like an underwater airplane. But gliders have no propellers or engines. Instead, gliders rely on buoyancy changes to propel them through the water. When they lose buoyancy, the nose of the glider becomes heavier and it sinks. But instead of sinking vertically, its wings cause it to move forward at an angle. Similarly, as the glider gains buoyancy and the nose lifts, the wings cause it to move forward in the water column at an angle. The resultant flight pattern resembles a sawtooth. While slow moving relative to propelled vehicles, the efficiency of their movement and their low cost allow them to carry out missions of a month or more (e.g., Schofield et al. 2007).

Many types of gliders exist, but the best known is the Slocum glider, named after Canadian-American adventurer Joshua Slocum (1844–1909), the first person to sail alone around the world (1895–1898). American engineer Douglas Webb (*b*. 1929) originally conceived of the glider in 1978 and then jointly developed it in the 1980s and 1990s with American oceanographer Henry Stommel (1920–1992; Nehring 2021). Like its namesake, the Slocum glider evokes a spirit of exploration and determination—but for robots.

The latest generation of gliders—**wave gliders**—use the energy of ocean waves for propulsion. The above-water portion of the platform—the float—resembles a surfboard, albeit one outfitted with an antenna and solar panel. Below the surface, a tether connects to an underwater sled—the sub—which features multiple fins arranged like Venetian blinds. These fins generate thrust when the float rises and falls in the ocean swell. Both float and sub may be outfitted with sensors (e.g., Pagniello et al. 2019; Grare et al. 2021). In 2013 a wave glider named Benjamin Franklin completed a 455-day journey of 7,939 nautical miles (14,703 km) from San Francisco Bay to Lady Musgrave Island off the coast of Australia. The feat earned the platform a Guinness World Record for the "longest journey of an unmanned autonomous surface vehicle" (Guinness World Records 2013).

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4.3: Towfish

Originally deployed in the 1960s in sonar systems for mapping the seafloor and locating sunken craft, the **towfish**, a winged platform pulled by a cable behind a moving vessel, remains an important tool in modern oceanographic research. The platform's resemblance to a torpedo and submariners' use of "fish" as a slang for torpedoes (e.g., Newpower 2006) likely led to adoption of the term for oceanographic purposes (e.g., Flemming 1976).

The simplest towfish resemble winged torpedoes. Other towfish look like sleds with wings attached. The wings allow the vehicles to "fly" up, down, or sideways while carrying instruments to measure various ocean properties. A pump may even be attached to deliver water samples to the surface. Some towfish carry nets to collect plankton, the microscopic organisms that drift with the currents in the ocean. Remotely operated towfish vehicles feature automated control functions. The vehicle can maintain a fixed depth or fly in what oceanographers refer to as the **tow-yo pattern**, a combination of towing and yo-yoing. Geologists were among the first to deploy towfish as part of side-scan sonar systems, which use sound pulses directed toward the seafloor at low angles to produce high-resolution images. Side-scan sonar has been instrumental in locating downed aircraft and sunken ships and providing highly detailed views of the seafloor (e.g., Schlee et al. 1995; Wu et al. 2021).

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4.4: Remotely Operated Vehicles

This next piece of technology has become so popular that you can find it for sale on Amazon. **Remotely operated vehicles** (ROVs) owe their inspiration to the human desire to find shipwrecks. While we commonly think of ROVs as a new technology, their origins date back to the 1950s, when French diver-photographer Dimitri Rebikoff (1921–1997) launched the first ROV, the *Poodle*. On its first mission in 1954, the ROV *Poodle* found ancient Phoenician shipwrecks more than 540 feet (165 m) deep (Marx 1990).

Of course, the most famous ROV discovery came in 2013 when the American ROV *Odysseus* located the remains of the tourist submersible, *Titan*. On June 18, 2023, the *Titan* imploded with five passengers aboard on a visit to the passenger ship *Titanic* at 12,500 feet deep (3.8 km) in the North Atlantic (Mongilio 2023). *Titanic*, as you know, collided with an iceberg in 1912 and sank, killing 1,500 people. More than 70 years later, an American-French expedition under the guidance of WHOI oceanographer Robert Ballard located the vessel using an ROV (e.g., Ballard and Drew 2021).

Modern ROVs serve a broad range of military, industrial, scientific, and commercial needs. They come in a variety of sizes, shapes, and capabilities (e.g., Moore et al. 2010). The smallest ones are barely the size of a toaster, while the largest ones are bigger than a compact SUV. Most "swim" using a system of propellers controlled via commands sent through a fiber-optic cable called a **tether** (Christ and Wernli 2014). The ROV operator, the pilot, may use a joystick on a control console to maneuver the ROV. If you're good with video games, you would probably make a good ROV pilot, especially if you know a little oceanography (hint, hint).

Some ROVs have wheels or treads like a tank that permit them to crawl over the seafloor, but most resemble snowmobiles, with sleds stretching the length of the vehicle so that they can land gently on the seafloor. Depending on the application, an ROV may be outfitted with one or more **manipulator arms**, extendable, rotational appendages that accommodate a variety of specialized attachments. Grippers hold objects and grabbers can pick them up. Shovels can be attached for digging, tubes deployed for collecting sediments, suction devices used to collect animals, and any number of other devices for sampling and carrying out research (Sivčev et al. 2018). It's quite the thrill to watch an ROV collect strange creatures never before seen by humans.

Many ROVs are equipped with cameras and banks of lights for high-definition photography and videography. Some even stream live over the internet. Oceanographers refer to this sensory technology as **telepresence**, a kind of virtual reality that lets viewers experience a place that is otherwise inaccessible to (most) humans. Telepresence allows land-based scientists (and you) to participate in missions, too. Experts from around the world watch the livestream and call in to offer scientific expertise and commentary on any of the features or organisms that the ROV encounters. Livestreams offer informative and occasionally goofy commentary on the geology, chemistry, physics, and biology of the seafloor. I confess to standing in line at the supermarket watching the live feed of an ROV camera probing the ocean depths from locations halfway across the world. Check it out next time they go live. (See https://oceanexplorer.noaa.gov/.)

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4.5: Autonomous Underwater Vehicles

If ROVs had besties, they would be **autonomous underwater vehicles,** better known as AUVs, untethered craft that operate independently on pre-programmed missions. In fact, the US Navy lumps ROVs and AUVs into a single category: **uncrewed underwater vehicles** (UUVs). AUVs represent the ultimate expression of a robotic deep-sea explorer. Free of any cables, commanded by a computer brain, and potentially able to wander the ocean for unlimited periods of time, AUVs travel in a way that ROVs cannot. Most fly through the water column. Some crawl along the seafloor. Most impressive is their ability to maintain level flight and react to circumstances with limited decision-making capabilities.

Though robotic solo flights present a number of technological and engineering challenges, AUVs have begun to make their mark on 21st-century oceanographic research (e.g., Searle et al. 2018; Meyer et al. 2019). In a 2015 study off Guadalupe Island on the west coast of Baja California, researchers used AUVs to track the behavior of great white sharks (*Carcharodon carcharias*). Though the sharks regularly attacked the AUVs (they apparently don't like being followed by a yellow torpedo), the work yielded new insights into the behavior of these magnificent animals (Kukulya et al. 2016).

Researchers have also begun to use AUVs with **adaptive tracking systems**. In essence, the AUV detects and automatically tracks specific features, such as a particular temperature of water or concentration of plankton. Researchers working off Hawaii in 2018 employed two long-range AUVs to automatically track and sample an **ocean eddy**—a self-sustaining rotating loop of water tens to hundreds of miles wide. Eddies can generate conditions ideal for the growth of **phytoplankton**—microscopic plant drifters—which concentrate in a layer known as the deep chlorophyll maximum. By programming the AUVs to track the chlorophyll maximum, researchers were able to observe this subsurface feature in unprecedented detail. To an oceanographer, that's impressive (Zhang et al. 2019; Zhang et al. 2021).

The latest generation of AUVs promises to greatly expand their capabilities. Hovering AUVs maintain their position over a phenomenon of interest such as a hydrothermal vent. Stealth AUVs rest on the seafloor listening for military targets. New, silicone-based soft robots—so-called **bionic AUVs**—mimic animals to blend in and observe organisms less intrusively. **Uncrewed surface vessels** (USVs) allow scientists (and the military) to make observations in remote locations (Braginsky et al. 2020). A catamaran-style USV can even tow a plankton net for sampling microplastics, plankton, and other floating particles (Bazilchuk 2022). For young ocean scientists and engineers, AUVs represent an emerging opportunity to push the boundaries of ocean exploration, a chance to go where no oceanographer has gone before (e.g., Katzschmann et al. 2018; Li et al. 2021; Mazzolai et al. 2022).

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4.6: Hybrid Platforms

Hybrid platforms combine the best features of ROVs and AUVs. Formally known as **hybrid remotely operated vehicles** (HROVs), these platforms permit researchers to operate the same vehicle with or without a tether (e.g., Bowen et al. 2009; Yoerger et al. 2021). As outlined by Xiang et al. (2015), an HROV can launch underwater in ROV mode and be guided to a research site, then operate as an AUV and return to the surface when its mission is complete.

Hybrid platforms allow oceanographers to reach the deepest depths in the ocean. The Japan Agency for Marine-Earth Science and Technology, or JAMSTEC, developed the *UROV11K*—with 12.4 miles (20 km) of fiber-optic cable. In 2017 the vehicle reached a maximum depth of 35,758 feet (10,899 m) in the Mariana Trench (Nakajoh et al. 2018). Unfortunately, the *UROV11K* has since sunk (Wang et al. 2020). HROVs remain a specialized robotic platform, yet their ability to receive and transmit data and move more flexibly and at greater distances than ROVs will likely propel their further development as a tool for undersea exploration and research.

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4.7: Benthic Landers

Not all robotic craft operate in the water column. A group of platforms known as **benthic landers**, nicknamed ocean elevators, sink to the seafloor. Once landed, they carry out any number of observations, such as imaging, remote sensing of ocean properties, sample collection, or experimentation. Landers have proved particularly useful for studying submarine canyons, where episodic events such as underwater mudslides occur. They're also perfect for observations in deep oceanic trenches that are largely inaccessible to other craft. The deepest-diving landers, the **hadal landers**, deploy baited cameras and traps to attract, film, and even capture deep-sea organisms. In 2014 oceanographers used landers to catch a **snailfish**, the deepest known vertebrate, collected at 26,135 feet (7,966 m) in the Mariana Trench (Gerringer et al. 2017). In 2017 a JAMSTEC lander filmed a snailfish at 26,831 feet (8,178 m), the deepest observation of any fish to date (JAMSTEC 2017). Hadal landers have also been used to study sediments and oxygen consumption in oceanic trenches (Lumberg et al. 2018; Glud et al. 2021). Though less sexy than propelled vehicles, landers offer one of the most cost-effective means for making observations in the deep ocean (e.g., Giddens et al. 2021; Du et al. 2023).

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4.8: Mini-Autonomous Underwater Explorers

Sometimes smaller is better. Enter the **mini-autonomous underwater explorer** (M-AUE). The M-AUE system operates as a swarm of instruments, a dense collection of subsurface drifters and GPS-enabled surface floats that track upper ocean motions in a kind of virtual electronic net. Roughly the size of stout 1.5-liter sports bottles, the subsurface drifters can provide a three-dimensional view of the upper ocean over distances of hundreds of feet to a few miles. Because the drifters can be programmed to automatically maintain their position in the water column, they can mimic the drift patterns of plankton, harmful algae, or oil spills (e.g., Jaffe et al. 2017). The fine-scale information provided by M-AUEs has already revealed insights into how marine larvae find their way home (e.g., Garwood et al. 2020). M-AUEs offer a preview of an emerging field of study known as **underwater swarm robotics**, the design and development of multi-robot systems that interact and coordinate their behavior to solve problems and carry out complex tasks (e.g., Connor et al. 2021). Such systems offer opportunities to better understand the connections between physical and biological processes in the ocean (e.g., Dickey 1991).

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4.9: Ocean Moorings

Ocean moorings provide a fixed platform to which various oceanographic instruments can be attached to acquire measurements of ocean properties for long periods of time. They excel in sampling temporal scales at an unprecedented resolution—minutes to weeks—and they can be left unattended for months to years at a time.

The foundation of an ocean mooring involves a piece of machinery all too familiar to us. Next time you're stuck at a railroad crossing, check out the wheels on the train. At several hundred pounds each, they make great anchors. And indeed, that's what oceanographers use them for. (And just to clear this up, there's absolutely no truth to the rumor that oceanographers steal wheels from parked trains at night.) Train wheels provide the foundation for a steel cable to which floats (often hollow glass balls) and various oceanographic instruments can be attached. The cable may stretch vertically all the way from the seafloor to the surface, or it may rise from the seafloor to a particular depth of interest. Meteorological instruments attached to the surface floats collect weather data. Below the surface, oceanographic instruments may be attached at various intervals to collect depth-specific information.

While several types of instruments may operate simultaneously at fixed depths, profiler moorings allow instruments to travel up and down a cable and sample the water column in a manner similar to an instrument on a cable on a ship. In either case—fixed or profiling—when an oceanographer wants to retrieve the instruments, they send a secretly coded acoustic signal to the mooring that activates a release mechanism, unhooking the cable from the railroad wheel and permitting the instruments to float to the surface. The wheel remains on the seafloor, forever a part of Davy Jones's locker.

Moorings have provided some of the longest continuous observations of the ocean on record. Off the coast of Bermuda in the Sargasso Sea (or the Bermuda Triangle, as some people call it), oceanographers with the Ocean Flux Program (OFP) have maintained a mooring since 1978. The OFP mooring hosts **sediment traps**, devices that collect and store sinking particles. Its data —more than 40 years' worth—offers invaluable insights on the ocean's recent past. These data have been especially useful for assessing the effects of climate change in the ocean (e.g., Conte and Weber 2014; Cael et al. 2021).

Because ocean moorings can provide critical meteorological information, the US established in 1967 the National Data Buoy Center (NDBC). The NDBC oversees the operations and data quality control of hundreds of moored buoys deployed in US coastal and oceanic waters across the Atlantic and Pacific. It also provides quality control and dissemination of data from hundreds of partner stations. Its **website** provides near-real-time data from stations in the Atlantic, Pacific, and Indian Oceans. The NDBC serves a wide range of scientific, military, governmental, private, and civilian needs. Fishers, sailors, and boaters, among others, go there for up-to-date information about the waters in which they travel.

Despite their many advantages, the harsh conditions to which moorings are subjected can cause breakdowns, corrosion, and, on occasion, total loss. Moorings attract fish that bite and fray the cables. Fish attract fishers, who accidentally snag moorings when trawling or intentionally latch onto moorings and steal their parts. A cable snaps or the anchor accidentally releases, and the mooring drifts away, never to be seen again. On some occasions, the release fails to respond to its acoustic signal, in which case the crew must drag an anchor through the water hoping to catch the subsurface cable and bring the mooring to the surface. Rescue missions to find moorings take up costly ship time and fray the nerves of the oceanographers responsible for maintaining them. Nonetheless, the benefits they serve, such as El Niño prediction, tsunami warning, storm warning, and weather forecasting, more than outweigh their costs. We would be blind to what's happening beneath the ocean's surface without them.

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4.10: Uncrewed Aerial Platforms

Increasingly, scientists are turning to **uncrewed aerial platforms**—drones—remotely controlled flight-capable platforms outfitted with video cameras and various sensors. This category of platforms also includes remotely piloted aerial systems and multirotor copters (e.g., Klemas 2015; Nguyen et al. 2022). The use of drones and drone-based sensors in oceanographic research represents one of the most recent examples of how new technological developments can revolutionize a field (e.g., Gray et al. 2022).

One of the earliest uses of drones for oceanographic research was simply to follow whales and dolphins (Fiori et al. 2017). Images and video from drones have enabled scientists to map intertidal reefs (e.g., Murfitt et al. 2017), track discharge plumes of groundwater (Lee et al. 2016), survey the size and shape of beaches (Casella et al. 2020), and measure snow thickness on sea ice (Molar-Candanosa 2022).

A new generation of sensors—deployable on drones and aircraft—now permit oceanographers to measure a wide variety of ocean properties. **Multispectral imagers** detect several different wide bands of electromagnetic radiation (colors). **Hyperspectral imagers** detect hundreds of narrow bands of electromagnetic radiation. Both routinely fly aboard airborne platforms to monitor the environment (Stuart et al. 2019). Using a drone-based hyperspectral sensor, researchers were able to document the extent and concentration of a harmful algal bloom in two bays in southern China (Li et al. 2021).

Not all modern oceanographic measurements require cutting-edge platforms. Kites, outfitted with state-of-the-art cameras or sensors, serve many coastal applications. **Kite aerial photography** has been used to map the distribution of organisms in the rocky intertidal and near-coastal zone and to acquire high-resolution images of entire islands or beaches (Bryson et al. 2013).

Balloons play a role in oceanographic research too. During the 2018 Microbiology-Ocean-Cloud-Coupling in the High Arctic (MOCCHA) campaign, oceanographers deployed a tethered balloon to sample biologically generated aerosols and the properties of low clouds (Zinke et al. 2021). In the near future, scientists hope to deploy **steerable stratospheric balloons**, such as Stratollites. As big as a blue whale, these craft can maintain a position above Earth's surface for several days (Good et al. 2018). Stratollites may be used to monitor storms, assist natural disaster efforts, and even remotely sense the ocean. By 2024 you'll be able to ride 19 miles high above Earth in a Stratollite (World View 2023).

And while technically not an aerial platform, the newest tool for carrying oceanographic instruments over large swaths of the ocean involves a hybrid device called a **saildrone**. Part windsurfer, part oceanographic buoy, this uncrewed wind- and solar-powered device can stay at sea for months at a time. On a 60-day voyage from San Francisco to Guadalupe Island, a saildrone carrying 16 ocean and atmospheric sensors provided unprecedented data on key oceanographic and atmospheric processes (Gentemann et al. 2020). NOAA soon hopes to deploy fleets of saildrones to replace some of its aging buoys at a fraction of the cost (Voosen 2018). Of course, on windless days, saildrones might also make a nice resting spot for migrating seabirds or a peaceful place for a textbook-weary student to get away from it all.

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4.11: Satellite Oceanography

Space-based observations of the ocean have revolutionized oceanography. Though physical oceanographers had long suspected the chaotic nature of ocean circulation, the first satellite images of ocean color in 1978 drew a collective "oh, my." The surface of the ocean and the phytoplankton suspended within it resembled the sky in Vincent van Gogh's painting *Starry Night* (1889): variable, complex, and organized in loose, rotating structures. The ocean's **mesoscale structure**—the highly variable eddies that characterize nearly all of the ocean's flows—suddenly became visible. Seemingly overnight, **satellite oceanography**, the study of the world ocean using sensors aboard space-based platforms, changed the way we thought about and studied the ocean. Barber and Hilting (2000) likened it to "seeing the ocean for the first time."

Prior to this grand awakening, weather and military satellites had routinely observed the Earth, ice caps, and ocean. But on June 26, 1978, the National Aeronautics and Space Administration (NASA) launched the very first satellite dedicated solely to oceanography, the Seafaring Satellite, or Seasat. Four months later, NASA launched the Nimbus 7, which carried the Coastal Zone Color Scanner (CZCS), the first sensor designed to measure ocean color. Its success drew greater attention to the optical properties below the ocean's surface and gave birth to the field of **bio-optical oceanography,** the study of the submarine light field and its variations due to biological processes (Smith and Baker 1978). This extraordinary technology continues to make significant contributions to our understanding of the world ocean in the 21st century.

Sea Surface Temperature

Covering 71 percent of Earth's surface, the world ocean dominates temperature regulation on our planet. As NOAA puts it, "the ocean is the largest solar energy collector on Earth" (Lindsey and Dahlman 2020). Through heat exchange across the **air–sea interface**—the boundary between the ocean and the atmosphere—the world ocean adds or removes heat from the atmosphere and vice versa. These exchanges of heat drive the motions of the atmosphere and the ocean and prove important for a whole heckuva lot of other things we'll learn about in the chapters ahead.

Satellite oceanography owes much of its early development to sensors used in aerial oceanography. One group of sensors, collectively known as **radiometers**, detects different kinds of electromagnetic radiation, the energy of light. Because the ocean and the stuff it contains remove, reflect, and scatter different wavelengths of electromagnetic radiation, we can learn about the ocean by measuring the wavelengths of light emitted by its surface. Sensors that detect different types of surface-emitted radiation are known as **passive sensors**.

On April 1, 1960, NASA launched the world's first weather satellite, the TIROS-1 (Television Infrared Observation Satellite), one of a series of satellites carrying television cameras into space. Images of cloud and weather patterns ushered in an era of space-based weather forecasting. TIROS set the stage for the Earth-observing satellite systems that now deliver weather information every hour of every day across the globe.

Scientists soon developed additional tools for space-based observations of Earth. Measurements of the temperature of the sea surface—a property known as **sea surface temperature** (SST)—began with the Nimbus satellites launched between 1964 and 1978. These satellites carried high-resolution infrared radiometers designed to measure the temperatures of cloud tops and the sea surface at night (when sunlight wouldn't interfere with the measurement). In 1978 NASA launched TIROS-N (N for NOAA), which carried the first of a series of Advanced Very-High-Resolution Radiometers (AVHRRs), multichannel, infrared-sensing instruments for measuring SST. The data from AVHRRs flown on TIROS-N and subsequent satellites represent the longest near-continuous measurements of SST from space, a period of more than 40 years (e.g., Casey et al. 2010; O'Carroll et al. 2019; Minnett et al. 2019).

One limitation of AVHRR sensors is their inability to "see" through clouds, which block surface-emitted infrared radiation. To overcome this limitation, NASA and the Japanese Aerospace Exploration Agency launched satellites that carried **passive microwave sensors**. These sensors detect microwave radiation which passes through clouds and from which estimates of SST and other properties can be derived. Unfortunately, microwave sensors lack the resolution of infrared sensors and tend to be less accurate (Castro et al. 2008). So oceanographers take the best of both worlds and blend data from infrared and microwave sensors into a combined product, the Multi-scale Ultra-high-Resolution SSTs (MUR-SSTs). Global and regional maps of MUR-SSTs adhere to standards developed by the Group for High Resolution Sea Surface Temperature, which promotes best practices for monitoring, processing, and reporting satellite-derived SST (Minnett et al. 2019).

SST measurements serve operational oceanography, climate change research, fisheries, marine heatwave tracking, and other interests (e.g., Beggs 2010; O'Carroll et al. 2019). NOAA's Coral Reef Watch uses satellite SST data to inform resource managers, scientists, and the public about the potential for **coral bleaching**, the phenomenon whereby coral animals expel their algal "helpers" in response to prolonged elevated seawater temperatures. In recent decades, coral bleaching has devastated corals around the world (e.g., Hughes et al. 2018). Satellite-based forecasts of coral bleaching allow scientists to "rescue" rare coral species and house them in a laboratory. When the warm waters subside, the corals can be returned to their natural environment. It's not the ideal solution, but coral rescues play an important role in coral conservation and management (e.g., Vardi et al. 2021).

Sea Ice Extent

Soon after the *Titanic* sank following its collision with an iceberg in 1912, the governments of the US and Europe formed the International Ice Patrol. Tasked with monitoring the whereabouts of **icebergs**, seaborne chunks of fractured glaciers, the Ice Patrol was the first to regularly monitor ice conditions at polar latitudes. Interest in polar ocean ecosystems and climate change led to efforts in the 1960s to develop tools for observing icebergs and **sea ice**, the frozen surface of polar oceans (Zwally et al. 1983). Fortunately, passive microwave sensors proved ideal for the job.

Observations of sea ice using passive microwave sensors aboard aircraft began in the Arctic in 1967 (Gloersen et al. 1992). The first passive microwave instruments were flown on Russian satellites in 1968 (Tikhonov et al. 2016). But the Electrically Scanning Microwave Radiometer flown aboard the Nimbus 5 satellite in 1972 began the era of "all-weather, all-seasons" sea ice observations that has continued to this day (e.g., Parkinson et al. 1987). A 40-year record from passive microwave sensors has revealed striking and alarming retreats of sea ice in the Arctic and Antarctic Oceans (Parkinson 2019). Multiyear ice, sea ice that remains present for longer than one year—thought to be critical for maintaining sea ice volume—has shown similar declines (Haibo et al. 2020).

A desire for higher-resolution imagery led to the launch of **active microwave sensors**, instruments that produce their own electromagnetic signal and detect the reflected signal (like the radar gun used to catch speeders). By bouncing a beam of energy off the surface of the ocean, oceanographers can measure a number of ocean properties with very high resolution (e.g., Gens 2008). An active microwave system known as **synthetic aperture radar** (SAR) flew aboard Seasat and performed so well it inspired a generation of SAR-carrying satellites in the 1980s and 1990s (Tsatsoulis and Kwok 1998). SAR works by electronically mimicking a large antenna, enabling it to produce detailed images of sea ice and other properties. SAR remains an integral part of Earth-observing satellite systems in the 21st century.

Sea Surface Height

By bouncing a beam of energy off the surface of the ocean, oceanographers can measure the shape of the sea surface–the **sea surface topography**, the bumps and depressions of the ocean surface. The best-known devices, the **satellite altimeters**, measure the time it takes for a microwave radar signal to bounce off the ocean surface and return to the satellite. Based on the return time and precise knowledge of the height and path of the satellite, oceanographers can calculate the distance between the sea surface and the satellite.

Satellite altimeter measurements allow mapping of **sea surface height**, the height of the sea surface relative to a baseline, such as Earth's ellipsoid or geoid (i.e., its equi-gravitational surface; see Chapter 20). Sea surface height measurements permit oceanographers to learn about ocean circulation and ocean tides. It also provides knowledge of sea level changes in response to a warming ocean and melting ice caps. As you might expect, these observations and the computations required to generate useful **satellite products**—the results provided by satellite measurements—involve very accurate measurements and lots of computing power.

Arguably the most successful oceanographic satellite altimeter mission to date is TOPEX/Poseidon, the Ocean Topography Experiment/Poseidon mission. Launched in 1992 in a collaboration between NASA and the French space agency, Centre National d'Etudes Spatiales, TOPEX/Poseidon allowed oceanographers to observe changes in world ocean circulation over seasonal and annual cycles, advanced our understanding of tides and sea level rise, and enabled significant refinement of general circulation models. It provided unprecedented observations of the 1997–1998 El Niño, among the strongest in 100 years. After more than 13 years and nearly 62,000 orbits of Earth, TOPEX/Poseidon ended operations in October 2005. Legendary oceanographer Walter Munk (1917–2019) called it "the most successful ocean experiment of all times" (Munk 2002).

The Jason satellite altimetry missions extended the data record begun by TOPEX/Poseidon. Jason-3 (launched in 2016) currently operates in tandem with the altimeter-carrying Sentinel-6 Michael Freilich satellite. This satellite was named after the former director of NASA's Earth Science Division, Michael Freilich (1954–2020)—a "passionate advocate" of measurements of Earth from space (Cook 2020). This satellite can track sea level rise with an error of less than a tenth of an inch (<1 mm) per year (Donlon et al. 2021).

Ocean Color

If you've ever spent time near an ocean in middle latitudes, you've undoubtedly noticed that the color of the water changes from season to season. Here in Southern California, the winter ocean appears blue, turns green in spring, blues up in summer, and greens again slightly in fall. These changes in ocean color originate from changes in the abundance of phytoplankton and their primary light-absorbing pigment, **chlorophyll**. Think green trees in summer and fallen leaves in winter. It's a similar phenomenon in the ocean. As the concentrations of phytoplankton vary, so does the color of the water: more phytoplankton, greener water. Viewed from space, these organisms give the ocean a palette of greenish hues in what might otherwise be a blue desert.

Oceanographers define **ocean color** as the "relative amounts of water-leaving radiance in the various portions of the visible spectrum" (Austin 1993). In other words, ocean color is the color of the ocean. Pure ocean water absorbs mostly every color except blue. That's why the open ocean appears blue. It's the only color remaining after all others are absorbed. The CZCS (mentioned above) provided biological oceanographers their first global views of ocean color, whose hues varied with the concentration of phytoplankton in the water. Images from the CZCS revealed an intimate connection between ocean physics (i.e., seasonal stratification, upwelling, eddies) and phytoplankton.

The CZCS greatly exceeded expectations and outlived its life expectancy, but it ceased operations in 1986. A decade later, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) lifted off from Vandenberg Air Force Base (August 1, 1997). By this time, oceanographers had developed in-water optical sensors and improved biochemical analyses of seawater. A new generation of oceanographers, the **bio-optical oceanographers**, stepped in. Their mission was to advance our understanding of biological oceanography through a study of ocean optics. Of them, Barale writes: "The space oceanographers . . . were like those pioneers who opened new trade routes, as what they discovered . . . surpassed many times what was expected in the beginning" (Barale 2010).

The design and execution of SeaWiFS built on the lessons learned from the CZCS, including the need for continuous **ground truthing**, the practice of verifying satellite observations with measurements obtained from within the water column. Though traditionally carried out on ships, ground truthing with AUVs is now under development (e.g., Bailey and Werdell 2006; Bennion et al. 2019). Buoys are also used, such as the Marine Optical Buoy system moored off the coast of Hawaii (e.g., Brown et al. 2007).

More than a dozen missions have been launched since SeaWiFS. The Moderate Resolution Imaging Spectroradiometer (MODIS) launched aboard the Terra satellite (December 1999) and the Aqua satellite (May 2002) brought improvements to sensor design and performance. The Visible and Infrared Imager/Radiometer Suite (VIIRS), the successor to MODIS, aboard the Suomi National Polar-orbiting Partnership, and a host of international sensors and satellites devoted to ocean color measurements ensure that global measurements of the ocean biosphere continue to this day.

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4.12: Ocean Observatories

If robots had underwater cities, they might look like **ocean observatories**, an integrated array of ocean-observing sensors and platforms on and above the seafloor designed to address questions of scientific and societal importance (e.g., Crise et al. 2018). Ocean observatories were conceived in the 1980s by American geological oceanographers as the oceanographer's version of an astronomical or volcano observatory (Delaney et al. 1987). Like these observatories, ocean observatories carry out observations over broad spatial and temporal scales. Uniquely, however, ocean observatories span hundreds of miles in waters thousands of feet deep. They involve fixed and mobile platforms connected either physically via cables or virtually via acoustic or optical signals. At heart, ocean observatories provide long-term and sustained observations of the ocean, in contrast to the brief encounters offered by shipboard oceanography.

To get an idea of what they look like, imagine an oceanic neighborhood with strings of instrumented moorings and AUV docking stations spaced at regular intervals like gas stations. Bottom-attached instruments of all shapes and sizes cover the seafloor like tiny houses. Attached cables act as their power lines. Dish-shaped antennae transmit and receive acoustic and optical data. Drifters and gliders and AUVs fly through the surrounding water like a scene from *The Jetsons* (Hanna-Barbera 1962–1963). Bottom-roaming benthic explorers excavate sediments and retrieve and deploy instrument packages like All-Terrain Walkers on an undersea Tatooine (e.g., Lucas 1977–2019). Of course, the occasional human visitor interrupts the robotic seascape—arriving via ship or submersible or as a deep-sea diver—acting as a necessary overlord to keep the city operating smoothly.

Ocean observatories generally fall into one of three categories, regional cabled arrays, coastal arrays, and global arrays. Each serves different goals and purposes.

Regional cabled arrays represent what geologists envisioned when they proposed ocean observatories in the 1980s. These arrays use optical-electrical telecommunication cables to provide power and two-way communication capabilities to suites of instruments on the seafloor. The regional cabled array off the coasts of Washington and Oregon serves as the best example. This array, touted as "the first US ocean observatory to span a tectonic plate," consists of seven primary nodes, each with its own set of instruments and name (such as International District Vent Field 1). One array, the Axial Caldera Cabled Array, captured the eruption of an active undersea volcano on the Juan de Fuca Ridge on April 24, 2015 (Delaney et al. 2016).

Coastal arrays focus on oceanographic processes that occur on or above the continental shelf (e.g., Trowbridge et al. 2019). A coastal array off the Oregon Shelf, the Coastal Endurance Array, employs moorings (fixed and profiler) in concert with gliders to provide high-resolution, top-to-bottom observations of ocean and atmospheric processes. The Coastal Endurance Array has observed hypoxia events (i.e., low oxygen), ocean heatwaves, and the response of marine organisms to a solar eclipse (Barth et al. 2018).

Global arrays refer to ocean observatories in select deep water locations that shed light on major science themes, such as air–sea exchange, climate variability, ocean circulation, and ocean ecosystems. Global arrays rely on deep ocean moorings and gliders to sample vertical and horizontal variability in the upper ocean. The Global Irminger Sea Array off Greenland has already provided tantalizing new observations that may change how we view circulation in this part of the world ocean (de Jong et al. 2018).

Ocean observatories represent an emerging conceptual, technological, and strategic shift in how oceanographers carry out their work. But there are concerns that the enormous financial outlay needed to build and sustain ocean observatories will drain resources from traditional approaches (Witze 2013; Kintisch 2015). As stated by the National Research Council (2015), a "healthy balance" should be sought between "infrastructure to provide access to the ocean and advance the science . . . funds for scientists and trainees to conduct research and provide value for the infrastructure investment." How oceanographers and funding agencies achieve this balance may determine the long-term vitality of future oceanographic research.

As a final note, I want to emphasize that ocean observatories will prove a massive undertaking. They represent, perhaps, the culmination of nearly 150 years of oceanographic research that began with the *Challenger* expedition. Heightened awareness of the rapid changes in Earth's climate and the growing knowledge of multiple stressors on the marine environment makes the mission of ocean observatories ever more urgent (e.g., Speich et al. 2019). With the UN Decade of Ocean Science for Sustainable Development upon us (2021–2030), the opportunities for ocean scientists look ever more promising. As Visbeck (2018) put it:

The increased awareness of the importance of the ocean to the future of humanity gives grounds for cautious optimism and motivation for ambitious multilateral cooperation. The scientific community has been given a stage on which to shine during the

Decade of Ocean Science for Sustainable Development. Let us come together, respect our disciplines and agendas, but also be ready to embark on an exciting and transformative journey to realize the ocean we need for the future we want.

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4.13: Chapter References

Adams, Douglas. 1995. *The Hitchhiker's Guide to the Galaxy: A Trilogy in Five Parts*. London: Heinemann. https://www.penguin.co.uk/books/104/1041878/the-hitch-hiker-s-guide-to-the-galaxy/9780434023394.html

Austin, R. W. 1993. "Optical Remote Sensing of the Oceans: BC (Before CZCS) and AC (After CZCS)." In *Ocean Colour: Theory and Applications in a Decade of CZCS Experience*. Edited by Vittorio Barale and Peter M. Schlittenhardt. Dordecht: Kluwer Academic Publishers. https://doi.org/10.1007/978-94-011-1791-3

Bailey, Sean W., and P. Jeremy Werdell. 2006. "A Multi-sensor Approach for the On-Orbit Validation of Ocean Color Satellite Data Products." *Remote Sensing of the Environment* 102(1–2): 12–23. https://doi.org/10.1016/j.rse.2006.01.015

Ballard, Robert D., and Christopher Drew. 2021. *Into the Deep: A Memoir from the Man Who Found Titanic*. Washington, DC: National Geographic. https://www.simonandschuster.co.uk/books/Into-the-Deep/Robert-D-Ballard/9781426220999

Barale, Vittorio. 2010. "Preface." In *Oceanography from Space: Revisited*. Edited by V. Barale, J. Gower, and L Alberotanza, 249–271. Dordrecht: Springer. https://doi.org/10.1007/978-90-481-8681-5_15

Barber, Richard T., and Anna K. Hilting. 2000. "Achievements in Biological Oceanography." In *50 Years of Ocean Discovery: National Science Foundation 1950–2000*. Washington, DC: National Academies Press. https://doi.org/10.17226/9702

Barth, John A., Jonathan P. Fram, Edward P. Dever, Craig M. Risen, Chris E. Wingard, Robert W. Collier, and Thomas D. Kearney. 2018. "Warm Blobs, Low-Oxygen Events, and an Eclipse: The Ocean Observatories Initiative Endurance Array Captures Them All." *Oceanography* 31(1): 90–97. https://doi.org/10.5670/oceanog.2018.114

Bazilchuk, Nancy. 2022. "'Pamela' Makes Studying the Ocean Easy and Affordable." Ecomagazine. July 29, 2022. https://ecomagazine.com/news/industry/pamela-makes-studying-the-ocean-easy-and-affordable

Beggs, Helen M. 2010. "Use of TIR from Space in Operational Systems." In *Oceanography from Space: Revisited*. Edited by V. Barale, J. Gower, and L. Alberotanza, 249–271. Dordrecht: Springer. https://doi.org/10.1007/978-90-481-8681-5_15

Bennion, David H., David M. Warner, Peter C. Esselman, Brett Hobson, and Brian Kieft. 2019. "A Comparison of Chlorophyll *a* Values Obtained from an Autonomous Underwater Vehicle to Satellite-Based Measures for Lake Michigan." *Journal of Great Lakes Research* 45(4): 726–734. https://doi.org/10.1016/j.jglr.2019.04.003

Bowen, Andrew D., Dana Yoerger, Chris Taylor, Robert McCabe, Jonathan Howland, Daniel Gomez-Ibanez, James C. Kinsey, Matthew Heintz, Glenn McDonald, Donald B. Peters, John Bailey, Eleanor Bors, Tim Shank, Louis L. Whitcomb, Stephen C. Martin, Sarah E. Webster, Michael V. Jakuba, Barbara Fletcher, Chris Young, James Buescher, Patricia Fryer, and Samuel Hulme. 2009. "Field Trials of the Nereus Hybrid Underwater Robotic Vehicle in the Challenger Deep of the Mariana Trench." *Oceans* 2009: 1–10. https://doi.org/10.23919/OCEANS.2009.5422311

Braginsky, Boris, Alon Baruch, and Hugo Guterman. 2020. "Development of an Autonomous Surface Vehicle Capable of Tracking Autonomous Underwater Vehicles." *Ocean Engineering* 197: 106868. https://doi.org/10.1016/j.oceaneng.2019.106868

Brown, Steven W., Stephanie J. Flora, Michael E. Feinholz, Mark A. Yarbrough, Terrence Houlihan, Darryl Peters, Yong Sun Kim, James L. Mueller, B. Carol Johnson, and Dennis K. Clark. 2007. "The Marine Optical Buoy (MOBY) Radiometric Calibration and Uncertainty Budget for Ocean Color Satellite Sensor Vicarious Calibration." *Proceedings SPIE 6714: Sensors, Systems, and Next-Generation Satellites* XI: 67441M. https://doi.org/10.1117/12.737400

Bryson, Mitch, Matthew Johnson-Roberson, Richard J. Murphy, and Daniel Bongiorno. 2013. "Kite Aerial Photography for Low-Cost, Ultra-high Spatial Resolution Multi-Spectral Mapping of Intertidal Landscapes." *PLoS One* 8(9): e73550. https://doi.org/10.1371/journal.pone.0073550

Cael, B. B., Kelsey Bisson, Maureen Conte, Manon T. Duret, Christopher L. Follett, Stephanie A. Henson, Makio C. Honda, Morten H. Iversen, David M. Karl, Richard S. Lampitt, Colleen B. Mouw, Frank Muller-Karger, Corinne A. Pebody, Kenneth L. Smith Jr., and David Talmy. 2021. "Open Ocean Particle Flux Variability from Surface to Seafloor." *Geophysical Research Letters* 48(9): e2021GL092895. https://doi.org/10.1029/2021GL092895

Casella, Elisa, Jan Dreschel, Christian Winter, Markus Benninghoff, and Alessio Rovere. 2020. "Accuracy of Sand Beach Topography Surveying by Drones and Photogrammetry." *Geo-Marine Letters* 40: 255–268. https://doi.org/10.1007/s00367-020-00638-8

Casey, Kenneth S., Tess B. Brandon, Peter Cornillon, and Robert Evans. 2010. "The Past, Present, and Future of the AVHRR Pathfinder SST Program." In *Oceanography from Space*. Edited by V. Barale, J. Gower, and L Alberotanza, 273–287. Dordrecht: Springer. https://doi.org/10.1007/978-90-481-8681-5_16

Castro, Sandra L., Gary A. Wick, Darren L. Jackson, and William J. Emery. 2008. "Error Characterization of Infrared and Microwave Satellite Sea Surface Temperature Products for Merging and Analysis." *Journal of Geophysical Research* 113: C03010. https://doi.org/10.1029/2006JC003829

Christ, Robert D., and Robert L. Wernli. 2014. *The ROV Manual*. Waltham: Butterworth-Heinemann. https://www.sciencedirect.com/book/9780080982885/the-rov-manual

Colavito, Jason. 2014. *Jason and the Argonauts through the Ages*. Jefferson: McFarland & Company. https://mcfarlandbooks.com/product/jason-and-the-argonauts-through-the-ages/

Connor, J., B. Champion, and M. A. Joordens. 2021. "Current Algorithms, Communication Methods and Designs for Underwater Swarm Robotics: A Review." *IEEE Sensors Journal* 21(1): 153–169. https://doi.org/10.1109/JSEN.2020.3013265

Conte, Maureen H., and J. C. Weber. 2015. "Particle Flux in the Deep Sargasso Sea: The 35-Year Oceanic Flux Program Time Series." *Oceanography* 27(1): 142–147. https://doi.org/10.5670/oceanog.2014.17

Cook, Terri. 2020. "Obituary: Michael Freilich (1954–2020)." European Geosciences Union. August 7, 2020. https://www.egu.eu/news/678/obituary-michael-freilich-1954-2020/

Crease, James. 1962. "Velocity Measurements in the Deep Water of the Western North Atlantic: Summary." *Journal of Geophysical Research* 67(8): 3173–3176. https://doi.org/10.1029/JZ067i008p03173

Crise, Alessandro, Maurizio Ribera d'Alcalà, Patrizio Mariana, George Petihakis, Julie Robodart, Daniele Iudicone, Ralf Bachmayer, and Francesca Malfatti. 2018. "A Conceptual Framework for Developing the Next Generation of Marine OBservatories (MOBs) for Science and Society." *Frontiers in Marine Science* 5: 318. https://doi.org/10.3389/fmars.2018.00318

de Jong, M. Femke, Marilena Oltmanns, Johannes Kartensen, and Laura de Steur. 2018. "Deep Convection in the Irminger Sea Observed with a Dense Mooring Array." *Oceanography* 31(1); 50–59. https://doi.org/10.5670/oceanog.2018.109

Delaney, John R., Fred N. Speiss, Sean C. Solomon, Robert Hessler, Jill L. Karsten, John A. Baross, Robin T. Holcomb, Denis Norton, Russell E. McDuff, Fred Sayles, John Whitehead Jr., Dallas Abbott, and LeRoy Olsen. 1987. "Scientific Rationale for Establishing Long-Term Ocean Bottom Observatory/Laboratory Systems." In *Marine Minerals: Advances in Research and Resource Assessment*. Edited by P. G. Teleki, M. R. Dobson, J. R. Moore, and U. von Stackelberg. NATO ASI Series 194: 389–411. Dordrecht: D. Reidel Publishing. https://doi.org/10.1007/978-94-009-3803-8_27

Delaney, John R., Deborah S. Kelley, Aaron Marburg, Mark Stoermer, Hunter Hadaway, Kim Juniper, and Friedrich Knuth. 2016. "Axial Seamount—Wired and Restless: A Cabled Submarine Network Enables Real-Time Tracking of a Mid-Ocean Ridge Eruption and Live Video of an Active Hydrothermal System Juan de Fuca Ridge, NE Pacific." *OCEANS 2016 MTS/IEEE Monterey, 2016*: 1–8. https://doi.org/10.1109/OCEANS.2016.7761484

Dickey, Tommy D. 1991. "The Emergence of Concurrent High-Resolution Physical and Bio-optical Measurements in the Upper Ocean and Their Applications." *Reviews of Geophysics* 29(3): 383–413. https://doi.org/10.1029/91RG00578

Donlon, Craig J., Robert Cullen, Luisella Giulicchi, Pierrik Vuilleumier, C. Richard Francis, Mieke Kuschnerus, William Simpson, Abderrazak Bouridah, Mauro Caleno, Roberta Bertoni, Jesus Rancaño, Eric Pourier, Andrew Hyslop, James Mulcahy, Robert Knockaert, Christopher Hunter, Alan Webb, Marco Fornari, Parag Vaze, Shanon Brown, Joshua Willis, Shailen Desai, Jean-Damien Desjonqueres, Remko Scharroo, Cristain Martin-Puig, Eric Leuliette, Alejandro Egido, Walter H. F. Smith, Pascal Bonnefond, Sophie Le Gac, Nicolas Picot, and Gilles Tavernier. 2021. "The Copernicus Sentinel-6 Mission: Enhanced Continuity of Satellite Sea Level Measurements from Space." *Remote Sensing of the Environment* 258: 112395. https://doi.org/10.1016/j.rse.2021.112395

D'Ortenzio, Fabrizio, Vincent Taillandier, Hervé Claustre, Louis Marie Prieur, Edouard Leymarie, Alexander Mignot, Antoine Poteau, Christophe Penkerc'h, and Catherine Marie Schmechtig. 2020. "Biogeochemical Argo: The Test Case of the NAOS Mediterranean Array." *Frontiers in Marine Science* 7: 120. https://doi.org/10.3389/fmars.2020.00120.

Du, Zengfeng, Xiong Zhang, Chao Lian, Zhendong Luan, Shichuan Xi, Lianfu Li, Liang Mu, Jianxing Zhang, Wenzao Zhou, Xiufeng Chen, Zhijun Lu, Chuanbo Wang, Yu Chen, Jun Yan, and Xin Zhang. 2023. "The Development and Applications of a Controllable Lander for In-Situ, Long-Term Observation of Deep Sea Chemosynthetic Communities." *Deep Sea Research Part I: Oceanographic Research Papers* 193: 103960. https://www.sciencedirect.com/science/article/pii/S0967063722002734?via%3Dihub

Fiori, Lorenzo, Ashray Doshi, Emmanuelle Martinez, Mark B. Orams, and Barbara Bollard-Breen. 2017. "The Use of Unmanned Aerial Systems in Marine Mammal Research." *Remote Sensing* 9(6): 543. https://doi.org/10.3390/rs9060543

Flemming, B. W. 1976. "Side-Scan Sonar: A Practical Guide." *International Hydrographic Review* 53(1): 65–82. https://journals.lib.unb.ca/index.php/ihr/article/view/23734

Garwood, Jessica C., Andrew J. Lucas, Perry Naughton, Matthew H. Alford, Paul L. D. Roberts, Jules S. Jaffe, Laura deGelleke, and Peter J. S. Franks. 2020. "A Novel Cross-Shore Transport Mechanism Revealed by Subsurface, Robotic Larval Mimics: Internal Wave Deformation of the Background Velocity Field." *Limnology and Oceanography* 65(7): 1456–1470. https://doi.org/10.1002/lno.11400

Gens, Rudi. 2008. "Oceanographic Applications of SAR Remote Sensing." *GIScience & Remote Sensing* 45(3): 275–305. http://dx.doi.org/10.2747/1548-1603.45.3.275

Gentemann, C. L., Joel P. Scott, Piero L. F. Mazzini, Cassia Pianca, Santha Akella, Peter J. Minnett, Peter Cornillon, Baylor Fox-Kemper, Ivona Cetinić, T. Mike Chin, Jose Gomez-Valdes, Jorge Vazquez-Cuervo, Vardis Tsontos, Lisan Yu, Richard Jenkins, Sebastien De Halleux, Dave Peacock, and Nora Cohen. 2020. "Saildrone: Adaptively Sampling the Marine Environment." *Bulletin of the American Meteorological Society* 101(6): E744–E762. https://doi.org/10.1175/BAMS-D-19-0015.1

Gerringer, Mackenzie E., Thomas Linley, Alan J. Jamieson, Erica Goetze, and Jeffrey C. Drazen. 2017. "*Pseudoliparis swirei* sp. nov.: A Newly-Discovered Hadal Snailfish (Scorpaeniformes: Liparidae) from the Mariana Trench." *Zootaxa* 4358(1): 161–177. https://doi.org/10.11646/zootaxa.4358.1.7

Giddens, Jonatha, Alan Turchik, Whitney Goodell, Michelle Rodriguez, and Denley Delaney. 2021. "The National Geographic Society Deep-Sea Camera System: Low-Cost Remote Video Survey Instrument to Advance Biodiversity Observation in the Deep Ocean." *Frontiers in Marine Science* 7: 601411. https://doi.org/10.3389/fmars.2020.601411

Gillis, Justin. 2014. "In the Ocean, Clues to Change." *New York Times*. August 11, 2014. https://www.nytimes.com/2014/08/12/science/in-the-ocean-clues-to-change.html

Gloersen, Per, William J. Campbell, Donald J. Cavalieri, Josefino C. Comiso, Claire L. Parkinson, and H. Jay Zwally. 1992. *Arctic and Antarctic Sea Ice, 1987–1987: Satellite Passive-Microwave Observations and Analysis*. Washington, DC: Scientific and Technical Information Branch, National Aeronautics and Space Administration. https://ntrs.nasa.gov/citations/19940012966

Glud, Ronnie N., Peter Berg, Bo Thamdrup, Morten Larsen, Heather A. Stewart, Alan J. Jamieson, Anni Glud, Kazumasa Oguri, Hamed Sanei, Ashley A. Rowden, and Frank Wenzhöfer. 2021. "Hadal Trenches Are Dynamic Hotspots for Early Diagenesis in the Deep Sea." *Communications Earth & Environment* 2(21): 1–8. https://doi.org/10.1038/s43247-020-00087-2

Goni, Gustavo J., Robert E. Todd, Steven R. Jayne, George Halliwell, Scott Glenn, Jili Dong, Ruth Curry, Ricardo Domingues, Francis Bringas, Luca Centurioni, Steven F. DiMarco, Travis Miles, Julio Morell, Luis Pomales, Hyun-Sook Kim, Pelle E. Robbins, Glen G. Gawarkiewicz, John Wilkin, Joleen Heiderich, Becky Baltes, Joseph J. Cione, Greg Seroka, Kelly Knee, and Elizabeth R. Sanabia. 2017. "Autonomous and Lagrangian Ocean Observations for Atlantic Tropical Cyclone Studies and Forecasts." *Oceanography* 30(2): 92–103. https://doi.org/10.5670/oceanog.2017.227

Good, William S., Bradley Mallare, Zachary Payne, Jordan Wachs, Charles Wamsley, Joy Fasnacht, Rolfe Bode, and Sebastian Padilla. 2018. "Demonstration of Persistent, High Resolution Remote Sensing from an Advanced Stratollite Platform." In 2018 *AIAA Information Systems-AIAA Infotech@Aerospace*, 0193. https://doi.org/10.2514/6.2018-0193

Grare, Laurent, Nicholas Statom, Nick Pizzo, and Luc Lenain. 2021. "Instrumented Wave Gliders for Air-Sea Interaction and Upper Ocean Research." *Frontiers in Marine Science* 8: 664728. https://doi.org/10.3389/fmars.2021.664728

Gray, Patrick Clifton, Gregory D. Larsen, and David W. Johnson. 2022. "Drones Address an Observational Blind Spot for Biological Oceanography." *Frontiers in Ecology and the Environment* 20(7): 413–421. https://doi.org/10.1002/fee.2472

Guinness World Records. 2013. "Longest Journey by an Unmanned Autonomous Surface Vehicle." Accessed June 6, 2022. https://www.guinnessworldrecords.com/world-records/longest-journey-by-an-unmanned-autonomous-surface-vehicle

Haibo, Bi, Yu Liang, Yunhe Wang, Xi Liang, Zehua Zhang, Tingqin Du, Qinglong Yu, Jue Huang, Mei Kong, and Haijin Huang. 2020. "Arctic Multiyear Sea Ice Variability Observed from Satellites: A Review." *Journal of Oceanology and Limnology* 38: 962–984. https://doi.org/10.1007/s00343-020-0093-7

Hughes, Terry P., Kristen D. Anderson, Sean R. Connolly, Scott F. Heron, James T. Kerry, Janice M. Lough, Andrew H. Baird, Julia K. Baum, Michael L. Berumen, Tom C. Bridge, Danielle C. Claar, C. Mark Eakin, James P. Gilmour, Nicholas A. J. Graham, Hugo Harrison, Jean-Paul A. Hobbs, Andrew S. Hoey, Mia Hoogenboom, Ryan J. Lowe, Malcolm T. McCulloch, John M. Pandolfi, Morgan Pratchett, Verena Schoepf, Gergely Torda, and Shaun K. Wilson. 2018. "Spatial and Temporal Patterns of Mass Bleaching of Corals in the Anthropocene." *Science* 359: 80–83. https://doi.org/10.1126/science.aan8048

Jaffe, Jules S., Peter J. S. Franks, Paul L. D. Roberts, Diba Mirza, Curt Schurgers, Ryan Kastner, and Adrien Boch. 2017. "A Swarm of Autonomous Miniature Underwater Robot Drifters for Exploring Submesoscale Ocean Dynamics." *Nature Communications* 8: 14189. https://doi.org/10.1038/ncomms14189

JAMSTEC. 2017. "Deepest Fish Ever Recorded—Documented at Depths of 8,178 m in Mariana Trench." Japan Agency for Marine-Earth Science and Technology (JAMSTEC). August 24, 2017. https://www.jamstec.go.jp/e/about/press_release/20170824/.

Jayne, Steven R., and Neil M. Bogue. 2017. "Air-Deployable Profiling Floats." *Oceanography* 30(2): 29–31. https://doi.org/10.5670/oceanog.2017.214

Jayne, Steven R., Dean Roemmich, Nathalie Zilberman, Stephen C. Riser, Kenneth S. Johnson, Gregory C. Johnson, and Stephen R. Piotrowicz. 2017. "The Argo Program: Present and Future." *Oceanography* 30(2): 18–28. https://doi.org/10.5670/oceanog.2017.213

Katzschmann, Robert K., Joseph DelPreto, Robert McMurdy, and Daniela Rus. 2018. "Exploration of Underwater Life with an Acoustically Controlled Soft Robotic Fish." *ScienceRobotics* 3(16): eaar3449. https://doi.org/10.1126/scirobotics.aar3449

Kintisch, Eli. 2015. "A Moment of Truth Arrives for U.S. Ocean Science." *Science* 347(6221): 463. https://doi.org/10.1126/science.347.6221.463

Klemas, Victor. 2015. "Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview." *Journal of Coastal Research* 315(5): 1260-1267. http://dx.doi.org/10.2112/JCOASTRES-D-15-00005.1

Knauss, John A., and Newell Garfield. 2017. *Introduction to Physical Oceanography*, 3rd ed. Long Grove: Waveland Press. https://www.waveland.com/browse.php?t=504

Kukulya, Amy L., Roger Stokey, Carl Fesiter, Edgar Mauricio Hoyos-Padilla, and Gregory Skomal. 2016. "Multi-vehicle Autonomous Tracking and Filming of White Sharks *Carcharodon carcharias*." *2016 IEEE/OES Autonomous Underwater Vehicles (AUV)*: 423–430. https://doi.org/10.1109/AUV.2016.7778707

Lee, Craig M., Theresa Paluszkiewicz, Daniel L. Rudnick, Melissa M. Omand, and Robert E. Todd. 2017. "Autonomous Instruments Significantly Expand Ocean Observing: An Introduction to the Special Issue on Autonomous and Lagrangian Platforms and Sensors (ALPS)." *Oceanography* 30(2): 15–17. https://doi.org/10.5670/oceanog.2017.211

Li, Guorui, Xiangping Chen, Fanghao Zhou, Yiming Liang, Youhua Xiao, Xunuo Cao, Zhen Zhang, Mingqi Zhang, Baosheng Wu, Shunyu Yin, Yi Xu, Hongbo Dan, Zheng Chen, Wei Song, Wenjing Yang, Binbin Pan, Jiaoyi Hou, Weifend Zou, Shunping He, Xuxu Yang, Guoyong Mao, Zheng Jia, Haofei Zhou, Tiefeng Li, Shaoxing Qu, Zhongpin Xu, Zhilong Huang, Yingwu Luo, Tao Xie, Jason Gu, Shiqiang Zhu, and Wei Yang. 2021. "Self-Powered Soft Robot in the Mariana Trench." *Nature* 591: 66–71. https://doi.org/10.1038/s41586-020-03153-z

Li, Xue, Shaoling Shang, Zhongping Lee, Gong Lin, Yongnian Zhang, Jingyu Wu, Zhenjun Kang, Xiangxu Liu, Cheng Yin, and Yue Gao. 2021. "Detection and Biomass Estimation of *Phaeocystis globosa* Blooms off Southern China from UAV-Based Hyperspectral Measurements." *IEEE Transactions on Geoscience and Remote Sensing* 60: 1–13. https://doi.org/10.1109/TGRS.2021.3051466

Lindsey, Rebecca, and Luann Dahlman. 2020. "Climate Change: Ocean Heat Content." NOAA Climate. August 17, 2020. https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

Lipsett, Lonny. 2014. "A Long-Lost Legacy of Ocean Research Resurfaces." *Oceanus*. February 6, 2014. https://www.whoi.edu/oceanus/feature/bumpus/

Lumberg, Johannes, Frank Wenzhöfer, Machael Hofbauer, Paul Färber, and Volker Meyer. 2018. "Benthic Crawler NOMAD." *2018 OCEANS – MTS/IEEE Kobe Techno-Oceans (OTO)*, 1–7. https://doi.org/10.1109/OCEANSKOBE.2018.8559446

Lumpkin, Rick, Tamay Özgökmen, and Luca Centurioni. 2017. "Advances in the Application of Surface Drifters." *Annual Review of Marine Science* 9: 59–81. https://doi.org/10.1146/annurev-marine-010816-060641

Marx, Robert F. 1990. *The History of Underwater Exploration*. Kiribati: Dover Publications. https://www.google.com/books/edition/The_History_of_Underwater_Exploration/oiWFhoRzPBQC?hl=en

Mazzolai, Barbara, Federico Carpi, Koichi Suzumori, Matteo Cianchetti, Thomas Speck, Stoyan K. Smoukov, Ingo Burgert, Tobias Keplinger, Gilberto Siqueira, Felix Vanneste, Oliver Goury, Christian Duriez, Thrishantha Nanayakkara, Bram Vanderborght, Joost Brancart, Seppe Terryn, Steven Rich, Ruituan Liu, Kenjiro Fukuda, Takao Someya, Marcello Calisti, Cecilia Laschi, Wenguang Sun, Gang Wang, Li Wen, Robert Baines, Sree Kalyan Patiballa, Rebecca Kramer, Daniela Rus, Peer Fischer, Friedrich Simmel, and Andreas Lendlein. 2022. "Roadmap on Soft Robotics: Multifunctionality, Adaptability, and Growth Without Borders." *Multifunctional Materials* 5(3): 032001. https://doi.org/10.1088/2399-7532/ac4c95

Meyer, H. K., E. M. Roberts, H. T. Rapp, and A. J. Davies. 2019. "Spatial Patterns of Arctic Sponge Ground Fauna and Demersal Fish Are Detectable in Autonomous Underwater Vehicle (AUV) Imagery." *Deep Sea Research Part I: Oceanographic Research Papers* 153: 103137. https://doi.org/10.1016/j.dsr.2019.103137

Minnett, P. J., A. Alvera-Azcárate, T. M. Chin, G. K. Corlett, C. L. Gentemann, I. Karagali, X. Li, A. Marsouin, S. Marullo, E. Maturi, R. Santoleri, S. Saux Picart, M. Steele, and J. Vazquez-Cuervo. 2019. "Half a Century of Satellite Remote Sensing of Sea-Surface Temperature." *Remote Sensing of the Environment* 233: 111366. https://doi.org/10.1016/j.rse.2019.111366

Molar-Candanosa, Robert. "NASA Is Helping Fly Drones in the Arctic. Here's What That Means for Sea Ice and Sea Level Change." NASA. February 24, 2022. https://www.nasa.gov/feature/goddard/2022/nasa-helps-fly-drone-in-alaska-to-study-sea-ice-thickness

Mongilio, Heather. 2023. "Titan Submersible Debris Found Near Titanic Wreck; Navy Sensors Detected Implosion." USNI News. June 22, 2023. https://news.usni.org/2023/06/22/coast-guard-titan-submersible-suffered-catastrophic-loss-debris-found-near-titanic-wreck

Moore, Steven W., Harry Bohm, and Vickie Jensen. 2010. *Underwater Robotics: Science, Design & Fabrication*. Monterey: Marine Advanced Technology Education Center. https://www.marinetech.org/underwater-robotics-textbook-2/

Munk, Walter. 2002. Testimony to the US Commission on Ocean Policy. San Pedro, California. April, 18, 2002. https://govinfo.library.unt.edu/oceancommission/meetings/apr18_19_02/apr18_19_02.html#agenda

Murfitt, Sarah L., Blake M. Allan, Alecia Bellegrove, Alex Rattray, Mary A. Young, and Daniel Ierodianconou. 2017. "Applications of Unmanned Aerial Vehicles in Intertidal Reef Monitoring." *Scientific Reports* 7: 10259. https://doi.org/10.1038/s41598-017-10818-9

Nakajoh, Hidehiko, Takashi Murashima, and Fumitaka Sugimoto. 2018. "Development of Full Depth Fiber Optic Cable ROV (UROV11K) System." *OCEANS 2018 MTS/IEEE Charleston*: 1–8. https://doi.org/10.1109/OCEANS.2018.8604795

National Research Council. 2015. *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: National Academies Press. https://doi.org/10.17226/21655

Nehring, Abigail. 2021. “Douglas Webb: Tinkerer, Engineer and Oceanographer Emeritus.” The Enterprise. January 26, 2021. https://www.capenews.net/falmouth/news/douglas-webb-tinkerer-engineer-and-oceanographer-emeritus/article_c8fd4ab2-bdb0-57e5-b0df-373f47fb14d5.html

Newpower, Anthony. 2006. *Iron Men and Tin Fish: The Race to Build a Better Torpedo During World War II*. Westport: Praeger Security International. https://www.abc-clio.com/products/d1212c/

Nguyen, Kien, Clinton Fookes, Sridha Sridharan, Yingli Tian, Feng Liu, Xiaoming Liu, and Arun Ross. 2022. “The State of Aerial Surveillance: A Survey.” *IEEE Transactions* arXiv:2201.03080v2. https://doi.org/10.48550/arXiv.2201.03080

Niiler, Peter. 2001. “The World Ocean Surface Circulation.” In *Ocean Circulation and Climate: Observing and Modelling the Global Ocean*. Volume 77. Edited by Gerold Siedler, John Church, and John Gould, 193–204. Oxford: Academic Press. https://doi.org/10.1016/S0074-6142(01)80119-4

O’Carroll, Anne G., Edward M. Armstrong, Helen M. Beggs, Marouan Bouali, Kenneth S. Casey, Gary K. Corlett, Prasanjit Dash, Craig J. Donlon, Chelle L. Gentemann, Jacob L. Høyer, Alexander Ignatov, Kamila Kabobah, Misako Kachi, Yukio Kurihara, Ioanna Karagali, Eileen Maturi, Christopher J. Merchant, Salvatore Marullo, Peter J. Minnett, Matthew Pennybacker, Balaji Ramakrishnan, RAAJ Ramsankaran, Rosalia Santoleri, Swathy Sunder, Stéphane Saux Picart, Jorge V**á**zquez-Cuervo, and Irernfrid Wimmer. 2019. “Observational Needs of Sea Surface Temperature.” *Frontiers of Marine Science* 6: 420. https://doi.org/10.3389/fmars.2019.00420

Pagniello, Camille M. L. S., Megan A. Cimino, and Eric Terrill. 2019. “Mapping Fish Chorus Distributions in Southern California Using an Autonomous Wave Glider.” *Frontiers in Marine Science* 6: 526. https://doi.org/10.3389/fmars.2019.00526

Parkinson, Claire. 2019. “A 40-y Record Reveals Gradual Antarctic Sea Ice Increases Followed by Decreases at Rates Far Exceeding the Rates Seen in the Arctic.” *PNAS* 116(29): 14414–14423. https://doi.org/10.1073/pnas.1906556116

Parkinson, Claire L., Josefino C. Comiso, H. Jay Zwally, Donald J. Cavalieri, and Per Gloersen. 1987. *Arctic Sea Ice, 1973–1976: Satellite Passive-Microwave Observations*. Washington DC: Scientific and Technical Information Branch, National Aeronautics and Space Administration. https://ntrs.nasa.gov/citations/19870015437

Patel, Kasha. “Nimbus: NASA Remembers First Earth Observations.” NASA. August 6, 2017. https://www.nasa.gov/content/goddard/nimbus-nasa-remembers-first-earth-observations

Roemmich, Dean, Matthew H. Alford, Hervé Claustre, Kenneth Johnson, Brian King, James Moum, Peter Oke, W. Brechner Owens, Sylvie Pouliquen, Sarah Purkey, Megan Scanderberg, Toshio Suga, Susan Wijffels, Nathalie Zilberman, Dorothee Bakker, Molly Baringer, Mathieu Belbeoch, Henry C. Bittig, Emmanuel Boss, Paulo Calil, Fiona Carse, Thierry Carval, Fei Chai, Diarmuid Ó. Conchubhair, Fabrizio d’Ortenzio, Giorgio Dall’Olmo, Damien Desbruyeres, Katja Fennel, Ilker Fer, Raffaele Ferrari, Gael Forget, Howard Freeland, Tetsuichi Fujiki, Marion Gehlen, Blair Greeenan, Robert Hallberg, Toshiyuki Hibiya, Shigeki Hosoda, Steven Jayne, Markus Jochum, Gregory C. Johnson, KiRyong Kang, Nicolas Kolodziejczyk, Arne Körtzinger, Pierre-Yves Le Traon, Yueng-Djern Lenn, Guillaume Maza, Kjell Arne Mork, Tamaryn Morris, Takeyoshi Nagai, Jonathan Nash, Alberto Naveira Garabato, Are Olsen, Rama Rao Pattabhi, Satya Prakash, Stephen Riser, Catherine Schmechtig, Claudia Schmid, Emily Shroyer, Andreas Sterl, Philip Sutton, Lynne Talley, Toste Tanhua, Virginie Thierry, Sandy Thomalla, John Toole, Ariel Troisi, Thomas W. Trull, Jon Turton, Pedro Joaquin Velez-Belchi, Waldemar Walczowski, Haili Wang, Rik Wanninkhof, Amy F. Waterhouse, Stephanie Waterman, Andrew Watson, Cara Wilson, Annie P. S. Wong, Jianping Xu, and Ichiro Yasuda. 2019. “On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array.” *Frontiers in Marine Science* 6: 439. https://doi.org/10.3389/fmars.2019.00439

Sanabia, Elizabeth, and Steven R. Jayne. 2020. “Ocean Observations Under Two Major Hurricanes: Evolution of the Response Across the Storm Wakes.” *AGU Advances* 1(3): e2019AV000161. https://doi.org/10.1029/2019AV000161

Schlee, John S., Herman A. Karl, and M.E. Torresan. 1995. *Imaging the Sea Floor*. (No. 2079). US Government Printing Office. https://doi.org/10.3133/b2079

Schofield, Oscar, Josh Kohut, David Aragon, Liz Creed, Josh Graver, Chip Haldeman, John Kerfoot, Hugh Roarty, Clayton Jones, Doug Webb, and Scott Glenn. 2007. “Slocum Gliders: Robust and Ready.” *Journal of Field Robotics* 24(6): 473–485. https://doi.org/10.1002/rob.20200

Searle, R. C., C. J. MacLeod, C. Peirce, and T. J. Reston. 2018. “The Mid-Atlantic Ridge Near 13°20´N: High-Resolution Magnetic and Bathymetry Imaging.” *Geochemistry, Geophysics, Geosystems* 20(1): 295–313. https://doi.org/10.1029/2018GC007940

Sivčev, Staja, Joseph Coleman, Edin Omerdić, Gerard Dooly, and Daniel Toal. 2018. “Underwater Manipulators: A Review.” *Ocean Engineering* 163: 431–450. https://doi.org/10.1016/j.oceaneng.2018.06.018

Smith, Raymond C., and Karen S. Baker. 1978. Optical Classification of Natural Waters. *Limnology and Oceanography* 23(2): 260–267. https://doi.org/10.4319/lo.1978.23.2.0260

Speich, Sabrina, Tong Lee, Frank Muller-Karger, Laura Lorenzoni, Ananda Pascual, Di Jin, Eric Delory, Gilles Reverdin, John Siddorn, Marlon R. Lewis, Nuria Marba, Pier Luigi Buttigieg, Sanae Chiba, Justin Manley, Amos Tiereyangn Kabo-Bah, Kruti Desai, and Abby Ackerman. 2019. “Editorial: Oceanobs’19: An Ocean of Opportunity.” *Frontiers in Marine Science* 6: 570. https://doi.org/10.3389/fmars.2019.00570

Stommel, Henry. 1965. *The Gulf Stream*. Berkeley: University of California Press. Reissued 2022. https://www.ucpress.edu/book/9780520318557/the-gulf-stream

Storch, Hans Von, Amders Omstedt, and Ulrich Callies. 2020. “Drift Bottles in the Southern Baltic Sea—an Experiment-of-Opportunity.” Unpublished manuscript. April 2020. https://www.researchgate.net/publication/340885296_Drift_bottles_in_the_southern_Baltic_Sea_-_an_experiment-of-opportunity

Stuart, Mary B., Andrew J. S. McGonigle, and Jon R. Willmott. 2019. “Hyperspectral Imaging in Environmental Monitoring: A Review of Recent Developments and Technological Advances in Compact Field Deployable Systems.” *Sensors* 19(14): 3071. https://doi.org/10.3390/s19143071

Swallow, John. 1955. “A Neutral Buoyancy Float for Measuring Deep Currents.” *Deep Sea Research* 3: 74–81. https://doi.org/10.1016/0146-6313(55)90037-X

Tikhonov, V. V., M. D. Raev, E. A. Sharkov, D. A. Boyarskii, I. A. Repina, and N. Yu Komarova. 2016. “Satellite Microwave Radiometry of Sea Ice of Polar Regions: A Review.” *Izvestiya, Atmospheric and Oceanic Physics* 52: 1012–1030. https://doi.org/10.1134/S0001433816090267

Trowbridge, John, Robert Weller, Deborah Kelley, Edward Dever, Albert Plueddemann, John A. Barth, and Orest Kawka. 2019. “The Ocean Observatories Initiative.” *Frontiers of Marine Science* 6: 74. https://doi.org/10.3389/fmars.2019.00074

Tsatsoulis, Costas, and Ronald Kwok. 1998. “Recent Advances in the Analysis of SAR Data of the Polar Oceans.” In *Analysis of SAR Data of the Polar Oceans*. Edited by Costas Tsatsoulis and Ronald Kwok. Heidelberg: Springer Berlin. https://doi.org/10.1007/978-3-642-60282-5

Vardi, Tali, Whitney C. Hoot, Jessica Levy, Elizabeth Shaver, R. Scott Winters, Anastazia T. Banaszak, Iliana B. Baums, Valéries F. Chamberland, Nathan Cook, David Gulko, Margaux Y. Hein, Les Kaufman, Michelle Loewe, Petra Lundgren, Caitlan Lustic, Petra MacGowan, Mikhail V. Matz, Miles McGonigle, Ian McLeod, Jennifer Moore, Tom Moore, Sandrine Pivard, F. Joseph Pollock, Baruch Rinkevich, David, J. Suggett, Samuel Suleiman, T. Shay Viehman, Tatiana Villalobos, Virginia M. Weis, Chelsea Wolke, and Phanor H. Montoya-Maya. 2021. “Six Priorities to Advance the Science and Practice of Coral Reef Restoration Worldwide.” *Restoration Ecology* 29(8): e13498. https://doi.org/10.1111/rec.13498

Visbeck, Martin. 2018. “Ocean Science Research Is Key for a Sustainable Future.” *Nature Communications* 9: 690. https://doi.org/10.1038/s41467-018-03158-3

Voosen, Paul. 2018. “Saildrone Fleet Could Help Replace Aging Buoys.” *Science* 359(6380): 1082–1083. https://doi.org/10.1126/science.359.6380.1082

Wang, Jian, Yuan-gui Tang, Chuan-xu Chen, Ji-xu Li, Cong Chen, Ai-qun Zhang, Yi-ping Li, and Shuo Li. 2020. “Terrain Matching Localization for Hybrid Underwater Vehicle in the Challenger Deep of the Mariana Trench.” *Frontiers of Information Technology & Electronic Engineering* 21: 749–759. https://doi.org/10.1631/FITEE.1900556

Witze, Alexandra. 2013. “Marine Science: Oceanography’s Billion-Dollar Baby.” *Nature* 501: 480–482. https://doi.org/10.1038/501480a

Woods Hole Oceanographic Institution. “Dean F. Bumpus.” Accessed June 5, 2022. https://www.whoi.edu/who-we-are/about-us/people/obituary/dean-f-bumpus/

World View. 2023. “Engineering Peak Experiences in the Stratosphere.” Accessed March 13, 2023. https://worldview.space/space-tourism/

Wu, Ziyin, Fanlin Yang, and Yong Tang. 2021. “Side-scan Sonar and Sub-bottom Profiler Surveying.” In *High-resolution Seafloor Survey and Applications*, 95–122. Singapore: Springer. https://doi.org/10.1007/978-981-15-9750-3_4

Xiang, Xianbo, Zemin Niu, Lionel Lapierre, and Mingjiu Zuo. 2015. “Hybrid Underwater Robotic Vehicles: The State-of-the-Art and Future Trends.” *HKIE Transactions* 22(2): 103–116. https://doi.org/10.1080/1023697X.2015.1038322

Yoerger, Dana R., Annette F. Govindarajan, Jonathan C. Howland, Joel K. Llopiz, Peter H. Wiebe, Molly Curran, Justin Fujii, Daniel Gomez-Ibanez, Kakani Katija, Bruce H. Robison, Brett W. Hobson, Michael Risi, and Stephen M. Rock. 2021. “A Hybrid Underwater Robot for Multidisciplinary Investigation of the Ocean Twilight Zone.” *ScienceRobotics* 6(55): 1–12. https://doi.org/10.1126/scirobotics.abe1901

Zhang, Yanwu, John P. Ryan, Brett W. Hobson, Brian Kieft, Anna Romano, Benedetto Barone, Christina M. Preston, Brent Roman, Ben-Yair Raanan, Douglas Pargett, Mathilde Dugenne, Angelicque E. White, Fernanda Henderikx Freitas, Steve Poulos, Samuel T. Wilson, Edward F. DeLong, David M. Karl, James M. Birch, James G. Bellingham, and Christopher A. Scholin. 2021. “A System of Coordinated Autonomous Robots for Lagrangian Studies of Microbes in the Oceanic Deep Chlorophyll Maximum.” *ScienceRobotics* 6(50): eabb9138. https://doi.org/10.1126/scirobotics.abb9138

Zhang, Yanwu, John P. Ryan, Brian Kieft, Brett W. Hobson, Robert S. McEwen, Michael A. Godin, Julio B. Harvey, Benedetto Barone, James G. Bellingham, James M. Birch, Christopher A. Scholin, and Francisco P. Chavez. 2019. “Targeted Sampling by Autonomous Underwater Vehicles.” *Frontiers in Marine Science* 6: 415. https://doi.org/10.3389/fmars.2019.00415

Zinke, Julika, Matthew E. Salter, Caroline Leck, Michael J. Lawler, Grace C. E. Porter, Michael P. Adams, Ian M. Brooks, Benjamin J. Murray, and Paul Zieger. 2021. “The Development of a Miniaturised Balloon-Borne Cloud Water Sampler and Its First Deployment in the High Arctic.” *Tellus B: Chemical and Physical Meteorology* 73(1): 1–12. https://doi.org/10.1080/16000889.2021.1915614

Zwally, H. Jay, Josefino C. Comiso, Claire L. Parkinson, William J. Campbell, Frank D. Carsey, and Per Gloersen. 1983. *Antarctic Sea Ice, 1973-1976: Satellite Passive-Microwave Observations*. Washington, DC: Scientific and Technical Information Branch, National Aeronautics and Space Administration. https://ntrs.nasa.gov/citations/19840002650

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SECTION OVERVIEW

Voyage II Ocean Geology and Chemistry

5: The Beach

5.1: What Is a Beach?
5.2: Anatomy of a Beach
5.3: The Origins of Beach Sand
5.4: From the Mountains to the Sea
5.5: Wave-Driven Sediment Transport
5.6: The Littoral Cell
5.7: Human Impacts on Beaches
5.8: The Last Beach?
5.9: Chapter References

6: The Seafloor

6.1: Planet Earth vs. Planet Ocean
6.2: A Few Words About “Seafloor”
6.3: Marine Geomorphometry
6.4: Seafloor Provinces
6.5: Deep-Sea Mining
6.6: Chapter References

7: Seawater and Its Elements

7.1: Anatomy of a Molecule
7.2: The Periodic Table of the Elements
7.3: The Name’s Bond, Chemical Bond
7.4: Chemical Formulas
7.5: The Water Molecule
7.6: What Are Salts?
7.7: Seawater Constituents
7.8: Chapter References

8: The Water Cycle and Ocean Salinity

8.1: A Useful and Simple Model
8.2: The Global Water Cycle
8.3: The Three States of Water
8.4: Water, the Dissolver of Rocks
8.5: Salinity over Long Timescales
8.6: Salinity over Short Timescales
8.7: Airborne Sources of Salts
8.8: Biological Sources and Sinks
8.9: Residence Time
8.10: Measuring Salinity

8.11: The Global Water Crisis
8.12: Chapter References

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CHAPTER OVERVIEW

5: The Beach

One night in the summer of 1983 while headed to Los Angeles in a cramped VW Beetle to start graduate school, I drove along a dusty dirt road in Northern California toward a beach campground known as Gold Bluffs. According to my tattered tour book, the campground offered views of coastal redwood trees and the Pacific Ocean, and since I had three weeks to spare before school started, I thought I would check it out.

The next morning I awoke to thunderous surf. Rolling out of my tent, I felt like I had stepped back into the *Land of the Giants* (Allen 1968). Mammoth redwood trees stood like sentinels on hundred-foot cliffs, guarding Earth, shrouded in a dense mist, seemingly frozen in time. At the base of the cliffs, several gigantic trees lay upended, tossed to their death on the beach below. They were no match for the wallop packed by the Pacific Ocean during a storm, a bitter war between land and sea waged across the millennia.

As I sat on a weathered picnic table eating Cheerios from the box—because that's what you do when you're camping—I heard a sound. Out of the gloomy mist and morning chill, beyond the breakers and a few sparse blades of kelp, I saw a gray whale surface and expel his lungs. It was an odd time of year for a gray whale to visit these parts. Typically, they roam the coast between November and May. But I guessed that this fellow was a loner—not unlike me on that morning—one of the old-school males who'd had enough of those ten-thousand-mile annual migrations. He rolled gently just outside the surf, feeding perhaps, or just enjoying a solitary moment in time, as I was. It was one of those instances when time stands still and everything in life is just the way it's supposed to be. "Welcome to California," I thought.

I visited Gold Bluffs Beach again in 2005 with my mom on her California journey to live with me after my father died. A few more giant trees had fallen, and a herd of elk grazed among colorful wildflowers. Otherwise, it was exactly as I remembered it. It was a special place to share with my mom. After all, she was the person who introduced me to the beach when I was just a few weeks old. As you can probably tell, the beach holds great meaning for me. I hope it does for you too.

In this chapter, we examine that strip of land along the rim of the world ocean, the beach. Because most of us have formed our deepest impressions of the ocean here, the beach makes a natural starting point for exploring the geology and chemistry of the ocean—subjects in our chapters ahead.

5.1: What Is a Beach?
5.2: Anatomy of a Beach
5.3: The Origins of Beach Sand
5.4: From the Mountains to the Sea
5.5: Wave-Driven Sediment Transport
5.6: The Littoral Cell
5.7: Human Impacts on Beaches
5.8: The Last Beach?
5.9: Chapter References

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5.1: What Is a Beach?

The term **beach** commonly refers to the loose bits and fragments of material along the shore of a body of water, including lakes, rivers, and the world ocean. These bits and fragments consist mostly of **sediments**, solid particles of various sizes fragmented from rocks. While we think of beaches as mostly sand, they may include any of the six major size classes of sediments as defined in a geological classification system known as the **Udden-Wentworth scale**. From smallest to largest, they include clay, silt, sand, pebbles, cobbles, and boulders (Udden 1914; Wentworth 1922). Many beaches exhibit the full range of sediment sizes, from clay to boulders.

Sediments also originate from biological and chemical processes. Fragments of shells, corals, and even calcified algae can be found on beaches. Sanibel Island on the west coast of Florida features beaches made almost entirely of intact or broken fragments of shells. Bahamian beaches accumulate **ooids**, light-colored ovals of calcium carbonate that resemble the hard mint candies known as Tic Tacs. Ooids originate from the precipitation of solids in supersaturated seawater.

Beaches may host a wide variety of other materials, too—natural and manmade. Beaches in the state of Washington are often covered in driftwood and logs, castaways from the logging industry. The Skeleton Coast on the northern coast of Namibia accumulates the bones of whales, seals, and shipwrecks. And as you well know, debris from humans—especially plastics—can be found on every beach in the world, including those in Antarctica.

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5.2: Anatomy of a Beach

Though beaches vary widely in their sediments, they generally exhibit a similar appearance—a common structure—with recognizable features. Identification of these different parts helps us appreciate the nature of beaches and better understand the processes that shape them. (Our discussion here generally follows Pilkey et al. 2004.)

When you enter from a parking lot or a cliff, you first encounter the back of the beach, a typically flat portion known as the **backshore**. At some locations (such as Oceano Dunes near Pismo Beach, California), you may walk over sand dunes prior to entering the backshore. The backshore is generally the most stable portion of the beach because it is only occasionally inundated by waves.

The backshore may also contain accumulations of sand in the form of **berms**, which represent shelves of sand left by waves in a receding tide. Multiple berms may be present on a backshore, especially in the days following the highest tides (e.g., spring tides). During periods of high surf or seasonally extreme tides—popularly known as **king tides**—the backshore may be completely submerged on some beaches. Much of the debris found on the upper portion of the backshore is deposited during periods of high surf or unusually high tides. Large swaths of sand may be removed from the backshore during these times as well. Otherwise, if the sand on the backshore is untouched by waves or tides, winds may create accumulations of sand as beach dunes.

The lower portion of the beach is called the **foreshore**. The part that slopes toward the sea—alternately submerged and exposed during a tidal cycle and subject to daily wave action—is called the **beach face**. The backshore berm, or clifflike **beach scarp**, if present, marks the upper boundary of the foreshore, while the lower boundary of the foreshore ends at the location of sea level during low tide. Note that the width of the foreshore changes dynamically as a result of the action of waves and tides. The foreshore may grow during periods of high-energy waves and spring tides (when tidal range is greatest). Waves and high water levels push the berm toward the backshore. During periods of low-energy waves and neap tides (when tidal range is lowest), the foreshore shrinks as the berm migrates seaward.

A common feature on the upper boundary of the foreshore is a line of seaweed and debris known as the **wrack line** (pronounced “rack”). Kelp wrack is common on Atlantic and Pacific coast beaches where kelp grows nearby. Ocean currents drag sargassum weed from the Sargasso Sea and deposit it (often in great quantities) on Florida beaches. In truth, any kind of dislodged seaweed and marine debris may be deposited on the beach face as the tide recedes. The location of the wrack line on any given day indicates the height of the highest tide at the beach. At times when the height of the highest tide is lower each succeeding day, you may observe several wrack lines, each corresponding to the height of the highest tide of the previous days.

Beach cusps, a series of crescent- or scallop-shaped deposits of sand parallel to the beach, are another common feature on the upper beach face. Scientists remain uncertain as to the mechanisms that form beach cusps. A type of shore-parallel wave called an edge wave may play some role. However they form, beach cusps are fascinating to observe and a prominent feature on a beach face.

On some beaches the lower portion of the beach face may be flat and exposed during low tide. This is the **low-tide terrace**. I like to think of it as the ocean’s patio, albeit one with holes, bumps, and streams. The low-tide terrace represents the shallowest portion of the seafloor. If you’re standing on the low-tide terrace, you can truly say that you are walking on the seafloor.

Sandbars often mark the seaward side of a low-tide terrace. Sandbars represent a “reservoir” of sand that forms when high-energy waves move sand offshore. Under low-energy conditions, the sandbar may be pushed toward the beach and build up the foreshore.

As the waves and tide recede and expose the low-tide terrace, water that has penetrated the sand will flow back into the ocean. Because the foreshore is sloped, the water may flow out of the sand as little streams. As these streams of water flow, they move sand, and, much like a river, they erode the sand and leave tell-tale signs of their flow. The tree-like, or dendritic, patterns left by water seeping out of the sand at low tide are called **rills**. Look for them the next time you’re at the beach at low tide.

Often the low-tide terrace is separated from the foreshore by a **runnel**, a strip of shallow water parallel to the beach. A runnel most often appears in the summer, when small waves push sand toward the beach. Small fish, sea stars, conch shells, and other kinds of marine life may get trapped in these temporary pools. Look, but don’t take. A living creature plays a valuable role in the ocean ecosystem, something it can’t do sitting on a shelf collecting dust in your home.

Directly offshore of the low-tide terrace, you will encounter the area that many people travel to the beach to experience—the **surf zone**. It extends from the point where the waves begin to break to the edge of the beach. A current may be present here which flows parallel to the beach between the surf zone and the foreshore (see below).

The region below the low-tide terrace and beyond is called the **offshore**. The term also refers to a direction—away from the shore. Winds blowing from the land toward the ocean—such as occurs during Santa Ana wind conditions in Southern California—are classified as **offshore winds**.

Finally, the region of the ocean from the low-tide terrace to the edge of the continental shelf is called the **coastal ocean** (or neritic zone). The coastal ocean includes all the waters above the continental shelf (discussed in Chapter 7). Beyond that, we're in the **open ocean**, the deep blue sea, largely removed from any terrestrial influences.

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5.3: The Origins of Beach Sand

The individual bits of materials on a beach are called **grains**, as in grains of sand. Individual grains generally consist of a single **mineral**, defined as solids of inorganic material with a unique chemical composition and crystalline structure. **Rocks** consist of aggregates of minerals and non-minerals according to Fullerton College emeritus geology professor Richard Lozinsky, aka "Doc Rock" (Lozinsky 2010). Thus, sand grains and their minerals come from rocks (as we shall see).

Close inspection of the grains of sand from a typical Southern California beach will show that the sand consists mostly of white or clear grains, identified as the mineral **quartz**; yellowish grains, identified as the mineral **feldspar**; and gray or black grains, identified as the mineral **biotite**. Identification of the minerals present in a sample of sand provides clues as to where the sand originated. They can also help detectives catch criminals, a field called forensic geology (e.g., Ruffell and McKinley 2008).

Three major types of rocks can be found on Earth:

- **Igneous rocks**, rocks originating from the solidification of magma (molten material below Earth's surface) or lava (molten material extruded onto Earth's surface)
- **Sedimentary rocks**, rocks formed from the fragmentation and consolidation of other rocks
- **Metamorphic rocks**, rocks modified by heat, pressure, and fluids

According to Best (1995), igneous-type rocks comprise nearly 65 percent of the rocks found in Earth's continental crust and more than 95 percent of rocks forming the seafloor. Sedimentary rocks make up about 8 percent of the volume of Earth's continental crust and less than 2 percent of oceanic crust. Metamorphic rocks make up slightly more than 27 percent of Earth's continental crust and a small percentage of oceanic crust.

Earth's rocks rarely remain the same. Any of these three rock types may be transformed into another. Geologists refer to these transformations of rock and the processes that cause them as the **rock cycle**. Plate tectonics plays a major role in the transformations of the rock cycle. But a number of processes on Earth's surface also alter the properties of rocks, as we shall see.

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5.4: From the Mountains to the Sea

Our search for the origins of beach sand begins in the most unlikely of places, the mountains. This is where many sediments begin their life. Geologists refer to the source material that produces sediments as the **parent rock**. The rock(s) from which sediments originate defines the sediments' **heritage**—the properties inherited by the sediments from the parent rock. Just as your heritage may be defined by the genes and cultures of your parents, the heritage of a particular type of sediment comes from the characteristics of the rock that gave rise to it. Sediments have parents, and they inherit properties from those parents, just like us.

To understand how sediments move from the mountains to a beach, it's useful to introduce the concept of a **watershed**, an interconnected region of waterways that drains water, dissolved materials, sediments, and debris to a common outlet. Watersheds drain water from higher elevations to lower elevations. Eventually, the water and any associated dissolved or solid materials come to rest in a lake, a manmade reservoir, or the ocean (e.g., Dobson and Beck 2022).

Most watersheds are associated with rivers, and these may be supplemented by smaller creeks and streams, what are known as **tributaries**. A river's watershed includes all the tributaries that feed water into the main artery of a river. In outline, a watershed may resemble a branched tree, where the smaller branches (i.e., creeks) merge into larger branches (i.e., the streams) and the larger branches connect to the main trunk (the main channel of the river). You might think of these pathways as being like capillaries that connect with veins that merge in the heart. All paths lead to the same place. The waters where the river begins are referred to as **headwaters**. At the other end, the common outlet of the watershed is called the **mouth** (e.g., Dobson and Beck 2022).

As one example, the Santa Ana River Watershed—the largest watershed in Orange County, California—represents all the creeks, streams, and rivers that flow into the main body of the Santa Ana River, an area of 2,840 square miles (7,356 km^2; SAWPA 2019). The headwaters of the Santa Ana waters lie near Mt. San Gorgonio, the highest peak in Southern California (the seventh highest in the lower 48 states). The mouth of the river—some 100 miles (161 km) downstream—opens between Newport Beach and Huntington Beach and empties into the Pacific Ocean.

The concept of a watershed is an important one for understanding how each of us plays an important role in protecting the ocean. Anything thrown or poured on the ground—even dozens of miles from the shore—represents a potential pollutant. With sufficient flows—which occur during heavy rainfall or rapid snowmelt—this material enters the watershed and flows to the ocean. As Long Beach oceanographer and Algalita founder Captain Charles Moore says, "The ocean is downhill from everywhere."

Weathering

We now return to the three most common minerals found in Southern California beaches—quartz, feldspar, and biotite. Based on what we just learned, we know that they must have come from a rock containing these minerals. As it turns out, we find these minerals in granite, a common igneous rock. Could granite from the mountains be the parent of beaches?

Next time you venture into your local mountains, look carefully at the foot of a rocky outcrop. You will see chunks of smaller rocks and sediments broken off from the main rock. These sediments formed as a result of **weathering**, the disintegration and alteration of rock at Earth's surface. Geologists recognize three major types of weathering (e.g., Carroll 1970):

- **Physical (or mechanical) weathering**, the breakdown of rocks by physical processes
- **Chemical weathering**, the breakdown of rocks by chemical processes
- **Biological weathering**, the breakdown of rocks by biological processes (some geologists lump this category with the other two because organisms can physically or chemically break down rocks)

Physical weathering refers to any process that bangs rocks together and breaks them apart or physically separates them through wrenching or brute force. **Rockslides**, the tumbling of rocks downhill, and earthquakes, the violent shaking of the ground (which also causes rockslides), are two examples. Heating and cooling of rocks—**thermal expansion** and **thermal contraction**, respectively, that wrench and weaken rocks—is another. **Moving water**—rivers, waves, currents—and even strong winds can clang rocks against each other and cause them to fragment. And water that freezes and expands in the cracks of rocks causes a type of weathering called **frost wedging**.

Chemical weathering occurs as a result of **dissolution** (i.e., dissolving) of the more soluble parts of rocks, usually by water. Some rocks contain salts, which, of course, readily dissolve in water. In fact, dissolution of salts in rocks and drainage of the saltwater into a basin create hypersaline lakes. Rainfall, too, plays a role. Raindrops naturally dissolve carbon dioxide in the atmosphere. By

the time they reach the ground, they are slightly acidic. The slightly acidic rainfall is responsible for the weathering of statues and tombstones, which makes them appear as if they have melted.

Biological weathering refers to the activities of organisms that contribute to the fragmentation of rocks. **Lichens**—a fascinating partnership between fungi and algae—secrete chemicals that accelerate rock decomposition. Trees are very good at wedging their roots between cracks and physically breaking rocks apart. Think about that next time you are skating down a sidewalk and come to an abrupt "ramp" caused by a tree root.

All of these weathering processes can produce prodigious amounts of sediment. Consider that more than 30,000 feet of sediments (more than 9 km)—nearly as deep as the Mariana Trench—fill the Los Angeles Basin at its deepest spot beneath Downey (Yerkes et al. 1965). That sediment came from the surrounding mountains. But how did it get there?

Sediment Transport

Scientists who study sediments—**sedimentologists**—refer to the movements of sediments over space and time as **sediment transport**. For the most part, sediment transport refers to motions of grains due to moving fluids, such as winds or moving water (e.g., rivers, currents, street runoff). But gravity-driven flows, such as those that occur when glaciers push sediments downhill, also contribute to the movements of sediments.

When a moving fluid encounters a particle, it exerts a force on the particle. The force exerted by the fluid depends on a number of factors, such as:

- the properties of the fluid (i.e., its density and viscosity)
- the speed of the fluid and the nature of its flow (i.e., steady or turbulent)
- the size, shape, density, saturation, and compaction of the particles
- the shape of the surface on which the particle rests
- other factors

Now, like us, a particle can withstand a certain amount of flow without budging: we don't get blown away every time the wind blows. However, there comes a point when the fluid motion is strong enough that the particle begins to rock and roll. The fluid speed at which a particle begins to move is called the **threshold velocity**.

Three definitions describe the motion of an individual particle in a moving fluid. The particle can tumble across a surface, generally (but not always) in the direction of fluid flow, a process called **rolling**. The particle can hop, that is, it can become temporarily suspended in the fluid and move forward before landing back on a surface, a process called **saltation**. Or the particle can "fly" within the fluid: it can move as part of the fluid, a process called **suspension**. In most environments, an individual particle will experience all three of these processes—rolling, saltation, and suspension—as the motions of a fluid generally vary with time and distance. (See Biju-Duval 2002 for a more extensive treatment of this topic.)

Sediments in Motion

Now, let's stop and think about these simple concepts as they might apply to sediments, and especially to different size classes of sediments. Fluids such as water or air exert a force on objects immersed within them. Fluid velocity determines whether a given particle will roll, hop, or become suspended in the flow. The faster the fluid, the more likely a given particle will become suspended.

However, the likelihood of a particle taking off, so to speak, also depends on the size of the particle. Smaller particles move more easily than larger particles. Consider your own experience with house dust, which consists of particles in the silt and clay size fractions. A swift blow across a dusty surface quickly sends the dust into the air (i.e., the dust becomes suspended). Yet try this with a boulder, and you will likely become winded before the rock budges. Smaller particles—ones without a lot of mass to resist fluid motions—will move sooner and become suspended faster than larger particles. Put another way, we can say that smaller particles have lower threshold velocities than larger particles do.

Given this, it should make sense to you that the threshold velocity of particles increases as the size of the particles increases. Specifically, clay-sized particles have lower threshold velocities than silt, sand, gravel, and boulder-sized particles, which have higher threshold velocities. From this, it should also make sense that clay-sized particles will move under a wide range of fluid velocities while boulder-sized particles will only move at the highest fluid velocities, a narrow range of fluid velocities.

Of course, the type of fluid will make a difference, too. Eight hundred times denser than air, water packs a punch on anything in its path. If you've ever seen video of fast-moving water from a torrential rain, an overflowing river, or a tsunami, you've probably seen cars floating downstream. In places where flash floods occur, you should be familiar with the National Weather Service warning "turn around, don't drown." It takes only six inches of water to knock a person off of their feet and only a foot of water to levitate a small car. So while strong winds can make suspended sand feel like sandpaper on your bare legs, the wind, even at hurricane velocities, is not likely to move cars. But water moving at even moderate speeds can move boulders and larger objects.

If smaller particles move more easily, then it stands to reason that they also move more often and over greater distances than larger particles. Particles of clay, silt, and even sand will be carried by wind or moving water much more frequently and much farther than gravel and boulders. Trade winds can blow clay-sized particles clear across the Atlantic Ocean, from the Sahara Desert to Florida and Texas (e.g., Toon 2003; Goudie and Middleton 2006; Conway and John 2014). Particles of ash from volcanoes or large fires may be carried around the world (Carn et al. 2015; Peterson et al. 2018). So, too, water moves clay- and si (97)00066-1" onclick="javascript:window.open('https://doi.org/10.1016/S0146-6380(97)00066-1', '_blank', 'noopener'); return false;" rel="noopener">Hedges et al. 1997).

Sorting of Sediments

As a result of transport by fluids, different size classes of sediments separate from each other. Larger particles stay close to their source while smaller particles move farther from their source. The size separation of sediments that results from their transport by moving fluids is called **sorting**. If you've ever sorted laundry—separating socks and undergarments from shirts and pants—you have some idea of what sorting means. Generally, high winds and strong currents sort sediments faster than light winds and weak currents. Alternatively, light winds and weak currents acting over long periods of time will also sort sediments. Your mom may sort laundry faster than you, but given time, your slow and steady pace achieves the same result.

Because winds and currents sort sediments, sedimentologists can learn a great deal by studying the degree of sorting in a given deposit of sediments, a characteristic called the **grain size distribution**. If the range of grain sizes in a deposit is narrow, that is, if the grain sizes are similar, the deposit is said to be **well sorted**. Alternatively, if a wide range of grain sizes is found in a deposit, we can say that the deposit is **poorly sorted** (e.g., Folk and Ward 1957). Can you think of why a sample might be well-sorted or poorly sorted? (Hint: It has to do with fluid motions.)

Modification of Sediment Grains

All this moving causes sediment grains to lose some of their original character. Sedimentologists use the term **texture** to refer to the size, shape, and arrangement of particles in sediments or sedimentary rocks. As particles slide, hop, and glide in a moving fluid, they jostle and bump into each other, a kind of sedimentary mosh pit. The collisions between particles slowly wear them down and smooth out their rough edges. Particles that were initially angular in shape take on a more rounded appearance. If you've ever walked in a dry riverbed or along the shore of a lake with a cobble beach, you may have noticed the flat and smooth rocks. That's because these rocks have been modified by water as it flows over them and tumbles them against their fellow rocks. The action of the water works a lot like a **rock tumbler**, a device with a rotating drum used to polish rocks. Thankfully, nature does the same thing. How would we skip rocks across the surface of a lake if they weren't round and smooth?

Where the River Meets the Sea

Finally, we return to the beach. Let's review the journey of a grain of sand from the mountains to the beach:

- Weathering and fragmentation of parent rock into sediments
- Erosion and transport of sediments away from their parent rock
- Modification of sediments as they roll, jump, and fly downstream
- Deposition of sediments at a river's mouth or transport out to sea

Each of these steps unfolds over timescales of days to decades. In Southern California, rain falls mainly in winter, so weathering, transport, and modification of sediments will be greater in winter. In late spring, the Santa Ana River dries up. In fact, most times of the year, all you'll see is a dry riverbed. Little change in sediments or their properties will occur at these times. But when we get significant rainfall, such as happens in January–March, or during periods of El Niño, the river becomes a torrent. Higher flows mean a greater volume of sediment is transported and that the sediment will travel farther from its source.

Satellite images following extreme rainfall show plumes of sediments being carried offshore (e.g., Nezlin et al. 2008; Holt et al. 2017). These images likely represent suspended silts and clays, the smaller and more easily suspended sediments. Sand-sized sediments tend to be deposited at the mouths of rivers. There the energy of the river diminishes as the river enters the ocean. Slowing below the threshold velocity of suspension, the sand settles onto the river bottom. These deposits of sand at the mouth of a river form **deltas**—a landform shaped like a paper fan, a bird's foot, or other form. But deltas don't always form, and sand doesn't always pile up at the mouth of a river. Let's see why.

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5.5: Wave-Driven Sediment Transport

Ocean waves, the physical expression of energy moving through the ocean, transfer some of their energy to sediments as the waves break at the mouth of a river. If given sufficient energy by the moving water, the sand will roll, hop, or become suspended. And if the waves arrive at an angle relative to the river mouth—as opposed to straight on—a current of water—the **longshore current**—will be generated along the shore. This current—driven by the energy of the waves—can move sediments down the beach.

Longshore Transport

Once the river-transported grains of sand reach the ocean, they keep moving down the beach with the assistance of the energy provided by the wave-generated longshore current. This current moves sand (and even you!) down the beach if it's strong enough. Have you ever gone into the water on a day with high surf and found yourself way down the beach a few minutes later? You've experienced the longshore current.

Unlike ocean currents, the longshore current operates only within the surf zone. As a wave approaches at an angle, one part of the wave reaches the beach before the rest, and the water temporarily "piles up." Just like water flowing downhill owing to the force of gravity, the water piled up from the wave flows "downstream," that is, in the direction opposite the incoming wave. The result is the longshore current.

Grains of sand within the longshore current generally move parallel to the beach. But because of the back-and-forth nature of waves, the suspended materials often take a zig-zag path down the beach. This wave-generated movement of sand grains and other materials is called **longshore transport**.

Enormous volumes of sand may be transported along coastlines. Patsch and Griggs (2006) report that up to a million cubic yards of sand may move southward along the California coast annually. Considering that one cubic yard of sand weighs roughly 2,700 pounds—about the weight of a Kia Forte (Kia 2023)—that's a million Kias worth of sediment traveling down our coast each year. That's a lot of sand. Sedimentologists estimate that tens of thousands to possibly more than two million cubic yards of sand move southward along the US East Coast annually (e.g., van Gaalen et al. 2016).

The longshore transport of sediments by the longshore current has been eloquently referred to as a "river of sand" (Encyclopedia Britannica Films 1966). Just like a terrestrial river that moves sand from the mountains to the ocean, the river of sand (i.e., the longshore current) moves sand down the beach from the mouths of the rivers. This conceptual model of longshore transport proves useful for envisioning the transport of sediments along beaches, as we shall see.

Cross-Shore Transport

Waves also carry sediments back and forth across the beach, a process called **cross-shore transport**. When a wave strikes a beach, it transfers enough energy to the sand to cause the sand to become temporarily suspended. Once suspended, the sand flows with the motion of the water. As the wave slides up the beach, it carries sand with it. If the wave energy is high enough, the sand will remain in suspension and be carried back out toward the sea as the wave recedes from the shore. If the wave energy is low, the sand will be deposited at the point where the wave can no longer carry it. Simply put, high-energy waves move sand away from the beach and low-energy waves move sand onto the beach.

When big waves pound the shore, as they typically do in winter in Southern California, they remove sand from the beach face. The excavated sand moves offshore. In the deeper water, where the waves' energy is reduced, the sand settles and forms sandbars. When gentle waves caress the shore, as they typically do in summer in Southern California, they move sand from sandbars onto the beach. A sandbar acts as a reservoir of sand, at least on a temporary basis.

It's quite dramatic to see the changes that can occur on a beach. Beaches are ever changing, which is just another thing that makes them so darn interesting.

The Beach Profile

The movement of sand onto or away from the beach face by cross-shore transport alters the appearance of a beach, what is known as the **beach profile**. Like a profile of a person when viewed from the side, a beach profile refers to the changing slope of the beach from the backshore to the foreshore.

Measurements of beach profiles provide a simple and useful means for tracking seasonal and other kinds of changes in beaches. First described in 1961 by University of Southern California marine geologist Kenneth O. Emery (1914–1998), the method requires only two 2-meter-long measuring sticks and a tape measure. By holding the sticks in a line perpendicular to the beach and separating them by a known distance, the slope of the beach can be determined by observing the marks on the beach-side stick where the top of the oceanside stick lines up with the horizon. Known as the **Emery method**, this tool for determining beach profiles has found wide adoption among beach managers, beach scientists, and students. (See Emery 1961.) If you take an oceanography field class, you're very likely to encounter this technique in your studies.

Contributions from Beach Bluff Erosion

Recent research on some California beaches suggests that a percentage of their sand comes directly from the erosion of **coastal bluffs**, a type of rounded cliff found on coastlines. For example, bluff erosion contributes 31 percent of the sediments found on Laguna Beach (Patsch and Griggs 2007). Oceanside receives 80 percent of its sediments from the erosion of coastal bluffs (Young et al. 2010). Of course, many of these bluffs were created by sedimentary processes in times past. But recognition of beach bluff erosion adds a new wrinkle to the explanation of where sand comes from on our beaches.

Submarine Canyons

The final step in our journey from the mountains to the sea takes us to the resting place for sediments in the ocean. In many places along the coastline, the river of sand suddenly stops, as if the sediments have disappeared. In fact, as it turns out, sediments are drained from beaches by the presence of a **submarine canyon**, a steep-sided underwater valley whose shallow end—its head—comes close to shore.

Sediments carried by the longshore current often accumulate where a landform—such as a headland—interrupts their flow. The sediments may eventually move around the landform, but if a submarine canyon is present, they will be deposited at the head of the canyon. Here gravity takes over. If the mass of deposited sediment grows too large, it may become unstable, at which point it will tumble down the canyon. Such underwater landslides are called **turbidity currents** and they are one of the forces that create submarine canyons.

Submarine canyons can be found along all coastlines of the world. The **Southern California Continental Borderland**—roughly the coastal waters from Point Conception to the US-Mexican border—boasts 11 submarine canyons and 2 sea valleys (a similar feature) that drain sediments to basins (Normack et al. 2009). This includes the Newport submarine canyon, a branch of which lies less than 500 feet (150 m) from the Newport Beach pier (Felix and Gorsline 1971). Submarine canyons serve as a major sink for beach sediments and represent an important pathway for delivering sediments to deep basins (e.g., Sweet and Blum 2016).

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5.6: The Littoral Cell

The sand on a beach on any given day may be thought of as a **reservoir**, a place where something is stored. The size of this reservoir represents a balance between **sources**—processes that add to the reservoir—and **sinks**—processes that remove from the reservoir. Applying this idea, we may think of a beach as a reservoir of sand. Rivers and coastal erosion that bring sediments to the beach act as sources. Submarine canyons that remove sand from the beach are a sink. We can use this model to understand why some beaches grow in size, why some shrink, and why others seem to maintain a balance of sand over time.

The watershed-beach-submarine canyon system—the path of sand from the mountains to the seafloor—form a system known as a **littoral cell** (or coastal cell). The concept of a littoral cell originated from a desire to understand why sand disappears on some beaches. The littoral cell embodies the sources, transport path, and sinks that determine the size of a beach.

The balance between sources and sinks in a littoral cell can be modeled in terms of a **beach sand budget** (e.g., Bowen and Inman 1966). This accounting of the sources and sinks helps beach managers evaluate strategies for maintaining an adequate reservoir of sand. We won't go into the mathematics here, but understanding the basic idea that sources add sand to the beach and sinks take sand away will help you appreciate efforts to understand human impacts on beaches and efforts to preserve these critically important habitats.

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5.7: Human Impacts on Beaches

The longshore and cross-shore transport of sand from rivers and the journey of sand from the mountains to the sea are eloquently documented in an Encyclopædia Britannica video classic, *The Beach: A River of Sand* (1966). The film—now more than 50 years old—also tells another story, a darker story, one that reveals the ways people have altered the natural functioning of beaches.

Beaches serve as the centerpiece of a trillion-dollar global tourist ocean economy (Brumbaugh and Patil 2017). In the US alone, beaches generate billions of dollars in revenue from tourists and beachgoers (e.g., Houston 2018). Municipalities in charge of maintaining beaches have a strong desire to make sure that the sand on the beach stays clean and stays put—no sand, no tourists, the thinking goes.

Human activities can disrupt the natural flows of sand. In some cases, these activities lead to increases in the amount of sediments flowing downstream. In others, the supply of sand is diminished. Both have consequences for the coastal ecosystem and for human wealth, health, and safety.

State of the World's Beaches

Using observations from satellites, researchers can now reasonably estimate the state of the world's beaches and their changes over time. A recent study found that about a quarter of the world's beaches are eroding, about a quarter are growing, and about half appear stable (Luijendijk et al. 2018). Whether that's good news or bad news depends on where the beaches are located.

More than two billion people and a third of the world's "megacities" live in the coastal zone, defined as the area within 62 miles (100 km) of a coastline (Small and Nichols 2003). Compiling a global database on beaches using data from remote sensing platforms, researchers can identify "hotspots" where beaches are either losing sand or gaining sand (Luijendijk et al. 2018). Four of seven receding hotspots are in the United States. The world's fastest-growing beach is in southwest Namibia, where an active beach diamond mining operation adds sand to the beach.

Too Much Sand?

Several human activities increase the downstream flow of sand to beaches. Mining, deforestation, agriculture, and road construction rank highest on the list. These activities result in an oversupply of sediments that clog urban and coastal waterways, generate dangerous debris flows, and damage coastal ecosystems.

An overabundance of sediments has several negative consequences. Sediments can bury organisms, deliver toxins, reduce light penetration required for the growth of marine seaweeds and plants, and promote the growth of harmful bacteria (e.g., Granger et al. 2010; Mekonnen et al. 2015; Saunders et al. 2017; Lintern et al. 2018). However, these negative consequences can be reduced by restoring natural flows of sediments.

Too Little Sand?

Manmade structures can block the natural flow of sand. Paving of land (reducing erosion), construction of dams, and building of coastal infrastructure to trap sediments upstream (e.g., groins, jetties, and seawalls) may impede the flow of sediments to a beach. Anything that reduces the natural weathering processes or that alters the downstream transport of sediments will reduce the delivery of sediments to the ocean.

Beaches whose supply of sediments is shrinking experience **beach starvation**. In California, a study by the US Geological Survey revealed that 40 percent of beaches have experienced long-term erosion—over 120 years—and 66 percent exhibited severe short-term erosion—over 25 years (Hapke et al. 2009).

Starved beaches are more susceptible to extreme waves and more prone to flooding as a result of sea level rise, especially during times of king tides. When water moves closer to shore, coastal structures suffer damage by waves and intrusion of saltwater, which dissolves metals and corrodes machinery. People can no longer enjoy the beach because much of it is gone. Fewer beachgoers translates into economic losses for industries dependent on coastal tourism. Beach erosion can be deadly as well. In 2019, three people lost their lives when a coastal bluff collapsed at Grandview Surf Beach in Encinitas, California (Xia 2019).

One cause of beach starvation is the damming of rivers. Used for flood control or to generate power, dams prevent the flow of sand to the beach. The sand becomes trapped behind the dam. Starved of its natural supply of sediments, the beach shrinks. In recent years, dam removal has been carried out to restore coastal sediments. The largest project ever attempted—removal of two dams on

the Elwha River in the state of Washington—resulted in a release of 30 million tons of sediments into the watershed (Ritchie et al. 2018). Remarkably, after nearly a hundred years of beach and estuarine sediment starvation, a supply of sand was returned to the shoreline (Warrick et al. 2019).

Other impediments along coastlines are structures built along shorelines. **Groins**, concrete and rock structures built perpendicular to the shore, act as a barrier to maintain sand on beaches. While groins effectively trap sand on their upstream side, they cause a deficit of sand on their downstream side. **Coastal armoring**—paving or hardening of bluffs and seawalls to block wave action—protect shorelines, at least temporarily. However, armoring reduces bluff erosion, cutting off a source of sand. Seawalls intensify wave energy and increase erosion adjacent to the seawall. The net effect of these efforts is to reduce flows of sand and disrupt natural beach processes (e.g., Pilkey and Cooper 2012).

Beach Nourishment

Another temporary measure is the feeding of beaches. **Beach nourishment** refers to the practice of adding sand directly to the beach from an external source. Sand may be dredged from channels or river mouths and piped to beaches or transported from local deserts. Whatever the source, beach nourishment can be costly and may have negative consequences for coastal ecosystems (e.g., Speybroeck et al. 2006; Elko et al., 2021). Like the giant man-eating plant in the film *Little Shop of Horrors* (Corman 1960), some beaches just can't be fed enough.

To track beach nourishment efforts, the Program for the Study of Developed Shorelines at Western Carolina University in North Carolina maintains a public website (beachnourishment.wcu.edu). According to its database, more than 350 million cubic yards of sediment have been applied to 343 sites in California at a cost exceeding $281 million (2019 dollars).

Orange County, California, recently completed a $19.5 million sand management project—dredging the Santa Ana River mouth and using the dredged material to replenish local beaches (Connelly 2016). Despite these efforts, beach nourishment in California has met only about half of the sand deficit (Patsch and Griggs 2007). Long-term beach erosion and cliff retreat remain problems on at least 40 percent of California beaches (Hapke et al. 2009).

In New Jersey, nearly a billion dollars has been spent on beach nourishment in the past three decades. The choice is one to maintain the beach (through nourishment) or rebuild coastal homes every decade or two. As one coastal manager justifies it, "We live on the shore. We love the beach. We need to maintain it. . . . Yes, it's expensive, but it's not the most expensive thing you can do for shore protection" (O'Neill 2015).

Sand Mining

Journalist and Los Angelino Vince Beiser calls sand "the most important solid substance on Earth." You might think he's joking until you realize that sand is part of just about everything we build. As marvelously portrayed in Beiser's book, *The World in a Grain: The Story of Sand and How It Transformed Civilization* (2018), the world is running out of sand.

It turns out that sand is an essential ingredient of concrete, the stuff of which modern civilization is built. The other two ingredients are cement and gravel, but these are abundant. And though sand is also abundant, it turns out that only a special kind of sand works to make concrete. That sand is largely found on beaches. Desert sand has grains that are too smooth. Smooth grains in a concrete make it fall apart. Beach sand, on the other hand, has angular grains that lock together in the matrix of the cement. In essence, beach sand makes concrete hard. And the bulk of sand goes into construction. To build using concrete, you need sand. Lots and lots and lots of sand.

Sand can only be obtained by mining it—**sand mining**—shoveling sand off beaches or sucking it off the seafloor. Not surprisingly, sand mining operations can be found on beaches and coastal waters all around the world. Unfortunately, sand mining operations often destroy the habitats where the sand is extracted. As you might guess, mining of sand from beaches accelerates beach erosion. It can also negatively impact sensitive nearshore habitats, such as coral reefs, mangrove forests, and seagrass beds (Beiser 2018). Environmental concerns led the state of California to shut down one of the longest-operating sand mining operations in the United States, the CEMEX Sand Mine in Marina, California (very near Cal State University, Monterey Bay). The plant, blamed for accelerating beach erosion, ended operations in December 2020 (Shalev 2020).

As sources for sand dwindle, people turn to illegal means to obtain it. Beiser describes what he calls the "sand mafia." In parts of India, where the illegal sand economy is estimated at $2.3 billion annually, local residents describe torture and murder in the name of sand (Beiser 2018). Stealing and smuggling have become so prevalent that some countries have now banned exports of sand.

Experts believe that the only way to reduce environmental threats and violence is to implement some kind of "global sand governance system" (Torres et al. 2017). Better data on the global demand for sand will enable development of a global sand budget. And efforts must be taken to raise public awareness of the "sand crisis" to spur policymakers to take action. Regulations with sensitivity to local concerns and means for enforcement and monitoring will enable "the global community . . . to use sand more sustainably and avert a tragedy of the sand commons" (Torres et al. 2017).

Beach Diamond Mining

Though limited to one region of the world, **beach diamond mining** in southern Namibia, near South Africa, deserves mention. Diamond mining developed in 1908 when Zacharias Lewala, a Namibian railway worker who had worked previously in a diamond mine, recognized on the ground several kimberlite rocks, the kind of deep mantle rocks that contain diamonds. He showed them to his German boss, August Stauch (1878–1947), who staked a claim on the area and became a millionaire. For his part, Lewala's name earned a place in the history books, but little else is known about the man (e.g., Badenhorst 2003).

Similar to alluvial mining, beach miners sift the sand for rock and diamonds, often using heavy machinery and giant sifters. Front loaders and shovels may be used where diamond-bearing material occurs. To gather the diamonds, workers use brooms and hand collection. Conditions for workers appear less harsh than in "blood diamond" regions, primarily because of strong agreements between the sole mining company, De Beers, and the Namibian government (Munier 2016). But the mines are nearing the end of their profitability—less than 15 years may remain—so alternative employment (including cutting and polishing of diamonds) and other possible industries (such as tourism) are being considered to offset unemployment as the diamonds dwindle.

Living Shorelines

Ultimately, best practices for protecting coastal habitats from upstream threats involves ecosystem-based management principles, which encompass the full range of interconnections between ocean, estuarine, wetland, freshwater, and land habitats. Sheaves (2009) refers to the connectivity between land and sea as "the coastal ecosystem mosaic."

One recent approach involves a kind of hybrid between constructed and natural landscapes. Known as **living shorelines**, this approach combines structural materials (natural and artificial) with natural vegetation and marine organisms to protect coastlines and preserve the ecological services that coastal habitats provide (e.g., Sutton-Grier et al. 2015).

As the concept of living shorelines has matured and gained acceptance, coastal stakeholders have increasingly turned to its principles to ensure success of their projects (e.g., Bilkovic et al. 2017). Structures that reduce erosion upstream prevent those materials from moving downstream. Installation of permeable surfaces traps sediments and debris in place. Biological filters help remove nutrients and toxins and other harmful substances. While solutions based on incorporating natural processes into urban systems remain relatively new, their potential to solve a wide variety of environmental threats makes them promising, if not essential.

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5.8: The Last Beach?

In their sobering book *The Last Beach* (2014), renowned coastal geologists Orrin Pilkey (*b*. 1934) and Andrew Cooper (*b*. 1962) spell out clearly the impacts of humans on beaches:

> *The hands of humans are very clearly on the beaches of the world. Many of our actions are fairly benign—we swim, fish, sunbathe, stroll, or just enjoy the view, the sea breezes, and the smells of the sea. But we also dump trash and discharge our waste pipes onto beaches. We rake them to "clean them up," drive on them, and mine them for minerals, gravel, and sand. We bulldoze them to make "dunes" to protect houses, pump or truck sand around the beach to "improve" it, and build walls and breakwaters of various types to block waves and hold the sand in place.*

Though progress has been made, many questions remain regarding the future of beaches and our efforts to maintain them for human and natural uses. As Vitousek and colleagues (2017) put it: "The science of the coastal zone is bursting at the seams with unanswered questions. . . . The future of the coastline will be what we engineer it to be."

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5.9: Chapter References

Allen, Irwin, director. 1968—1970. *Land of the Giants*. Irwin Allen Productions. https://www.imdb.com/title/tt0062578/

Badenhorst, S. G. 2003. "The Unique Namdeb Trilogy—Our Past, Present, and Future Mining Applications in This Unique Deposit." *Journal of the South African Institute of Mining and Metallurgy* 103(9): 539–549. https://journals.co.za/doi/pdf/10.10520/AJA0038223X_2834

Beiser, Vince. 2018. *The World in a Grain: The Story of Sand and How It Transformed Civilization*. New York: Riverhead Books. https://www.penguinrandomhouse.com/books/537681/the-world-in-a-grain-by-vince-beiser/

Best, Myron G. 1995. "Classification of Rocks and Their Abundances on the Earth." In *Rock Physics and Phase Relations: A Handbook of Physical Constants*. Vol. 3. Edited by Thomas J. Ahrens, 1–7. Washington, DC: American Geophysical Union. https://doi.org/10.1029/RF003p0001

Biju-Duval, B. 2002. *Sedimentary Geology: Sedimentary Basins, Depositional Environments, and Petroleum Formation*. Paris: TECHNIP. https://www.editionstechnip.com/en/catalogue-detail/723/sedimentary-geology.html

Bilkovic, Donna Marie, Molly M. Mitchell, Megan K. La Peyre, and Jason D. Toft, eds. 2017. *Living Shorelines: The Science and Management of Nature-Based Coastal Protection*. Boca Raton: CRC Press. https://www.routledge.com/Living-Shorelines-The-Science-and-Management-of-Nature-Based-Coastal-Protection/Bilkovic-Mitchell-Peyre-Toft/p/book/9781498740029?utm_source=CRCPress&utm_medium=cms&utm_campaign=180615993#

Bowen, A. J., and D. L. Inman. 1966. "Budget of Littoral Sands in the Vicinity of Point Arguello, California." *USACE Technical Memorandum* 19, 1–41. http://resolver.tudelft.nl/uuid:ced71bcf-8862-4f9d-b04c-1da28c101fcb

Brenner, Owen T., Erika E. Lentz, Cheryl J. Hapke, Rachel E. Henderson, Kat. E. Wilson, and Timothy R. Nelson. 2018. "Characterizing Storm Response and Recovery Using the Beach Change Envelope: Fire Island, New York." *Geomorphology* 300: 189–202. https://doi.org/10.1016/j.geomorph.2017.08.004

Brumbaugh, Rob, and Pawan Patil. 2017. "Sustainable Tourism Can Drive the Blue Economy: Investing in Ocean Health Is Synonymous with Generating Ocean Wealth." World Bank Blogs. May 22, 2017. https://blogs.worldbank.org/voices/Sustainable-Tourism-Can-Drive-the-Blue-Economy

Carn, S. A., K. Yang, A. J. Prata, and N. A. Krotkov. 2015. "Extending the Long-Term Record of Volcanic SO_2 Emissions with the Ozone Mapping and Profiler Suite Nadir Mapper." *Geophysical Research Letters* 42: 925–932. https://doi.org/10.1002/2014GL062437

Carroll, Dorothy. 1970. *Rock Weathering*. New York: Springer. https://doi.org/10.1007/978-1-4684-1794-4

Connelly, Laylan. 2016. "Why Would Orange County Beaches Need a $19.5 Million Project to Get Sand?" *Orange County Register*. November 21, 2016. https://www.ocregister.com/2016/11/21/why-would-orange-county-beaches-need-a-195-million-project-to-get-sand/

Conway, T. and S. John. 2014. "Quantification of Dissolved Iron Sources to the North Atlantic Ocean." *Nature* 511: 212–215. https://doi.org/10.1038/nature13482

Corman, Roger, director. 1960. *The Little Shop of Horrors*. The Filmgroup and Santa Clara Productions. https://www.imdb.com/title/tt0054033/

Dobson, Clive, and Gregor Gilpin Beck. 2022. *Watersheds: A Practical Handbook for Healthy Water*. Ontario: Firefly Books. https://www.fireflybooks.com/catalogue/adult-books/nature-and-science/ecology/product/1096-watersheds-a-practical-handbook-for-healthy-water

Elko, Nicole, Tiffany Roberts Briggs, Lindino Benedet, Quin Robertson, Gordon Thomson, Bret M. Webb, and Kimberly Garvey. 2021. "A Century of US Beach Nourishment." *Ocean & Coastal Management* 199(1): 105406. https://doi.org/10.1016/j.ocecoaman.2020.105406

Emery, K. O. 1961. "A Simple Method of Measuring Beach Profiles." *Limnology and Oceanography* 6(1): 90–93. https://doi.org/10.4319/lo.1961.6.1.0090

Encyclopædia Britannica Films. 1966. “The Beach: A River of Sand.” Chicago: American Geological Institute. https://youtu.be/L5vcWnLehWw

Felix, D. W., and D. S. Gorsline. 1971. “Newport Submarine Canyon, California: An Example of the Effects of Shifting Loci of Sand Supply Upon Canyon Position.” *Marine Geology* 10(3): 177–198. https://doi.org/10.1016/0025-3227(71)90062-4

Folk, Robert Louis, and William Ward. 1957. “Brazos River Bar : A Study in the Significance of Grain Size Parameters.” *Journal of Sedimentary Research* 27(1): 3–26. https://doi.org/10.1306/74D70646-2B21-11D7-8648000102C1865D

Goldberg, Noah, and Rong-Gong Lin II. 2023. “California Battered with Huge Waves Up and Down the Coast.” *Los Angeles Times*. January 5, 2023. https://www.latimes.com/california/story/2023-01-05/california-coast-huge-waves-storm

Goudie, Andrew S., and Nicholas J. Middleton. 2006. *Desert Dust in the Global System*. Heidelberg: Springer Berlin. https://doi.org/10.1007/3-540-32355-4

Granger, S. J., R. Bol, S. Anthony, P. N. Owens, S. M. White, and P. M. Haygarth. 2010. “Chapter 3—Towards a Holistic Classification of Diffuse Agricultural Water Pollution from Intensively Managed Grasslands on Heavy Soils.” *Advances in Agronomy*, Vol. 105. Edited by Donald L. Sparks. https://doi.org/10.1016/S0065-2113(10)05003-0

Hapke, Cheryl J., Dave Reid, and Bruce Richmond. 2009. “Rates and Trends of Coastal Change in California and the Regional Behavior of the Beach and Cliff System.” *Journal of Coastal Research* 253: 603–615. https://doi.org/10.2112/08-1006.1

Hedges, J. I., R. G. Keil, and R. Benner. 1997. “What Happens to Terrestrial Organic Matter in the Ocean?” *Organic Geochemistry* 27(5–6): 195–212. https://doi.org/10.1016/S0146-6380(97)00066-1

Holt, Benjamin, Rebecca Trinh, and Michelle Gierach. 2017. “Stormwater Runoff Plumes in the Southern California Bight: A Comparison Study with SAR and MODIS Imagery.” *Marine Pollution Bulletin* 118(1–2): 141–154. https://doi.org/10.1016/j.marpolbul.2017.02.040

Houston, James R. 2018. “The Economic Value of America’s Beaches—a 2018 Update.” *Shore & Beach* 86(2): 3–13. https://asbpa.org/wp-content/uploads/2018/05/Houston_Spring-2018_86_2_color.pdf

Kia. 2023. “2023 Forte LX.” Accessed March 13, 2023. https://www.kia.com/us/en/forte/specs

Lintern, A., J. A. Webb, D. Ryu, S. Liu, U. Bende-Michl, D. Waters, P. Leahy, P. Wilson, and A. W. Western. 2018. “Key Factors Influencing Differences in Stream Water Quality Across Space.” *WIREs Water* 5: e1260. https://doi.org/10.1002/wat2.1260

Lozinsky, Richard. 2010. *Our Backyard Geology in Orange County, California*. New York: McGraw Hill. https://www.google.com/books/edition/Our_Backyard_Geology_in_Orange_County_Ca/XsmLrgEACAAJ

Luijendijk, Arjen, Gerben Hagenaars, Roshanka Ranasinghe, Fedor Baart, Gennadii Donchyts, and Stefan Aarninkhof. 2018. “The State of the World’s Beaches.” *Scientific Reports* 8: 6641. https://doi.org/10.1038/s41598-018-24630-6

Mekonnen, Mulatie, Saskia D. Keesstra, Leo Stroosnijder, Jantiene E. M. Baartman, and Jerry Maroulis. 2015. “Soil Conservation Through Sediment Trapping.” *Land Degradation & Development* 26: 544–556. https://doi.org/10.1002/ldr.2308

Munier, Nathan. 2016. “Diamonds Without Blood: A Look at Namibia.” *African Security* 9(1): 21–41. https://doi.org/10.1080/19392206.2016.1132903

Nezlin, Nikolay P., Paul M. DiGiacomo, Dario W. Diehl, Burton H. Jones, Scott C. Johnson, Michael J. Mengel, Kristen M. Reifel, Jonathan A. Warrick, and Menghua Wang. 2008. “Stormwater Plume Detection by MODIS Imagery in the Southern California Coastal Ocean.” *Estuarine, Coastal and Shelf Science* 80(1): 141–152. https://doi.org/10.1016/j.ecss.2008.07.012

Normack, W. R., D. J. W. Piper, B. W. Romans, J. A. Covault, P. Dartnell, and R. W. Sliter. 2009. “Submarine Canyon and Fan Systems of the California Continental Borderland.” *Special Paper of the Geological Society of America* 454: 141–168. https://doi.org/10.1130/2009.2454(2.7)

O’Neill, Erin. 2015. “More Than $1B Spent Replenishing NJ Beaches Over Past 30 Years.” NJ.com. October 8, 2015. https://www.nj.com/news/2015/10/jersey_shore_beach_replenishment_cost_pegged_at_1b_over_past_30_years.html

Patsch, Kiki, and Gary Griggs. 2006. “Littoral Cells, Sand Budgets, and Beaches.” California Coastal Sediment Management WorkGroup. https://dbw.parks.ca.gov/?page_id=29332

———. 2007. “Development of Sand Budgets for California’s Major Littoral Cells.” California Coastal Sediment Management WorkGroup. https://dbw.parks.ca.gov/?page_id=29332

Peterson, David A., James R. Campbell, Edward J. Hyer, Michael D. Fromm, George P. Kablick III, Joshua H. Cossuth, and Matthew T. DeLand. 2018. “Wildfire-Driven Thunderstorms Cause a Volcano-Like Stratospheric Injection of Smoke.” *NPJ Climate and Atmospheric Science* 1: 30. https://doi.org/10.1038/s41612-018-0039-3

Pilkey, O. H., and J. A. G. Cooper. 2012. “‘Alternative’ Shoreline Erosion Control Devices: A Review.” In *Pitfalls of Shoreline Stabilization: Selected Case Studies*. Edited by J. Cooper, and O. Pilkey, 187–214. Dordrecht: Springer. https://doi.org/10.1007/978-94-007-4123-2_12

Pilkey, Orrin H., and J. Andrew Cooper. 2014. *The Last Beach*. Durham: Duke University Press. https://www.dukeupress.edu/the-last-beach

Pilkey, Orrin H., Tracy Monegan Rice, and William J. Neal. 2004. *How to Read a North Carolina Beach: Bubble Holes. Barking Sands, and Rippled Runnels*. Chapel Hill: University of North Carolina Press. https://uncpress.org/book/9780807855102/how-to-read-a-north-carolina-beach/

Ritchie, Andrew C., Jonathan A. Warrick, Amy E. East, Christopher S. Magirl, Andrew W. Stevens, Jennifer A. Bountry, Timothy J. Randle, Christopher A. Curran, Robert C. Hilldale, Jeffrey J. Duda, Guy R. Gelfenbaum, Ian M. Miller, George R. Pess, Melissa M. Foley, Randall McCoy, and Andrea S. Ogston. 2018. “Morphodynamic Evolution Following Sediment Release from the World’s Largest Dam Removal.” *Scientific Reports* 8: 13279. https://doi.org/10.1038/s41598-018-30817-8

Ruffel, Alistair, and Jennier McKinley. 2008. *Geoforensics*. Hoboken: John Wiley & Sons. https://www.wiley.com/en-us/Geoforensics-p-9780470057353

Santa Ana Watershed Project Authority (SAWPA). 2019. *One Water One Watershed Plan Update 2018*. SAWPA. https://www.sawpa.org/wp-content/uploads/2019/02/OWOW-Plan-Update-2018-1.pdf

Saunders, Megan Irene, Scott Atkinson, Carissa Joy Klein, Tony Weber, and Hugh P. Possingham. 2017. “Increased Sediment Loads Cause Non-Linear Decreases in Seagrass Suitable Habitat Extent.” *PLoS ONE* 12(11): e0187284. https://doi.org/10.1371/journal.pone.0187284

Shalev, Asaf. 2020. “Sand Mining at the Cemex Plant in Marina Ends Ahead of Deadline.” *Monterey County Weekly*. December 3, 2020. https://www.montereycountyweekly.com/news/local_news/sand-mining-at-the-cemex-plant-in-marina-ends-ahead-of-deadline/article_05c85f08-34fe-11eb-a622-57584938c36e.html

Sheaves, Marcus. 2009. “Consequences of Ecological Connectivity: The Coastal Ecosystem Mosaic.” *Marine Ecology Progress Series* 391: 107–115. https://doi.org/10.3354/meps08121

Small, Christopher, and Robert J. Nichols. 2003. “A Global Analysis of Human Settlement in Coastal Zones.” *Journal of Coastal Research* 19(3): 584–599. https://www.jstor.org/stable/4299200

Speybroeck, Jeroen, Dries Bonte, Wouter Courtens, Tom Gheskiere, Partrick Grootaert, Jean-Pierre Maelfait, Mieke Mathys, Sam Provoost, Koen Sabbe, Eric W. M. Steinen, Vera Van Lancker, Magda Vincx, and Steven Degraer. 2006. “Beach Nourishment: An Ecologically Sound Coastal Defence Alternative? A Review.” *Aquatic Conservation: Marine and Freshwater Ecosystems* 16(4): 419–435. https://doi.org/10.1002/aqc.733

Sutton-Grier, Ariana E., Kateryna Wowk, and Holly Bamford. 2015. “Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our Coastal Communities, Economies, and Ecosystems.” *Environmental Science & Policy* 51: 137–148. https://doi.org/10.1016/j.envsci.2015.04.006

Sweet, Michael L., and Michael D. Blum. 2016. “Connections Between Fluvial to Shallow Marine Environments and Submarine Canyons: Implications for Sediment Transfer to Deep Water.” *Journal of Sedimentary Research* 86(10): 1147–1162. https://doi.org/10.2110/jsr.2016.64

Toon, O. 2003. “African Dust in Florida Clouds.” *Nature* 424: 623–624. https://doi.org/10.1038/424623a

Torres, Aurora, Jodi Brandt, Kristen Lear, and Jianguo Liu. 2017. “A Looming Tragedy of the Sand Commons.” *Science* 357(6355): 970–971.https://doi.org/10.1126/science.aao0503

Udden, Johan August. 1914. “Mechanical Composition of Clastic Sediments.” *GSA Bulletin* 25(1): 655–744. https://doi.org/10.1130/GSAB-25-655

van Gaalen, Joseph F., Sarah F. Tebbens, and Christopher C. Barton. 2016. “Longshore Sediment Transport Directions and Rates from Northern Maine to Tampa Bay, Florida: Literature Compilation and Interpretation.” *Journal of Coastal Research* 32(6): 1277–1301. https://doi.org/10.2112/JCOASTRES-D-15-00002.1

Vitousek, Sean, Patrick L. Barnard, and Patrick Limber. 2017. “Can Beaches Survive Climate Change?” *Journal of Geophysical Research: Earth Surface* 122(4): 1060–1067. https://doi.org/10.1002/2017JF004308

Warrick, Jonathan A., Andrew W. Stevens, Ian M. Miller, Shawn Harrison, Andrew C. Ricthie, and Guy Gelfenbaum. 2019. “World’s Largest Dam Removal Reverses Coastal Erosion.” *Scientific Reports* 9: 13968. https://doi.org/10.1038/s41598-019-50387-7

Wentworth, Chester K. 1922. “A Scale of Grade and Class Terms for Clastic Sediments.” *Journal of Geology* 30(5): 377–392. https://www.jstor.org/stable/30063207

Xia, Rosanna. 2019. “A Cliff Collapse. Three Deaths. More Bluff Failures Expected with Rising Seas.” *Los Angeles Times*. August 9, 2019. https://www.latimes.com/california/story/2019-08-08/encinitas-cliff-collapse-erosion-california-coast

Yerkes, R. F., T. H. McCulloh, J. E. Schoellhamer, and J. G. Vedder. 1965. “Geology of the Los Angeles Basin, California—An Introduction.” Geological Survey Professional Paper 420-A. Washington, DC: US Government Printing Office. https://doi.org/10.3133/pp420A

Young, Adam P., Jessica H. Raymond, John Sorenson, Elizabeth A. Johnson, Neal W. Driscoll, Reinhard E. Flick, and Robert T. Guza. 2010. “Coarse Sediment Yields from Seacliff Erosion in the Oceanside Littoral Cell.” *Journal of Coastal Research* 26(3): 580–585. https://doi.org/10.2112/08-1179.1

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CHAPTER OVERVIEW

6: The Seafloor

When you stand in the shallow water on the foreshore of a beach, you stand on the outermost edge of an expanse of Earth that covers 71 percent of our planet's surface. Simply put, you are standing on the floor of the ocean, the **seafloor**.

If you were to keep walking—outfitted, of course, in a deep-sea atmospheric dive suit (ADS) with plenty of rations for you and some fishy friends—you would come across some of the most extraordinary regions of our planet: grand canyons, majestic mountain ranges, and massive dunes that rival those of Arrakis, the desert planet in Frank Herbert's best-selling 1965 sci-fi novel *Dune*. The seafloor boasts its own Yellowstone-like geysers and mud pots and bizarre pools of methane that look like underwater lakes. It's a world largely unseen and unknown.

But technology is changing our ability to "see" the seafloor. Thanks to new tools for mapping the seafloor (Chapter 5) and telepresence technology that streams pictures and video to any internet-connected device (Chapter 4), you can explore these incredible habitats in the comfort of your home. In the 21st century, the seafloor has become visible to us in ways we could only dream of a few decades ago. Submersibles have provided access to the very deepest parts of the ocean (Chapter 3). Satellites and their ability to very precisely map the sea bottom from bumps and wiggles in the sea surface have brought the major seafloor features into view (Chapter 4). Remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have expanded our ability to see (via cameras) and map (via sonar devices) the seafloor (Chapter 4). Multibeam and side-scan sonar allow us to visualize the three-dimensional topography of the ocean bottom in unprecedented detail (Chapter 5). So while it's popular to say that we know more about the surface of the Moon or Mars than we know about the bottom of the ocean, that perception ignores the great advances that have been made in recent decades (e.g., Hillier et al. 2008; Harris and Macmillan-Lawler 2018; Jamieson 2023).

In this chapter, we survey the major features of the seafloor. In particular, we emphasize the significance of these features to geological, chemical, physical, and biological processes in the world ocean. If you've ever traveled anywhere on land, you know that a little advance knowledge of the places you intend to visit can make the experience more enjoyable. So, too, can knowledge of the seafloor open your eyes to a geological wonderland beneath the waves. So grab the controls of your virtual ADS and let's dive in, ocean explorer.

6.1: Planet Earth vs. Planet Ocean
6.2: A Few Words About "Seafloor"
6.3: Marine Geomorphometry
6.4: Seafloor Provinces
6.5: Deep-Sea Mining
6.6: Chapter References

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6.1: Planet Earth vs. Planet Ocean

To begin, let's consider the dimensions of the seafloor in relation to the rest of our planet and address a common misconception. I'm talking here about the notion that we should call our home Planet Ocean.

The idea that our planet should have been named after its water (i.e., Ocean) instead of its land (i.e., Earth) appears to have originated in 1963 with University of Virginia oceanographer G. Carlton Ray (Ray 1965; see quoteinvestigator 2017). Of course, British author Sir Arthur Clarke (1917—2008) popularized the notion when—according to British atmospheric chemist James Lovelock (1919—2022)—he said, "How inappropriate to call our planet Earth when it is clearly Ocean" (Lovelock 1979, 1990). It's not clear when or where Clarke said this. And as much as I respect these gentlemen's work and would love to live on Planet Ocean, the fact of the matter remains that Earth is mostly rock. The ocean makes up a tiny percentage of our planet compared to its solid part, a mere 0.14 percent of Earth's volume and only 0.025 percent of its mass. Yes, the world ocean covers 71 percent of Earth's surface, but the geosphere dominates our planet. So Earth remains an apt name for our rocky planet.

We must also consider that not all of the seafloor belongs to the ocean proper. A significant part of it, about 6.3 percent, is attached to the continents (i.e., the continental shelf). Oceanographers define **ocean basins** as the region of the seafloor from the shelf break (where the seafloor rapidly drops beyond the continental shelf) to the deepest locations in the world ocean (and all parts in between). By that measure the ocean basins cover about 64.7 percent of Earth's surface (approximately 127,275,090 square miles, or 329,640,970 square kilometers, km^2). Thus, from the outset, you should be aware that the seafloor—the part of Earth's surface submerged by ocean—includes part of the continents (e.g., Harris et al. 2014).

A Two-Part Crust: Oceanic vs. Continental

The distinction between continental and oceanic seafloor is more than academic. Scientists have long known that the ocean basins—the depressions in Earth's crust—must be composed of a different type of rock than the **continents**—the elevations in Earth's crust.

For basins to exist as "depressions" in Earth's surface and for continents to exist as "elevations," their rocks must be different, in accordance with a physical principle know as **isostasy**—the equilibrium "height" of Earth's crust as it floats on the mantle. Thinner and denser rocks (i.e., ocean basins) sink into Earth's surface, and thicker and less dense rocks (i.e., continents) rise above it.

Prior to acceptance of the theory of plate tectonics, scientists lacked a good explanation for how the heavier rock formed (e.g., Holmes 1945). Once deep-sea sounding revealed vast mountain ranges, ships began collecting seafloor rocks, and humans visited the seafloor in person using submersibles, scientists realized that the source of the heavier rock on the seafloor was undersea volcanism.

As it turns out, the crust of the ocean basins, the **oceanic crust**, consists of a dark, often vesicular (filled with holes) rock called **basalt** that forms from **lava**, which is molten rock that spills onto Earth's surface. In addition to making up most of the seafloor, basalt can also be found above water. If you've ever been to Kilauea or Mauna Loa on the island of Hawaii, the shores of the Columbia River in Washington or Oregon, or Pisgah Crater in the Mojave Desert near Barstow, California (or any of a number of other locations around the world), you've likely seen basalt. When lava erupts beneath the ocean and interacts with seawater, a curious structure called a **pillow basalt** forms. It's a pillow-shaped basalt (though I doubt you'd get a good night's sleep with your head resting on it). Many parts of the seafloor are covered in pillow basalts, especially in regions with volcanic activity.

The **continental crust** generally consists of **granite-like** rocks, similar to the "granite" countertops found in many homes (which mostly come from metamorphic rocks formed from squeezing and baking granite and other rocks). Granite forms from the slow cooling of **magma**, which is molten rock that remains below Earth's surface. In contrast to basalt, granite appears lighter in color, features larger crystals, and has a lower density than basalt. California's mountains and deserts and the Cascade and Rocky Mountains feature extensive outcrops of granite (as do many other locations around the world).

The density differences between basalt and granite account for the shape of Earth's surface. Geologists describe Earth's crust as having a global bimodal topography—that is, having two main features: depressions (ocean basins) and elevations (continents). Think of a two-humped camel. If we graph the area of different elevations on Earth—a type of graph called a **hypsographic curve**—we see in mathematical detail what our eyes have already told us: Earth's surface is composed of two kinds of crust.

I like to think of Earth as a kind of two-dough, deep-dish pizza where the bottom represents the heavier oceanic crust and the high edges represent the lighter continental crust. It might not be a great analogy, but I hope that the next time you eat pizza (shallow or deep), you'll think about Earth's crust.

Coastal vs. Oceanic

One final distinction bears importance in the chapters ahead. Oceanographers define the waters overlying the edges of the continents as **coastal waters**, or the coastal ocean. Coastal waters interact very closely with the land and the continental crust they cover (i.e., the continental seafloor), which tend to be quite shallow. Waters beyond the continents' edges are classified as **oceanic waters**, or the open ocean. Oceanic waters have very limited interaction with land and the seafloor, which reaches its greatest depths in oceanic waters.

This broad classification of the waters of the ocean also defines two types of oceanography: **coastal oceanography**, the study of the coastal ocean, and **blue water (or open ocean) oceanography**, the study of the open ocean. Scientifically speaking, oceanographers consider coastal oceanography to be the more difficult topic of study because terrestrial processes complicate the already complicated ocean environment. Such distinctions prove useful in considering human interactions with the world ocean, as most human impacts occur in the coastal ocean.

Earth's Geographic Continents

To gain familiarity with the surface of our planet, and especially the seafloor, it's helpful to review the major geographic features of our globe. Here we take a view that might be enjoyed by astronauts aboard the International Space Station.

Looking out the spacecraft's viewport, you will see brown, green, and white patchworks of land. Thanks to your fourth-grade teacher, you recognize these aboveground segments of Earth's crust as the seven continents. A query to an onboard computer helps identify them.

Asia, Earth's largest landmass, makes up nearly 30 percent of the continental landmass and hosts some 60 percent of the world's 8 billion people. It's also the site of the world's highest mountains, the **Himalayas**, which feature the highest mountain on Earth, **Mount Everest**, whose peak is some 5.49 miles (8.84 km) above sea level. That's roughly the walking distance from Fullerton College to Disney California Adventure Park.

Africa, the second-largest continent and where modern humans originated, is distinguished by the presence of the **Sahara Desert**. The world's largest hot desert, the Sahara stretches from the Red Sea to the Atlantic and frequently showers the Atlantic Ocean with golden plumes of dust caught in the trade winds.

The third-largest continent, **North America**, includes **Greenland**, the world's largest island, Canada, the US, Mexico, and Central America. For the record, the US ranks fifth in use of Earth's resources (i.e., ecological footprint per capita), an improvement over previous years (Global Footprint Network 2023).

South America stands out for its range of snow-capped peaks that stretch south to north along its western edge. These are the **Andes**, the longest continental range in the world.

Antarctica, an island-continent, holds more than 60 percent of Earth's freshwater. A lone volcano, **Mount Erebus**, pokes its fiery head out of the ice and puffs gray smoke that quickly vaporizes in the cold, incessant winds. The Antarctic is surrounded by the tumultuous Southern Ocean.

Europe, attached to Asia, ranks second to last in area. From a geological perspective, Europe and Asia constitute the continent of Eurasia, reducing the number of major continents to six. Nevertheless, Europe boasts the third-largest human population, about 10 percent. And it's home to many of the world's finest institutions dedicated to studying the world ocean. So we'll recognize it on its own here.

Australia has fewer people than any other continent except Antarctica. Though small in size and number of inhabitants, Australia boasts the largest structure ever built by any living beings, larger than anything humans have built: the **Great Barrier Reef,** some 1,400 miles (2,253 km) long and quite visible from space. Sadly, we may be experiencing the last decades of this natural wonder, as warming ocean waters threaten the corals and algae that built the reef.

Earth's Geographic Oceans

A view high above Antarctica reveals the Southern Ocean as a gateway to the three major ocean basins:

- The **Pacific Ocean**, the oldest, largest, and deepest
- The **Atlantic Ocean**, the youngest and most widely studied
- The **Indian Ocean**, the smallest of the major ocean basins, but traveled upon by humans for millennia

From this vantage point the **Southern Ocean** appears as a wheel surrounding Antarctica, with spokes in each of the three ocean basins. Though oceanographers once viewed the North Atlantic as the main driver of ocean circulation, they now see the Southern Ocean as the gatekeeper for the world ocean circulation. Regardless, the interconnectivity of the ocean basins, including the Arctic, underscores the idea of one ocean, the world ocean.

Whipping over Earth's northern pole, we see a partially frozen ocean surrounded by continents, the **Arctic Ocean**. In recent decades the Arctic's sea ice has thinned and diminished in extent—one sign of a warming planet. Similar signs of warming can be found on glacier-capped Greenland, home to 10 percent of the frozen water on our planet. Sapphire-blue lakes dot its surface with greater frequency, evidence of melting. Of all places on Earth, the Arctic has experienced the worst effects of human-caused climate change (Post et al. 2019; Kumar et al. 2020). Scientists predict the Arctic could experience ice-free summers as early as 2035 (Guarino et al. 2020).

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6.2: A Few Words About “Seafloor”

Before we go any further in this chapter, I’d like to make clear a couple things about the term “seafloor.” It’s not as simple as it sounds.

First, “sea” typically refers to the waters of the ocean. From this we might conclude that the ocean ends at the seafloor. However, seawater actually penetrates the seafloor, creating a region known as the **subseafloor environment**. We can’t be certain, but there’s evidence the subseafloor environment may extend as deep as a mile or more *beneath* the seafloor (Ciobanu et al. 2014; D’Hondt et al. 2019; Heuer et al. 2020). So while we casually think of the ocean as the seawater between the surface and the top of the seafloor, in truth, part of the ocean—and perhaps all of it on geologic timescales—circulates beneath the seafloor.

Second, and perhaps more important, we typically think of a floor as something that is flat, horizontal, or level. But where the sea’s “floor” is concerned, nothing could be further from the truth. The seafloor is rough on nearly every scale you can think of. As Pizer (1967) comments:

> *Oceanographers displayed little imagination when they chose “ocean floor” as the designation for the bottom of the world’s 140 million square miles of salt water. . . . The forces that created the ocean floor laid out the wildest roller coaster ride imaginable.*

In truth, the seafloor is as varied as the surface of the continents, if not more so. The seafloor hosts mountains and trenches and a whole bunch of other geologic features. You’ll get a good workout should you decide to walk across it.

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6.3: Marine Geomorphometry

The World Ocean Floor Map (1977) painted by Austrian Heinrich Berann (1915—1999) under the guidance of American oceanographers Bruce Heezen (1924—1977) and Marie Tharp (1920—2006) has long served as the standard bearer for maps of the seafloor. But the emergence of new methods has given rise to a new field calleds **marine geomorphometry**, the quantitative study of the seafloor (see LeCours et al. 2016). Geomorphometry takes advantage of advances in satellite-derived bathymetry, geographic information systems (GIS), digital bathymetric models, and spatial analysis software to quantitatively identify and statistically analyze various features of the seafloor.

In 2014 Australian geoscientist Peter Harris and colleagues published the first digital map of seafloor geomorphic features (Harris et al. 2014). Using quantitative tools, their analysis provides for the first time an assessment of the numbers and sizes of different seafloor features and offers new insights into the characteristics of seafloor features.

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6.4: Seafloor Provinces

We now focus our attention on the main subject of this chapter, the seafloor. Because most of us grew up in classrooms with a globe or a world map hanging on a wall, the continents and their features are (hopefully) somewhat familiar. However, once we cross the water's edge, our knowledge (understandably) diminishes considerably.

Traditionally, oceanographers have divided the ocean into three major **seafloor provinces**, regions of the seafloor bounded by recognizable features produced as a result of geologic processes (e.g., Lobeck 1939; Heezen et al. 1959). With the development of marine geomorphometry, oceanographers now define four major provinces (after Harris et al. 2014):

- The **continental shelf province**, the submerged flat portion of the continental margins
- The **continental slope province**, the steeply sloped part of the continental crust that extends from the shelf break to the abyss
- The **abyssal province**, from the foot of the continental slope to the start of the hadal regions
- The **hadal province**, the seafloor at depths below 19,685 feet (6,000 m)

The four major provinces encompass diverse **seafloor features**, "those parts of the ocean floor with measurable relief or delimited by relief" (e.g., Defense Mapping Agency 1981). **Relief** generally refers to the change in elevation from a high point to a low point, that is, how much something sticks up or goes down in comparison to its surroundings. A feature may have positive, negative, or no relief. A seamount looms above its surroundings like a mountain, positive relief. A submarine canyon cuts through the flatlands like Beggars Canyon on Tatooine (Lucas 1977), an example of negative relief. Relatively flat regions of the seafloor, the so-called abyssal plains, have little relief. As you read the descriptions below, take note of the seafloor features within each of the provinces. As noted by Harris et al. (2014), many seafloor features are unique to a particular province, but many can be found in more than one province.

The Continental Shelf Province

Though considered part of the seafloor, the continental shelf is underlain by continental crust. By definition the continental shelf begins at the low water line (defined as zero feet/meters and placed at the average height of the lowest tides) and ends where the slope of the seafloor increases sharply—the **shelf break**. The shelf and the slope encompass the submerged edges of the continents, what are known as the **continental margins**.

The continental shelf varies considerably in width. In Central California, the shelf narrows to less than a mile near the head of the Monterey Bay Submarine Canyon. By contrast, the Siberian Shelf in the Arctic Ocean spans 930 miles (1,500 km), the widest continental shelf in the world ocean.

Of course, the width of a particular continental shelf also depends on local sea level, or the height of the ocean relative to some point on land. During icehouse conditions (i.e., ice ages), when glaciers form on land, sea level may drop hundreds of feet below their present-day positions. Conversely, during hothouse conditions, sea level may rise as glaciers melt and seawater expands. This means that the position of the shoreline and the extent of the world's continental shelves have changed throughout geologic time.

Just off Long Beach, California, for example, you can find an ancient sandy beach, a **paleoshoreline**, at a depth of 200 feet (61 m). The sand was deposited there some 22,000 years ago during the peak of the last glaciation. The rise and fall of sea levels shape our modern coastlines too. As sea level rise caused by global warming threatens to submerge low-lying coastal areas, scientists are taking great interest in paleoshorelines for what they can teach us about coastlines under different sea levels.

Continental shelves may host complex geological features, as evidenced by the coast of Southern California. This continental shelf region, known as the **Southern California Continental Borderland**, or simply California Borderland, extends almost 200 miles (322 km) from the coastline to the Patton Escarpment, a wedge of sediments at the seaward edge of the shelf. The California Borderland includes dozens of basins (officially, shelf-perched basins), submarine canyons, and submarine fans, features typically associated with slope and abyssal regions. The archipelago of California's Channel Islands, first colonized by the Chumash and Tongva Native Americans, also rests within the California Borderland. These first settlers made extensive use of the rich oil deposits within the borderland deposited on beaches as **asphaltum**, a tar-like substance, used to waterproof boats and utensils (e.g., Brown et al. 2014). The California Borderland currently represents the largest repository of oil and gas on the West Coast of the United States (Zabanbark 2008). It also creates a mosaic of habitats important for diverse marine organisms and fisheries.

The Continental Slope Province

Beyond the continental shelf where the shelf break begins, we come to the continental slope. You may think of the continental slope as the edge of the continents, like the sides of a cake (except with a slope).

While continental slopes make up only 5.42 percent of the world ocean, they include one of its most fascinating features, the V-shaped **submarine canyons**. Submarine canyons offer complex and diverse habitats for benthic (i.e., bottom-dwelling) and pelagic (i.e., drifting or swimming in the water column) organisms. They also link the coastal and deep ocean, providing a conduit for sediments, biologically important nutrients, and, unfortunately, litter and pollutants. Submarine canyons occur in all ocean basins; a total of 9,477 of them have been identified in the entire world ocean (Harris et al. 2014).

Submarine canyons generally cut across the continental shelf perpendicular to the shoreline. The heads of these shelf-incised canyons are often very near the shore—within swimming distance in some places. Redondo Canyon in Redondo Beach, California (offshore from Veteran's Park south of the Redondo Beach Pier), offers spectacular scuba diving, especially at night in December through March, when the market squid come up from the depths to mate.

The Monterey Bay Submarine Canyon, off California's central coast, begins a half mile from the beach at Moss Landing and extends nearly 100 miles (161 km) out to sea, reaching depths of more than 2 miles (3.2 km). If you've ever seen Arizona's Grand Canyon, you have some idea of the size of the Monterey Bay Submarine Canyon. Unfortunately, because it is underwater in complete darkness, its awe-inspiring majesty can only be imagined from illustrations or scale models.

Most submarine canyons formed when rising sea levels at the end of an ice age buried the coastal portion of a river valley, causing the now-submerged valley to become part of the seafloor. As rivers moved sediments downstream and into the ocean, those sediments piled up in the submerged river valleys. At some point the sediment accumulations became unstable and began to flow downhill in a water-sand-mud mixture called a **turbidity current**. Just like the action of a river carves a valley or canyon on land, turbidity currents carve submarine canyons.

Turbidity current modification of submarine canyons continues today as rivers deliver sediments to the heads of the canyons. At least half of the submarine canyons in the California Borderland continue to generate turbidity flows in this way (Normack et al. 2009). Because the downslope motion of sand tends to occur only occasionally and in great bursts, it creates quite a spectacle. Imagine an underwater landslide, and you get the idea. Tectonic events, such as an earthquake or volcano, may trigger underwater landslides. The devastating tsunami that hit Indonesia in December 2018 was caused by a massive landslide following the volcanic eruption of Anak Krakatoa in the Sunda Strait. More than 400 people lost their lives.

As mapped by Harris et al. (2014), **polar submarine canyons** are the largest, twice the average size of nonpolar submarine canyons. The Bering–Bristol–Pribylov Canyon complex—located on the continental shelf slope of the Bering Sea—measures 12,873 square miles (33,340 km^2). It likely formed as a result of glacial runoff from rivers in Alaska and Siberia (Scholl et al. 1970).

A number of other processes, including faults, subterranean seepage, tectonic uplift, and subsidence, may also contribute to the formation and modification of submarine canyons. Oceanographers speculate that one or more of these processes may be responsible for **headless canyons,** a class of submarine canyons confined to continental slopes. Their heads may have been buried by sedimentation, or the canyon may have formed as a result of seepage of fluids along the slope that caused slumping of sediments. If you see the ghost of a headless canyon galloping on horseback down your street, fear not. They're only dangerous underwater.

The turbidity currents that carve submarine canyons create their own sedimentary deposits—**turbidites**—easily recognized by the pattern of sediment sizes that occur within them. Because heavier sediments settle faster, turbidites display a sequence of coarse-to-fine sediments with each event. Think of upside-down pecan pie: coarse nuts, nutty goo, fine-grained crust. Multiple turbidity flows create a deposit with alternating layers of coarse-to-fine sediments. Stack a series of upside-down pecan pie pieces and you have an edible physical model of a turbidite deposit. You can observe turbidites for yourself in places like Dana Point Harbor in Southern California or Point Lobos in Central California. Or you just go to your local bakery and grab a pie.

Turbidity currents can be very destructive. On November 18, 1929, a large earthquake (7.2 Mw) on the Grand Banks of Newfoundland (the location for the film *Perfect Storm*; Petersen 2000) triggered a turbidity current and broke the transatlantic

cable, a telecommunications cable laid across the North Atlantic Ocean. The event disrupted communications between America and Europe for nearly 10 months. It also generated a tsunami that killed 28 people (Ruffman and Hann 2006).

Like continental shelves, continental slopes may exhibit add-on features. Off the southeastern coast of the United States lies the Blake Plateau, a massive limestone platform between the shelf and deeper water. This **carbonate platform** was built and transformed by millions of years of biological, sedimentary, and geological activities (e.g., Sheridan and Enos 1979). Like the California Borderland, the Blake Plateau offers diverse habitats for marine organisms (e.g., Ross 2007; Hourigan et al. 2017).

The Abyssal Province

Beyond the continental shelf and slope, we encounter the largest province of the seafloor, the abyssal province. This region of the seafloor extends from the base of the continental slope to the edge of oceanic trenches (discussed below). The abyssal province includes many familiar seafloor features, such as basins, seamounts, oceanic ridges, and abyssal plains and hills. We also find less familiar features, such as troughs, bridges, sills, and plateaus. Much remains to be learned about the abyssal ocean. Once thought to be featureless and practically lifeless, the abyssal regions have revealed greater complexity and more abundant life as new technology brings this region into better focus.

Many features of the abyssal regions interact with the shelf and slope, especially near the continental margins. For example, sediments that flow down submarine canyons often spread out when they reach the abyssal seafloor, forming what are called **abyssal fans**. They're the underwater counterpart of alluvial fans, where eroded sediments spread out in the bird-tail shape of a hand fan at the base of canyons in mountains.

Delivery of sediments to the seafloor by submarine canyons contributes to the formation of the **continental rise**, a gently sloping region of sediments at the base of the continental slope, now considered part of the abyssal province. These deposits—some of the thickest sediment deposits found in the ocean—make up 8.24 percent of the global seafloor. In the Southern Ocean, the continental rise completely encircles the Antarctic continent (Harris et al. 2014).

Continental-rise sediments also arrive as a result of transport and deposition by **contour currents**, so called because they tend to flow along certain depth contours on the bottom. Oceanographers refer to contour current–generated sediment deposits as **contourites** to differentiate them from turbidites.

Beyond the continental margins, we encounter the ocean basins, formally defined as "seafloor depressions with closed bathymetric contours," that is, depth contours that form a closed curve. Harris et al. (2014) identify at least 29 major ocean basins larger than 309 square miles (800 km^2). The deepest occur in the northwestern Pacific. Of all the world ocean features, basins cover the largest percentage of the seafloor, some 43.8 percent, nearly a third of Earth's surface (31.1%).

Ocean basins may be further subdivided into flat regions, the **abyssal plains** (with a relief less than 984 ft or 300 m above the seafloor); hilly regions, **abyssal hills** (984–3,281 ft, 300–1,000 m above the seafloor); and mountainous regions, the **abyssal mountains** (greater than 3,281 ft, or 1,000 m above the seafloor), which include features such as seamounts, guyots, and similar elevated areas. They also feature the granddaddy of all oceanic features—**oceanic ridges**. Defined as an elongated narrow region of varying complexity with height exceeding 3,281 feet (1,000 m) and a length-to-width ratio greater than two, oceanic ridges appear much like the seams on a baseball, with fractures that look like stitches and a central valley where the seams come together. Oceanic ridges form a network of mountains that traverse the ocean basins for more than 47,000 miles (75,000 km; Harris 2020).

Abyssal plains make up 27.9 percent of the seafloor. They represent relatively flat regions where the slow buildup of sediments has smoothed out the seafloor. By way of comparison to a land feature, Colorado's Grand Dunes National Park, home of the tallest sand dunes in the United States (some as tall as 700 ft or 213 m), would qualify as an abyssal plain if it was underwater. Abyssal hills, covering 41.3 percent of the seafloor, resemble the Basin and Range Province of the southwestern United States. Abyssal hills (and the basin and range) were created by a pulling apart of Earth's crust, a geologic process called extensional tectonics. Together, abyssal plains and hills make up 69.2 percent of the seafloor, making them the most common feature on Earth (49.1%).

Within the category of abyssal mountains, we find another feature that bears resemblance to one we see on land. Oceanic **seamounts** resemble terrestrial volcanoes. The International Hydrographic Organization (IHO) defines a seamount as "a distinct generally equidimensional elevation greater than 3,281 feet (1,000 m) above the surrounding relief as measured from the deepest isobath that surrounds most of the feature" (IHO 2019). Think underwater stratovolcano—tall (more than 32,808 ft or 10,000 m)

and cone-shaped, like Mount Shasta in Northern California, Popocatépetl near Mexico City, Mount Fuji in Japan, or Mount Etna in Italy (e.g., Lutgens et al. 2018).

The exact number of seamounts in the world ocean varies with research methods and definitions and ranges from tens of thousands (Etnoyer et al. 2010; Yesson et al. 2011; Harris et al. 2014) to over 100,000 (Wessell et al. 2010). Restricting their definition to conical forms, Harris et al. (2014) identified 9,951 seamounts worldwide, with the majority of those (6,895, or 69%) occurring in the Pacific Ocean. Some scientists view height restrictions on the definition of a seamount to be an arbitrary distinction. Seamounts on the order of 328 feet (100 m) in height exhibit many of the same characteristics of larger seamounts, so some authors are content to relax the height requirement.

Oceanographers increasingly recognize the importance of seamounts as marine habitats (e.g., Etnoyer et al. 2010). Some marine scientists declare them the most important habitats in the world ocean. Seamounts support dense populations of marine organisms in what otherwise might be considered oceanic deserts. Seamounts act as a kind of underwater gathering spot for many pelagic species, including tuna, billfish, sharks, and marine mammals. Here they find food, mates, and **cleaning stations**—places where cleaner organisms (small shrimps and fishes) remove parasites.

The importance of seamounts as hot spots of biodiversity has led to efforts to protect them. In 2006 President George W. Bush established in the uninhabited islands to the northwest of Hawaii the Papahānaumokuākea (pronounced pa-pa-ha-no-mo-ku-ah-kay-uh) Marine National Monument, part of the 3,600-mile-long (5,800 km) Hawaiian–Emperor seamount chain. Expansion of the monument by President Barack H. Obama in 2016 now makes it one of the largest protected marine areas in the world, covering 582,578 square miles (1,508,870 km^2)—almost as large as the state of California. In the same year, President Obama also created the Northeast Canyons and Seamounts Marine National Monument, making it "the first and only national marine monument in the Atlantic Ocean" (NOAA Fisheries 2022).

Guyots represent the flat-topped cousins of seamounts. They may form on the top of a sinking island or seamount through a buildup of reef materials (i.e., carbonates), erosion, or both (e.g., Buchs et al. 2018). Other than their buzz cut, guyots exhibit all the characteristics of seamounts. Harris et al. (2014) mapped 283 guyots in their study. The largest—the 48-million-year-old Koko Guyot, named after the 58th emperor of Japan—can be found in the Hawaiian–Emperor seamount chain in the North Pacific Ocean.

Oceanic plateaus represent "flat or nearly flat elevated regions of the seafloor that drop off abruptly on one or more sides" (IHO 2019). They are thought to be formed from the breakup of supercontinents, from tectonic uplift, or from massive volcanic eruptions of lava on the seafloor. This latter process mirrors the formation of continental flood basalts on land, such as the Columbia Plateau that covers parts of Washington and Oregon. Harris et al. (2014) identified 184 oceanic plateaus covering about 5.11 percent of the seafloor.

The most extensive plateaus occur in the South Pacific and Indian Oceans. The Challenger Plateau, located west of New Zealand, is one of the largest. It's thought to represent a fragment of submerged continental crust—part of a complex that once belonged to an ancient continent known as Zealandia. Some geologists argue that Zealandia fits the definition of a continent and deserves designation as Earth's seventh geological continent (Mortimer et al. 2017).

One interesting area of research involves the effects of the formation of oceanic plateaus and continental flood basalts on Earth's atmosphere. The massive eruptions that formed these features likely released tremendous amounts of carbon dioxide into the atmosphere. The resultant atmospheric warming and ocean acidification are implicated in mass extinction events in Earth's geologic past.

Smaller elevated features, including banks, domes, knolls, sedimentary ridges, and terraces, also populate the basins of the world ocean. This is a subject that could fill volumes, yet we have other magnificent features to visit. Readers interested in exploring less-well-known features of the seafloor may refer to the Undersea Feature Names Gazetteer, maintained by the General Bathymetric Chart of the Oceans (GEBCO; see https://www.ngdc.noaa.gov/gazetteer).

The Hadal Province

We now visit the hadal province, the seafloor deeper than 19,685 feet (6,000 m). Much of the hadal province consists of **oceanic trenches**—narrow, V-shaped depressions with steep walls. Ocean trenches rank as the deepest seafloor features in the world ocean, often descending more than two miles deeper than the surrounding seafloor. Not all trenches plunge to hadal depths, however, so

we find trenches in both the abyssal and hadal provinces. Because oceanic trenches originate from movements of Earth's crust—plate tectonics—we'll cover them in greater detail in our next chapter.

The depths of the deepest oceanic trenches exceed the height of the highest places on land. The absolute deepest place in the world ocean, the **Challenger Deep**—located in the Mariana Trench off the coast of Guam—plunges to 6.788 miles deep (35,876 ± 20 ft, or 10,935 ± 6 m; Greenaway et al. 2021). Compare that to Mount Everest at 5.498 miles high (29,028.87 ft or 8,848 m). If you were Captain Planet (Pyle and Turner 1990–1996) and could uproot Mount Everest and place it on the bottom of the Challenger Deep, the top of the mountain would still be 1.29 miles (2.07 km) below the surface of the ocean. Of course, if you could do that, you probably wouldn't be reading this book; you'd be out doing superhero things, like stopping volcanoes and diverting raging rivers.

Harris et al. (2014) identified 56 trenches, a mere 0.95 percent of the seafloor. Most trenches occur in the Pacific Ocean, where they form a circle spanning the western coastlines of South, Central, and North America, the Aleutian Islands of Alaska and Russia, Japan, the Philippines, New Guinea, the Solomon Islands, New Caledonia, American Samoa, Tonga, and New Zealand. The Atlantic and Indian Oceans contain only a few short trenches, the Puerto Rico Trench and the Java Trench, respectively, among the most notable.

Despite their reputation as lifeless wastelands, ocean trenches host an extraordinary diversity of life with representatives from nearly every major group of marine organisms (except photosynthetic ones). Though often located far from land in waters with very low productivity, many receive particles of organic matter from shallower depths. Some are close enough to continents that supplements of plant and seaweed debris sink into their confines. Unfortunately, they also receive human debris. A plastic bag found at the bottom of the Mariana Trench made headlines in 2018. A 30-year study of plastic pollution in the abyss revealed that single-use plastics make up 92 percent of all plastics found at hadal depths (Chiba 2018).

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6.5: Deep-Sea Mining

While plastics and their impacts on marine life have captured the public's attention in recent years, another potentially destructive human activity is gaining momentum. **Ocean mining**, the extraction of mineral resources from the seafloor, raises the potential for serious impacts on ocean habitats, marine organisms, and even people. The possible harmful consequences of ocean mining deserve our attention.

Deep-Sea Metals

Though we rarely think about it, the manufacture of smartphones, green technologies, batteries, and many other devices requires minerals. At least 14 different minerals go into a smartphone. While many are present in tiny quantities, each is required for a smartphone to function properly (USGS 2017). Some 1.43 billion smartphones were sold globally in 2021 (Statista 2022). The rapidly increasing demand for renewable energy technologies (e.g., solar panels, wind turbines) and battery technologies (e.g., electric cars, electrical storage) has led to concerns about shortages in the supply of minerals. Making matters worse, the supply chain for minerals involves countries around the world, raising issues of security, diplomacy, regulation, ecology, and human welfare (Ali et al. 2017).

Worried about global shortages, governments and industries have increasingly looked toward the seafloor as a source of minerals. The deep seafloor exceeds land deposits in terms of abundance for nearly all minerals (e.g., Hein et al. 2013). Four types of deep-sea mineral deposits have received the most attention:

- **marine phosphorites**, phosphate-rich sedimentary rocks formed in oceanic upwelling regions with high biological productivity, mostly continental margins, but also some oceanic seamounts (Filippelli 2011)
- **polymetallic nodules**, also known as manganese nodules, tennis-ball-sized globes of different metals that precipitate slowly around a nucleus (a shell or bone fragment, for example) on the seafloor (Cuyvers et al. 2018)
- **polymetallic crusts**, similar to nodules in composition, forming as a coating on rocks along the flanks and summits of seamounts (Cuyvers et al. 2018)
- **seafloor massive sulfide deposits**, essentially, the sulfur-rich chimneys and deposits of hydrothermal vents (Cuyvers et al. 2018)

As reported by Mining-Technology.com (Davies 2019), "The deep sea could contain more cobalt, nickel and rare earth minerals than all land-based reserves combined forecast . . . to account for 15% of global supply by 2050."

Status of Deep-Sea Mining

Until now, deep-sea mining has remained in a testing phase. But pressure is mounting to allow commercial deep-sea mining to begin (e.g., Lyons 2021). In June 2021, the Micronesian island nation of Nauru (the third-smallest nation in the world next to Vatican City and Monaco) invoked a United Nations Law of the Sea rule known as the two-year rule, which would require a decision on seafloor exploitation by mid-2023 (Reid and Lewis 2021). As Blanchard et al. (2023) describe it, "A lot of work has yet to be done to evaluate how environmental considerations will be embedded into the DR , if deep-sea mining does indeed go ahead."

There seems little doubt mining can be carried out successfully. In 2017 Japan became the first country to excavate polymetallic sulfides from an inactive hydrothermal vent in the Okinawa Trough (Okamoto 2018). And in 2020 Japan was able to retrieve more than 1,400 pounds (649 kilograms) of copper and nickel-enriched crust from the seabed near Minami-Tori-shima Island (JOGMEC 2020). A number of countries and companies have obtained leases and manufactured equipment for deep-sea mining.

At the same time, efforts are underway to address potential environmental concerns. The International Seabed Authority, which works under the UN Law of the Sea treaty, continues to work on adoption of environmental regulations that would reduce environmental impacts. But uncertainty remains, particularly with regard to scientific understanding of deep-sea ecosystems and their response to disturbances from mining (Beaulieu et al. 2017). The European Union Parliament recently called for a moratorium on deep-sea mining "until its effects on the environment are better understood and can be managed" (Lewis 2021).

Impacts of Deep-Sea Mining

Oceanographers have reasons for concern. A 1989 seafloor "plowing" experiment in the Peru Basin so damaged the habitat that it had still not recovered 26 years later (Lledo et al. 2019). Track marks remained visible and microbial activity was severely reduced (Vonnahme et al. 2020). In some places, the sediments had become so compacted that animals could no longer inhabit them (Ackerman 2020). Though scientists acknowledge the limitations of extrapolating results from one region to another, their experiments underscore the need to proceed with caution.

Oceanographers have barely begun to explore the diversity of organisms inhabiting these regions. A 2016 study using remotely operated vehicles (Chapter 4) within the Clarion-Clipperton Zone—an abyssal plain southeast of Hawaii targeted for collection of polymetallic nodules—found seven species "new to science" and higher than average biodiversity (Amon et al. 2020). Such discoveries underscore how little scientists know about these regions of the ocean.

Seafloor impacts are not the only ones that concern scientists. A group of oceanographers recently expressed concerns about the impacts of deep-sea mining on organisms living within the water column. Plumes of sediments kicked up by mining operations may threaten midwater ecosystems, which "represent more than 90% of the biosphere contain fish biomass 100 times the annual fish catch" (Drazen et al. 2019). Sediments may impair the breathing of organisms, bury organisms directly, and impair the ability of organisms to find food or communicate (Christiansen et al. 2020). Locations targeted for mining boast some of the clearest waters in the world ocean and the impacts of increased sedimentation may be high (Smith et al. 2020). Increased ocean noise has also been cited as a concern (Christiansen et al. 2020).

Should We Mine the Deep Seafloor?

While some ask, "Should we mine the deep seafloor?" (Beaulieu et al. 2017), others respond, "Seabed mining is coming—bringing mineral riches and fears of epic extinctions" (Heffernan 2019). Indeed, deep-seafloor mining appears inevitable (e.g., Hein et al. 2010).

Whether inevitable or not, some people believe that deep-sea mining could be carried out in a manner that minimizes its impacts to organisms and the marine environment. At least one company—DeepGreen Metals—has partnered with research institutions to address scientific concerns (Moore 2020). Underscoring the need for this type of research, Smith et al. (2020) write:

The deep sea contains many of the most pristine, poorly studied, and evolutionarily remarkable ecosystems on our planet—in situ scientific knowledge addressing the full scales and intensities of seabed mining should be obtained and properly applied to sustain biodiversity and ecosystem functions in the deep sea if mining is to proceed.

Deep-sea mining—dubbed the "new gold rush" by one author (Tasoff 2017)—appears on the brink of rapid expansion once regulations and investments in technologies take hold. When it does, the riches will be there for those with the money and technology to find and extract them.

On the other hand, some argue that the need for deep-sea mining has been overhyped (Miller et al., 2021; Earle and Kammen 2022). Green energy and other metal needs can be met without deep-sea metals. They point to the fact that even some automakers support a moratorium on deep-sea mining. As Earle and Kammen state in the opening of their article, "Seldom do we have an opportunity to stop an environmental crisis before it begins. This is one of those opportunities."

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6.6: Chapter References

Ackerman, Daniel. 2020. “Deep-Sea Mining: How to Balance Need for Metals with Ecological Impacts.” *Scientific American*. August 31, 2020. https://www.scientificamerican.com/article/deep-sea-mining-how-to-balance-need-for-metals-with-ecological-impacts1/

Ali, Saleem H., Damien Giurco, Nicholas Arndt, Edmund Nickless, Graham Brown, Alecos Demetriades, Ray Durrheim, Maria Amélia Enriquez, Judith Kinnaird, Anna Littleboy, Lawrence D. Meinert, Roland Oberhänsli, Janet Salem, Richard Schodde, Gabi Schneider, Oliver Vidal, and Natalia Yakovleva. 2017. “Mineral Supply for Sustainable Development Requires Resource Governance.” *Nature* 543: 367–372. https://doi.org/10.1038/nature21359

Amon, Diva J., Amanda F. Ziegler, Thomas G. Dahlgren, Adrian G. Glover, Aurélie Goineau, Andrew J. Gooday, Helena Wikilund, and Craig R. Smith. 2016. “Insights into the Abundance and Diversity of Abyssal Megafauna in a Polymetallic-Nodule Region in the Eastern Clarion-Clipperton Zone.” *Scientific Reports* 6: 30492. https://doi.org/10.1038/srep30492

Beaulieu, Stace E., T. T. Graedel, and Mark D. Hannington. 2017. “Should We Mine the Deep Seafloor?” *Earth’s Future* 5(7): 655–658. https://doi.org/10.1002/2017EF000605

Berann, Heinrich C., Bruce C. Heezen, and Marie Tharp. 1977. *Manuscript Painting of Heezen-Tharp ‘World Ocean Floor’ Map*. https://www.loc.gov/item/2010586277/

Blanchard, Catherine, Ellycia Harrould-Kolieb, Emily Jones, and Michelle L. Taylor. 2023. “The Current Status of Deep-Sea Mining Governance at the International Seabed Authority.” *Marine Policy* 147: 105396. https://doi.org/10.1016/j.marpol.2022.105396

Brown, Kaitlin M., Jacques Connan, Nicholas W. Positer, René L. Vellanoweth, John Zumberge, and Michael H. Engel. 2014. “Sourcing Archaeological Asphaltum (Bitumen) from the California Channel Islands to Submarine Seeps.” *Journal of Archaeological Science* 43: 66–76. https://doi.org/10.1016/j.jas.2013.12.012

Buchs, David M., Rebecca Williams, Shin-ichi Sano, and V. Paul Wright. 2018. “Non-Hawaiian Lithostratigraphy of Louisville Seamounts and the Formation of High-Latitude Oceanic Islands and Guyots.” *Journal of Volcanology and Geothermal Research* 356(1): 1–23. https://doi.org/10.1016/j.jvolgeores.2017.12.019

Chiba, Sanae, Hideaki Saito, Ruth Fletcher, Takayuki Yogi, Makino Kayo, Shin Miyagi, Moritaka Ogido, and Katsunori Fujikura. 2018. “Human Footprint in the Abyss: 30 Year Records of Deep-Sea Plastic Debris.” *Marine Policy* 96: 204–212. https://doi.org/10.1016/j.marpol.2018.03.022

Christiansen, Bernd, Anneke Denda, and Sabine Christiansen. 2020. “Potential Effects of Deep Seabed Mining on Pelagic and Benthopelagic Biota.” *Marine Policy* 114: 103422. https://doi.org/10.1016/j.marpol.2019.02.014

Ciobanu, Maria-Cristina, Gaëtan Burgaud, Alexis Dufresne, Anja Breuker, Vanessa Rédou, Sarah Ben Maamer, Frédéric Gaboyer, Odile Vandenabeele-Trambouze, Julius Sebastian Lipp, Axel Schippers, Philippe Vandenkoornhuyse, Georges Barbier, Mohamed Jebbar, Anne Godfroy, and Karine Alain. 2014. “Microorganisms Persist at Record Depths in the Subseafloor of the Canterbury Basin.” *ISME Journal* 8: 1370–1380. https://doi.org/10.1038/ismej.2013.250

Cuyvers, Luc, Whitney Berry, Kristina M. Gjerde, Torsten Thiele, and Caroline Wilhem. 2018. *Deep Seabed Mining : A Rising Environmental Challenge*. Gland: IUCN and Gallifrey Foundation. https://doi.org/10.2305/IUCN.CH.2018.16.en

Davies, Ross. 2019. “A Modern El Dorado: Deep Sea Mining at the Clarion Clipperton Zone.” Mining Technology. August 21, 2019. https://www.mining-technology.com/features/a-modern-eldorado-deep-sea-mining-at-the-clarion-clipperton-zone

Defense Mapping Agency. 1981. *Gazetteer of Undersea Features*, 3rd ed. Washington, DC: Defense Mapping Agency. https://www.biodiversitylibrary.org/item/86680

D’Hondt, Steven, Robert Pockalny, Victoria M. Fulfer, and Arthur J. Spivack. 2019. “Subseafloor Life and Its Biogeochemical Impacts.” *Nature Communications* 10: 3519. https://doi.org/10.1038/s41467-019-11450-z

Drazen, Jeffery C., Craig R. Smith, Kristina Gjerde, Whitlow Au, Jesse Black, Glenn Carter, Malcolm Clark, Jennifer M. Durden, Pierre Dutrieux, Erica Goetze, Steven Haddock, Mariko Hatta, Chris Hauton, Paul Hill, Julian Koslow, Astrid B. Leitner, Chris

Measures, Aude Pacini, Frank Parrish, Thomas Peacock, Jessica Perelman, Tracey Sutton, Celine Taymans, Verena Tunnicliffe, Les Watling, Hiroyuki Yamamoto, Emily Young, and Amanda F. Ziegler. 2019. “Report of the Workshop Evaluating the Nature of Midwater Mining Plumes and Their Potential Effects on Midwater Ecosystems.” *Research Ideas and Outcomes* 5: e33527. https://doi.org/10.3897/rio.5.e33527

Earle, Sylvia, and Daniel Kammen. 2022. “The Case Against Deep-Sea Mining.” *Time*. October 25, 2022. https://time.com/6224508/deep-sea-mining-threat-ban/

Etnoyer, Peter J., John Wood, and Thomas C. Shirley. 2010. “How Large Is the Seamount Biome?” *Oceanography* 23(1): 206–209. https://doi.org/10.5670/oceanog.2010.96

Filipelli, Gabriel M. 2011. “Phosphate Rock Formation and Marine Phosphorus Geochemistry: The Deep Time Perspective.” *Chemosphere* 84(6): 759–766. https://doi.org/10.1016/j.chemosphere.2011.02.019

Gardner, James V., Peter Darnell, Larry A. Mayer, and John E. Hughes Clarke. 2003. “Geomorphology, Acoustic Backscatter, and Processes in Santa Monica Bay from Multibeam Mapping.” *Marine Environmental Research* 56(1–2): 15–46. https://doi.org/10.1016/S0141-1136(02)00323-9

Global Footprint Network. 2023. “Ecological Footprint Data.” Accessed March 13, 2023. https://data.footprintnetwork.org/

Greenaway, Samuel F., Kathryn D. Sullivan, S. Harper Umfress, Alice B. Beittel, and Karl D. Wagner. 2021. “Revised Depth of the Challenger Deep from Submersible Transects; Including a General Method for Precise, Pressure-Derived Depths in the Ocean.” *Deep Sea Research Part I: Oceanographic Research Papers* 178: 103644. https://doi.org/10.1016/j.dsr.2021.103644

Guarino, Maria-Vittoria, Louise C. Sime, David Schrӧeder, Irene Malmierca-Vallet, Erica Rosenblum, Mark Ringer, Jeff Ridley, Danny Feltham, Cecilia Bitz, Eric J. Steig, Eric Wolff, Julienne Stroeve, and Alistair Sellar. 2020. “Sea-Ice-Free Arctic During the Last Interglacial Supports Fast Future Loss.” *Nature Climate Change* 10: 928–932. https://doi.org/10.1038/s41558-020-0865-2

Harris, Peter T. 2020. “Seafloor Geomorphology—Coast, Shelf, and Abyss.” In *Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats*. Edited by Peter T. Harris and Elaine Baker, 115–160. Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-814960-7.00006-3

Harris, P. T., and M. Macmillan-Lawler. 2018. “Origin and Geomorphic Characteristics of Ocean Basins.” In *Submarine Geomorphology*. Edited by A., Micallef, S. Krastel, and A. Savini. New York: Springer. https://doi.org/10.1007/978-3-319-57852-1_8

Harris, P. T., M. Macmillan-Lawler, J. Rupp, and E. K. Baker. 2014. “Geomorphology of the Oceans.” *Marine Geology* 352: 4–24. https://doi.org/10.1016/j.margeo.2014.01.011

Heezen, Bruce C., Marie Tharp, and Maurice Ewing. 1959. *The Floors of the Ocean I. North Atlantic—Text to Accompany the Physiographic Diagram of the North Atlantic*. Geological Society of America Special Paper 65. New York: Geological Society of America. https://www.gutenberg.org/files/49069/49069-h/49069-h.htm

Heffernan, Olive. 2019. “Seabed Mining Is Coming—Bringing Mineral Riches and Fears of Epic Extinctions.” *Nature* 571: 465–468. https://doi.org/10.1038/d41586-019-02242-y

Hein, James R., Tracey A. Conrad, and Hubert Staudigel. 2010. “Seamount Mineral Deposits: A Source of Rare Metals for High-Technology Industries.” *Oceanography* 23(1): 184–189. https://doi.org/10.5670/oceanog.2010.70

Hein, James R., Kira Mizell, Andrea Koschinsky, and Tracy A. Conrad. 2013. “Deep-Ocean Mineral Deposits as a Source of Critical Metals for High- and Green-Technology Applications: Comparison with Land-Based Resources.” *Ore Geology Reviews* 51: 1–14. https://doi.org/10.1016/j.oregeorev.2012.12.001

Heuer, Verena B., Fumio Inagaki, Yuki Morono, Yusuke Kubo, Arthur J. Spivack, Bernhard Viehweger, Tina Treude, Felix Beulig, Florence Schubotz, Satoshi Tonai, Stephen A. Bowden, Margaret Cramm, Susan Henkel. Takehiro Hirose, Kira Homola, Tatsuhiko Hoshino, Akira Ijiri, Hiroyuki Imachi, Nana Kamiya, Mansanori, Kaneko, Lorenzo Lagostino, Hayley Manners, Harry-Luke McClelland, Kyle Metcalfe, Natsumi Okutsu, Donald Pan, Maija J. Raudsepp, Justine Sauvage, Man-Yin Tsang, David T. Wang, Emily Whitaker, Yuzuru Yamamoto, Kiho Yang, Lena Maeda, Rishi R. Adhikari, Clemens Glombitza, Yohei Hamada, Jens Kallmeyer, Jenny Wendt, Lars Wörmer, Yasuhiro Yamada, Masataka Kinoshita, and Kai-Uwe Hinrichs. 2020. “Temperature Limits

to Deep Subseafloor Life in the Nankai Trough Subduction Zone." *Science* 370(6521): 1230–1234. https://doi.org/10.1126/science.abd7934

Hillier, J. K., F. Tilmann, and N. Hovius. 2008. "Submarine Geomorphology: New Views on an 'Unseen' Landscape." *Basin Research* 20(4): 467–472. https://doi.org/10.1111/j.1365-2117.2008.00387.x

Holmes, Arthus. 1945. *Principles of Physical Geology*. New York: Ronald Press. https://www.google.com/books/edition/Principles_of_Physical_Geology/b3xCAAAAIAAJ?hl=en

Hourigan, Thomas F., Stephen D. Cairns, John Reed, and Steve W. Ross. 2017. "Deep-Sea Coral Taxa in the US Southeast Region: Depth and Geographic Distribution." NOAA. https://deepseacoraldata.noaa.gov/library/2015-state-of-dsc-report-folder/NOAA_DSC-Species-List_Southeast_Hourigan-et-al_2017.pdf

Infoplease. 2023. "Atlantic Ocean: Physical Geography." *The Columbia Electronic Encyclopedia*, 6th ed. Accessed March 1, 2023. https://www.infoplease.com/encyclopedia/places/other/oceans-continents/atlantic-ocean/physical-geography

International Hydrographic Organization. 2019. *Standardization of Undersea Feature Names*. Monaco: International Hydrographic Organization. https://iho.int/uploads/user/pubs/bathy/B-6_e4%202%200_2019_EF_clean_3Oct2019.pdf

Jamieson, Alan. 2023. "They Say We Know More about the Moon than about the Deep Sea. They're Wrong." The Conversation. January 15, 2023. https://theconversation.com/they-say-we-know-more-about-the-moon-than-about-the-deep-sea-theyre-wrong-197410

JOGMEC (Japan Organization for Metals and Energy Security). 2020. "JOGMEC Conducts World's First Successful Excavation of Cobalt-Rich Seabed in the Deep Ocean; Excavation Test Seeks to Identify Best Practices to Access Essential Green Technology Ingredients While Minimizing Environmental Impact." JOGMEC News Release. August 21, 2020. https://www.jogmec.go.jp/english/news/release/news_01_000033.html

Kumar, Avinash, Juhi Yadav, and Rahul Mohan. 2020. "Global Warming Leading to Alarming Recession of the Arctic Sea-Ice Cover: Insights from Remote Sensing Observations and Model Reanalysis." *Heliyon* 6: e04355. https://doi.org/10.1016/j.heliyon.2020.e04355

LeCours, Vincent, Margaret F. J. Dolan, Aaron Micallef, and Vanessa L. Lucieer. 2016. "A Review of Marine Geomorphometry, the Quantitative Study of the Seafloor." *Hydrology and Earth System Sciences* 20: 3207–3244. https://doi.org/10.5194/hess-20-3207-2016

Lewis, Jeff. 2021. "EU Should Promote Moratorium on Deep-Sea Mining, Lawmakers Say." Reuters. June 9, 2021. https://www.reuters.com/business/environment/eu-should-promote-moratorium-deep-sea-mining-lawmakers-say-2021-06-09/

Lobeck, A. K. 1939. *Geomorphology: An Introduction to the Study of Landscapes*. New York: McGraw-Hill. https://archive.org/details/in.ernet.dli.2015.280108

Lovelock, J. E. 1979. *Gaia: A New Look at Life on Earth*. Oxford: Oxford University Press. https://global.oup.com/academic/product/gaia-9780198784883

———. 1990. "Hands Up for the Gaia Hypothesis." *Nature* 344: 100–102. https://doi.org/10.1038/344100a0

Lucas, George, director. 1977. *Star Wars: Episode IV—A New Hope*. 20th Century Fox. https://www.imdb.com/title/tt0076759/

Lutgens, Frederick K., Edward J. Tarbuck, and Dennis G. Tasa. 2018. *Essentials of Geology*, 13th ed. New York: Pearson. https://www.pearson.com/en-us/subject-catalog/p/essentials-of-geology/P200000007002/9780134857299

Lyons, Katie. 2021. "Mining's New Frontier: Pacific Nations Caught in the Rush for Deep-Sea Riches." *The Guardian*. June 23, 2021. https://www.theguardian.com/world/2021/jun/23/inings-new-frontier-pacific-nations-caught-in-the-rush-for-deep-sea-riches

Miller, K. A., K. Brigden, D. Santillo, D. Curie, P. Johnson, and K. F. Thompson. 2021. "Challenging the Need for Deep Seabed Mining from the Perspective of Metal Demand, Biodiversity, Ecosystems Services, and Benefit Sharing." *Frontiers in Marine Science* 8: 706161. https://doi.org/10.3389/fmars.2021.706161

Moore, Paul. 2020. "DeepGreen Partners with Research Institutions to Characterise Potential Impacts of Pacific Polymetallic Nodule Mining." International Mining. August 26, 2020. https://im-mining.com/2020/08/26/deepgreen-partners-research-

institutions-charactise-potential-impacts-pacific-polymetallic-nodule-mining/

Mortimer, Nick, Hamish J. Campbell, Andy J. Tulloch, Peter R. King, Vaughan M. Stagpoole, Ray A. Wood, Mark S. Rattenbury, Rupert Sutherland, Chris J. Adams, Julien Collot, and Maria Seton. 2017. "Zealandia: Earth's Hidden Continent." *GSA Today* 27(3): 27–35. https://doi.org/10.1130/GSATG321A.1

NOAA Fisheries. 2022. "Northeast Canyons and Seamounts Marine National Monument." NOAA Greater Atlantic Regional Fisheries Office. November 8, 2022. https://www.fisheries.noaa.gov/new-england-mid-atlantic/habitat-conservation/northeast-canyons-and-seamounts-marine-national

Normark, William R., David J. W. Piper, Brian W. Romans, Jacob A. Covault, Peter Darnell, and Ray W. Sliter. 2009. "Submarine Canyon and Fan Systems of the California Continental Borderland." In *Earth Science in the Urban Ocean: The Southern California Continental Borderland*. Edited by H. J. Lee and W. R. Normark, 141–168. Geological Society of America Special Paper 454. https://doi.org/10.1130/2009.2454(2.7)

Okamoto, Nobuyuki, Satoshi Shiokawa, Seiya Kawano, Hironubu Sakurai, Norihiro Yamaji, and Masaomi Kurihara. 2018. "Current Status of Japan's Activities for Deep-Sea Commercial Mining Campaign." *IEEE*: 1-7. https://doi.org/10.1109/OCEANSKOBE.2018.8559373

Petersen, Wolfgang, director. 2020. *The Perfect Storm*. Warner Bros. https://www.imdb.com/title/tt0177971/

Pizer, Vernon. 1967. *The World Ocean: Man's Last Frontier*. New York: World Publishing.

Post, Eric, Richard B. Alley, Torben R. Christensen, Marc Macias-Fauria, Bruce C. Forbes, Michael N. Gooseff, Amy Iler, Jeffrey T. Kerby, Kristin L. Laidre, Michael E. Mann, Johan Olofsson, Julienne C. Stroeve, Fran Ulmer, Ross A. Virginia, and Muyin Wang. 2019. "The Polar Regions in a 2°C Warmer World." *Science Advances* 5(12): eaaw9883. https://doi.org/10.1126/sciadv.aaw9883

Pyle, Barbara, and Ted Turner, creators. 1990–1996. *Captain Planet and the Planeteers*. TV series. TBS Syndication.

Quote Investigator. 2017. "Planet 'Earth': We Should Have Called It 'Sea."' Quote Investigator. January 25, 2017. https://quoteinvestigator.com/2017/01/25/watr-planet/

Ray, G. Carlton. 1965. Remarks delivered during the *Scientific Use of Natural Areas Symposium*. XVI International Congress of Zoology, Washington. August 20–27, 1963. Edited by Henry Field and Julia Allen Field. https://www.google.com/books/edition/Scientific_Use_of_Natural_Areas/XURDAAAAIAAJ

Reid, Helen, and Jeff Lewis. 2021. "Deep-Sea Mining Rules to be Fast-Tracked in Push from Nauru." Reuters. June 29, 2021. https://www.reuters.com/business/environment/exclusive-deep-sea-mining-rules-be-fast-tracked-push-nauru-source-2021-06-25/

Ross, Steve W. 2007. "Unique Deep-Water Ecosystems Off the Southeastern United States." *Oceanography* 20(4): 130–139. https://doi.org/10.5670/oceanog.2007.13

Ruffman, Alan, and Violet Hann. 2006. "The Newfoundland Tsunami of November 18, 1929: An Examination of the Twenty-Eight Deaths of the 'South Coast Disaster.'" *Newfoundland Studies* 21(1): 97–148. https://id.erudit.org/iderudit/nflds21_1art04

Scholl, David W., Edwin C. Buffington, David M. Hopkins, and Tau Rho Alpha. 1970. "The Structure and Origin of the Large Submarine Canyons of the Bering Sea." *Marine Geology* 8(3–4): 187–210. https://doi.org/10.1016/0025-3227(70)90043-5

Schwarzhans, Werner W., Jørgen G. Nielsen, and Bruce C. Munday. 2022. "Revision of the Circumglobal Deep-Sea Genus *Leucicorus* (Teleostei, Ophidiidae) with Two New Species." *Zootaxa* 5100(4): 541–558. https://doi.org/10.11646/zootaxa.5100.4.5

Sheridan, Robert E., and Paul Enos. 1979. "Stratigraphic Evolution of the Blake Plateau After a Decade of Scientific Drilling." In *Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment*, Vol. 3. Edited by Manik Talwani, William Hay, and William B. F. Ryan. https://doi.org/10.1029/ME003p0109

Smith, Craig R., Verena Tunnicliffe, Ana Colaço, Jeffrey C. Drazen, Sabine Gollner, Lisa A. Levin, Nelia C. Mestre, Anna Metaxas, Tina N. Molodtsova, Telmo Morato, Andrew K. Sweetman, Travis Washburn, and Diva J. Amon. 2020. "Deep-Sea Misconceptions Cause Underestimation of Seabed-Mining Impacts." *Trends in Ecology & Evolution* 35(10): 853–857. https://doi.org/10.1016/j.tree.2020.07.002

Statista. 2022. “Number of Smartphones Sold to End Users Worldwide from 2007 to 2021.” Statista. March 2022. https://www.statista.com/statistics/263437/global-smartphone-sales-to-end-users-since-2007/

Tasoff, Harrison. 2017. “The Wild West of Deep-Sea Mining.” *Hakai Magazine*. May 19, 2017. https://hakaimagazine.com/news/wild-west-deep-sea-mining/

Tubau, Xavier, Charles K. Paull, Galderic Lastras, David W. Caress, Miquel Canals, Eve Lundsten, Krystle Anderson, Roberto Gwiazda, and David Amblas. 2015. “Submarine Canyons of Santa Monica Bay, Southern California: Variability in Morphology and Sedimentary Processes.” *Marine Geology* 365: 61–79. https://doi.org/10.1016/j.margeo.2015.04.004

USGS. 2017. “Ordinary Minerals Give Smartphones Extraordinary Capabilities.” USGS Communications and Publishing. April 4, 2017. https://www.usgs.gov/news/featured-story/ordinary-minerals-give-smartphones-extraordinary-capabilities

Vedder, J. G., L. A. Beyer, A. Junger, G. W. Moore, A. E. Roberts, J. C. Taylor, and H. C. Wagner. 1974. *Preliminary Report on the Geology of the Continental Borderland of Southern California*. Miscellaneous Field Studies Map 624. Sacramento: USGS. https://doi.org/10.3133/mf624

Vonnahme, T. R., M. Molari, F. Janssen, F. Wenzhöffer, M. Haeckel, J. Titschack, and A. Boetius. 2020. “Effects of a Deep-Sea Mining Experiment on Seafloor Microbial Communities and Functions after 26 Years.” *Science Advances* 6(18): eaaz5922. https://doi.org/10.1126/sciadv.aaz5922

Wessel, Paul, David T. Sandwell, and Seung-Sep Kim. 2010. “The Global Seamount Census.” *Oceanography* 23(1): 24–33. https://doi.org/10.5670/oceanog.2010.60

Yesson, Chris, Malcolm R. Clark, Michelle L. Taylor, and Alex D. Rogers. 2011. “The Global Distribution of Seamounts Based on 30 Arc Seconds Bathymetry Data.” *Deep Sea Research Part I: Oceanographic Research Papers* 58(4): 442–453. https://doi.org/10.1016/j.dsr.2011.02.004

Zabanbark, A. 2008. “Structure and Oil and Gas Perspectives of the Californian Borderland.” *Oceanology* 28: 129–137. https://doi.org/10.1134/S0001437008010153

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CHAPTER OVERVIEW

7: Seawater and Its Elements

We now contemplate the very medium about which this book is written, the ocean. But what is the ocean? Is it the water contained within the ocean basins? What makes some water “ocean water” and other water “not ocean water”? Aren’t the waters of the ocean connected to the waters of the land? If so, isn’t the water in our bodies similarly connected? Does that make us a part of the ocean?

Water is mysterious, hypnotic, intoxicating, sensual. Encountering the ocean’s edge, we stretch our eyes to see its farthest reaches, to make out the silhouette of a sailboat or the drum of a passing ship. When we hear crashing waves or rushing rivers, or the sound of rainfall against the windowpane, we immediately recognize it. A walk along a beach with the regular swish and swash of the waves soothes our stress-laden nerves. And who doesn’t love sleeping in a warm, cozy bed to the sound of rain? Our noses take notice of the smell of a lake or the sea, pungent for some, a perfume for others. We simply can’t live without daily (or twice-daily) showers. Artists and writers and thinkers claim that some of their best ideas come while in the shower. And though for many, baths are a thing of the past, a dip in a lake, a dash into the ocean, or a dally in a sun-filled pool brings a kind of peace and serenity that’s hard to find in the dry parts of the world.

Water is essential to all life, including humans. Humans—ancient and modern—have devised innumerable means to carry water with them: animal bladders, seashells, coconut shells, woven baskets, clay pots, metal canteens, glass containers, plastic bottles, bota bags, Camelbaks, and the trendy BPA-free reusable water bottle. In 2023 bottled water sales are expected to reach $342.4 billion worldwide (US dollars). In the US, we’ll spend $94 billion (Statista.com).

It’s no surprise people prefer living near or spending time on the water. More than a third of Americans live in counties bordering the shoreline of an ocean, estuary, or Great Lake (NOAA 2013). The most popular travel destinations for Americans in 2017 (pre-pandemic) were beach vacations and cruises. A watery vacation holds philosophical and meditative charms. Chilean poet Pablo Neruda (1904–1973) wrote, “I need the sea because it teaches me.”

A study of the ocean connects us to the world of water in which we live. We are intimately connected to and dependent on the waters of the world, especially the ocean. But to properly understand the ocean, we must understand the physical and chemical nature of water itself. Our understanding of the water molecule provides a jumping-off point for understanding the world ocean and our planet. Let’s dive in!

7.1: Anatomy of a Molecule
7.2: The Periodic Table of the Elements
7.3: The Name’s Bond, Chemical Bond
7.4: Chemical Formulas
7.5: The Water Molecule
7.6: What Are Salts?
7.7: Seawater Constituents
7.8: Chapter References

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7.1: Anatomy of a Molecule

If you could shrink yourself to a billion times smaller than you are now, a water molecule would be about the size of a footstool. Assuming you could get a water molecule to hold still (they like to jump around like little kids), you could determine that a single water molecule has a diameter of approximately 1.1×10^{-8} inches, or 280 picometers. (A pico is 10^{-12}, or 0.000000000001). Stepping back from your tamed water molecule and giving it a look-over, you take a quick breath and cover your mouth: "OMG! It looks like Mickey Mouse." Indeed, the **water molecule**—when depicted as the stick-and-ball model of a molecule—resembles Mickey Mouse's head, big ears and all.

The analogy offers an atomic view of water, too. Mickey's head and ears represent different atoms, namely, oxygen and hydrogen. One molecule of water consists of one atom of oxygen—Mickey's head—and two atoms of hydrogen—Mickey's ears. But the structure of water was discovered long before Mickey. In 1805 French chemist Joseph Louis Gay-Lussac (1778–1850) and famed German biogeographer Alexander von Humboldt (1769–1859) suggested a 2:1 ratio of hydrogen to oxygen (Scott 1887). But before we go any further with Mickey's head and the structure of water, let's do some quick basic training in chemistry.

Molecules are composed of **atoms**, the building blocks of matter, the "stuff" of which the universe is made. Atoms consist of **subatomic particles**, the number of which determines an atom's properties and classification. We often visualize atoms as miniature solar systems, where the center of the atom—the **nucleus**—corresponds to the sun. The **electrons**, which "orbit" the nucleus, correspond to the planets. The nucleus of an atom is made up of two subatomic particles: **protons**, subatomic particles with a positive charge, and **neutrons**, subatomic particles with a neutral charge—that is, no charge. The electrons have a negative charge equal to the proton's charge, but with the opposite sign.

In the language of chemistry, atoms with the same number of protons represent an **element**. By definition, elements cannot be broken apart by ordinary chemical reactions. On Earth there are 98 or so naturally occurring elements. These are the individual building blocks of all matter. We find these elements in the ocean, on land, and everywhere else in the universe. Each element—and, therefore, each atom of an element—is unique and has unique properties. Chemists represent elements with one or two letters—their **chemical symbol**. For example, the chemical symbol for hydrogen is H, and the chemical symbol for oxygen is O. Iron and silicon get two-letter chemical symbols, Fe and Si, respectively. Unknown or synthetic chemicals may receive temporary three-letter symbols (e.g., Chatt 1979).

One way to think of elements is to imagine a Lego set with 98 different varieties of plastic bricks, gears, Figures, and so forth. Elements are like the Lego set used to build Earth and the rest of the universe. It's pretty mind-blowing if you think about it. Everywhere around you are atoms in various combinations that give shape and substance to you and the world around you. A selfie is nothing more than an image of the billions upon billions upon billions of atoms of which you are made (7 billion billion billion, or 7×10^{27}, to be exact). Interestingly, just three elements—carbon, hydrogen, and oxygen—make up 99 percent of those atoms of beautiful you.

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7.2: The Periodic Table of the Elements

For convenience chemists organize elements into a chart known as the **periodic table of elements**, or simply the periodic table. Though different scientists prefer different arrangements of the periodic table—at least 1,000 different versions exist in the literature (e.g., Scerri 2013)—the purpose of the periodic table remains the same: to organize matter in a way that lets us quickly understand how it might behave in a chemical reaction.

Most commonly, elements are arranged according to their atomic structure and chemical properties. Rows of the periodic table correspond to energy levels of electrons. Columns represent elements with similar chemical behavior. We won't delve into the details, but students with an interest in chemistry—or science in general—will find the periodic table and its variations useful and fascinating.

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7.3: The Name's Bond, Chemical Bond

The periodic table tells us something about how different elements react with each other. When two or more atoms combine, they form a **bond**. A bond is a kind of sharing between atoms that results in their connection. It's like holding hands with someone you care about. You're bonded.

Like attractions between people, some chemical bonds are weak, some are strong, but most can be broken under natural conditions. Chemical bonding permits a coming together and coming apart of atoms. In fact, when one bond breaks, another almost always forms. The cool thing about these comings and goings of bonds is that energy is stored or released when bonds form or break, respectively. Organisms break and make chemical bonds as part of the biochemistry of staying alive. We won't go into the particulars here, but remember that energy is an important part of the discussion of matter; the two go hand in hand.

When two or more atoms bond to each other, a **molecule** is formed. Molecules may be composed of different atoms, such as carbon dioxide (CO_2) or glucose, a simple sugar ($C_6H_{12}O_6$). Molecules may also be composed of the same atom, such as oxygen (O_2) or nitrogen (N_2). These **homonuclear molecules** are composed of identical atoms that bond to themselves. They are a type of **diatomic molecule**, meaning they occur in nature as doubles. Diatomic molecules may also be **heteronuclear molecules**, that is, made of different elements, such as carbon monoxide (CO). A few, such as ozone (O_3), represent **triatomic molecules**. And if all these terms weren't enough, molecules composed of different atoms are called **compounds**. Compounds are composed of molecules that are composed of different kinds of atoms (i.e., different elements). So while water (H_2O) is a compound, oxygen (O_2) is not.

To simplify our discussion, I'll use the word **substance** to refer to atoms, molecules, and compounds. Substance refers to all forms of matter with a definite composition. Substances include elements and compounds. You can write the chemical formula for a substance. However, a word of caution is required. The term substance does not include matter with an indefinite composition, such as a solution of something. For solutions chemists use the term **mixture**. A mixture consists of a collection of two or more atoms or molecules in varying proportions. Seawater is a mixture. The air that you breathe is a mixture. Mixtures can be formed without chemical bonding; there are no chemical reactions involved in their formation. The key point here is that there are different types of atoms, different ways that they hook up, and different ways that they mix. You know, like people.

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7.4: Chemical Formulas

To represent the proportions of each type of atom in a molecule, chemists create chemical formulas. Chemical formulas include not only the chemical symbols for the elements but also the numbers of each atom in the molecule. The order of symbols obeys rules and conventions that don't concern us here, but understanding how to read these chemical formulas is important. Conventionally, the number of atoms is represented as a subscript after the atom's symbol. For example, the chemical formula O_2 indicates two oxygen atoms. Unfortunately, this convention confuses the heck out of people. For example, water has two hydrogen atoms and one oxygen atom. As a chemical formula, we symbolize water as H_2O. But your natural instinct (as one used to reading texts where numbers come before the noun they modify) is to think that the "2" refers to the O, leading you to erroneously conclude that water has two oxygen atoms. In the language of chemistry, the "2" refers to the H, meaning that water has two hydrogen atoms. Thus, water, symbolized as H_2O, has two hydrogen atoms and one oxygen atom per molecule. If it helps, you have my permission to symbolize water as H-O-H, which is a lot more fun to say.

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7.5: The Water Molecule

Writing water as H-O-H helps us visualize why water looks like Mickey Mouse. When the hydrogen and oxygen atoms come together as a water molecule—which they do because they are attracted to each other—they share their electrons in a **covalent bond**. Because oxygen is a larger atom with a bigger nucleus, it's a bit more "powerful" than hydrogen, and, frankly, it hogs the electrons. Because electrons are negatively charged, being held closer to oxygen gives oxygen a slightly negative charge. We say that the oxygen atom in a water molecule is **electronegative**. Because the hydrogen atoms are stripped of some of their electron blanket, they become slightly positive, or **electropositive**. This separation of charges—the positive charge on the hydrogen atoms and the negative charge on the oxygen atoms—makes water a **polar molecule**, one that exhibits electropositive and electronegative ends. This property of the bonding of two hydrogen atoms and one oxygen atom gives water its characteristic V shape. When the atoms are represented as circles, the water molecule looks like Mickey Mouse.

Hydrogen Bonds, Cohesion, and Surface Tension

Water's extraordinary ability to dissolve comes from its polarity. In the world of atoms, opposites attract. Positive charges attract negative charges, and vice versa. So it is with water. Because the oxygen atom of the water molecule is electronegative and the hydrogen atoms are electropositive, water molecules attract each other. In fact, the oxygen atom of one water molecule forms a bond with the hydrogen atom of another water molecule, a bond known as a **hydrogen bond**. This is not a strong bond—it's a weaker covalent bond—but it's strong enough to give water molecules some fascinating properties.

If you place a drop of water on a tabletop, what does it do? Rather than flattening out and running off the table like other liquids do, water beads up. Rain on a car hood will form beads of water.Dew on grass appears as beads of water. Beads of water pop out of your forehead when you sweat. The beading up of water comes about because of hydrogen bonds. It's a property of the water molecule known as **cohesion**, the "sticking together" of molecules. Water is a sticky molecule; it likes to stick to other water molecules.

At the surface of a body of water, the stickiness of water gives rise to another property: **surface tension**—the enhancement of cohesion at the surface of a liquid. It's this property that allows insects to skate across the top of a pond without falling in. A needle placed lengthwise on the top of a glass of water will remain afloat because of surface tension. The water molecules at the surface form stronger hydrogen bonds than the water molecules beneath them because there are no water molecules above them competing for their bonds. Think of it like being able to hold onto something with two hands instead of one—two hands are stronger. That's how it is with surface water molecules. The result is a kind of "skin" on the surface of water in a glass, pond, lake, or ocean.

Water Is Dense

Another somewhat obvious property of water is that it weighs a lot. If you've ever lugged a five-gallon container of water, you know what I mean. A single gallon of water weighs eight pounds! The weight of water doesn't come from the atoms that make it up; hydrogen is the lightest atom in the periodic table, and oxygen only has an atomic mass of 16. Compare that to the heaviest atom, uranium, at 238 atomic mass units. Where liquid water gets its weight is from its density. **Density** refers to the amount of matter packed into a given volume, or mass per unit volume. Liquid water is 800 times more dense than air. So there are a lot of water molecules packed into a liter of water compared to a liter of air, and that makes a bottle of water relatively heavy.

Most substances, especially gases, exhibit a change in density when their temperature changes or when they are subject to changes in pressure. Typically, an increase in temperature will reduce a substance's density—its molecules spread apart—while a decrease in temperature increases its density—the molecules move closer together. Greater pressure increases density, while lower pressure reduces it.

Pure water, however, doesn't quite obey the temperature rule. Pure water reaches its maximum density at about 39.2°F, or 4°C. Below 39.2°F, water becomes less dense. The reason for this involves some complicated aspects of the behavior of water molecules. But you can think of it this way: like people, water molecules prefer a certain amount of personal space. Get too close, and they balk. "Get back," they say. That limit of tolerance for closeness to other water molecules happens at about 39.2°F. But let's be clear: this holds only for pure water. Seawater doesn't exhibit this property.

Water, including seawater, also doesn't obey the pressure rule. For the most part, water is incompressible, unable to be compressed. However, water can be compressed slightly, and this gives rise to some interesting changes in seawater's temperature as pressure

increases with depth. We'll visit this topic in our chapter on deep circulation.

Water's abundance on Earth makes it useful as a standard for comparing the density of other liquids, a quantity known as specific gravity. Scientists define **specific gravity** as the density of a substance divided by the density of water. Thus, substances with a density greater than water will have a specific gravity greater than one, and substances with a density less than water will have a specific gravity less than one. See how that works? The density of water, and especially factors that change the density of seawater —namely, temperature and the saltiness of the seawater, its **salinity**—prove critical to understanding layering of the ocean and ocean circulation, as we shall see in later chapters.

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7.6: What Are Salts?

For those of us who grew up near the ocean and spent many a day splashing around in it, the saltiness of its waters seems natural and barely merits our notice. But for those people who were raised far inland, who were perhaps already in their teens or adult years prior to even seeing the ocean for the first time, seawater, when tasted, serves up a rather rude welcome. The sting of that first swallow on the virgin tongue begets an immediate spit and a loud ugh. “It’s salty,” they exclaim, as if somehow their elementary school teacher was only kidding when she said the sea was made of salt. “Yes, my dear,” you can hear their teacher explaining on the student’s retelling of the horrific tale, “seawater contains salt. It won’t harm you.”

Salt is the general term applied to all the dissolved substances that we find in seawater. But the dissolved substance in the greatest proportions in seawater has a familiar name and formula: **sodium chloride** (NaCl)—salt. As it turns out, seawater contains nearly all known natural elements in the periodic table—even gold. It’s said that if you could extract all the gold dissolved in the ocean—about 20 million tons—you would be a very rich person. Of course, what isn’t said is that the cost of extracting the gold using currently known chemical methods would exceed the amount you would make in selling it, or that if you put such a large quantity of gold on the market, the price per ounce would plummet. So don’t believe everything you read on the internet about gold in the ocean.

As solids, sodium and chlorine atoms stack up like a jungle gym, a playground structure made of crisscrossing metal pipes. They form a **crystal lattice**, the three-dimensional, symmetrical, and repetitive arrangement of atoms that forms a crystal. If you examine a sample of **halite**, a mineral formed from sodium chloride, you’ll notice regularly repeating cubes—the crystal lattice structure of sodium chloride. Diamonds also exhibit a crystal lattice structure. In a crystal of salt, the sodium and chloride atoms have exchanged electrons; the sodium atoms have given up an electron to the chlorine atom, and the chlorine atom has accepted that electron. This kind of bond, where atoms exchange electrons, is called an **ionic bond**. The ionic form of sodium is referred to as the **sodium ion** while the ionic form of chlorine is called the **chloride ion**. It is one of the two major kinds of chemical bonds, the other being the aforementioned covalent bond formed when atoms share electrons.

Dissolved Salts

As we learned above, water is a polar molecule. Not only do the positive and negative charges on the water molecule make it ideal for bonding with itself, they also allow water to bond with a great number of other kinds of atoms and molecules. In fact, any polar molecule will dissolve in water because opposite charges attract and form bonds. Even complex molecules, including some normally “insoluble” hydrocarbons, are at least partially soluble owing to a charge on their molecule. Strictly nonpolar molecules—those with a balance of charges and no dipole—are, of course, insoluble. Thus, a mixture of water and a nonpolar molecule, such as olive oil, will not combine. You know the saying, “Oil and water don’t mix.” Now you can explain why.

So powerful is water’s ability to bond with other atoms and molecules that it has been named the **universal solvent**. A **solvent** is a substance that dissolves another substance. The substance being dissolved is known as a **solute**. When water acts as a solvent, the substance that it dissolves is the solute.

Now, I want to make sure that you understand what the word “**dissolving**” means. When you dissolve one thing in another, the thing being dissolved becomes part of the solution of the other. But what does that mean exactly?

If you sprinkle a little bit of table salt in a bottle of water, the sodium and chlorine atoms in the salt become a few atoms among many molecules of water. In essence, they find a place to live within the spaces between the water molecules. They become part of a solution of water molecules and sodium and chlorine atoms. If you cap the bottle and keep it in a safe place for a hundred years and come back after that time and gaze upon that undisturbed, capped bottle of slightly salty water, where will you find the salt? You won’t. The salt will remain invisible because it is dissolved. It’s part of the matrix of the water. You will not—as many of my students erroneously answer when first asked—“find it at the bottom of the bottle.” The salts stay dissolved. As long as conditions inside the bottle remain unchanged (i.e., as long as we don’t freeze or evaporate the water), the salt will remain permanently dissolved, held in solution by water.

Now, in defense of those students who thought that the salt would be found at the bottom of the bottle, they did have one thing correct: Gravity acts on solutions. While the salts do not come out of solution—they do not turn into solids again—they can be very slightly concentrated in their dissolved form at the bottom of a column.

In the early 1800s, Gay-Lussac wondered something similar: Can the gravity-driven settling of salts explain the higher salinities in the deep ocean? He performed an experiment with six-foot-tall glass tubes in which he placed a salt solution for several months. At the end of that time, he measured the salinity at the top and the bottom of the tubes. He found no difference (e.g., Wallace 1974).

Nonetheless, calculations made by chemical oceanographer Ricardo Pytkowicz (1929–1991) indicate that had Gay-Lussac extended the experiment for years, and had he been able to measure salinity to an accuracy of thousandths, he would have found a salinity of about 34.994 parts per thousand (ppt) at the top and 35.006 ppt at the bottom, assuming a starting salinity of 35.000 ppt (Pytkowicz 1962). The salts remain dissolved, of course, but they do concentrate ever so slightly under the force of gravity as long as the water remains undisturbed. A minor point, perhaps, but one that illustrates how scientists do their best to think of every possibility.

Anions and Cations

When sodium chloride comes into contact with water, the ionic bonds between the sodium and chlorine atoms disappear. The atoms in the salts separate—dissociate—from one another. That's because the polar water molecules have a stronger attraction for the sodium and chlorine atoms than the two elements have for each other. With the ionic bond gone, the sodium atom takes on a positive charge, and the chloride atom takes on a negative charge. They become what are known as **ions**—atoms or molecules whose number of positively charged protons differs from their number of negatively charged electrons.

Ions by definition have a net electrical charge—the sum of their positive charges and negative charges does not equal zero. Ions with a negative charge, such as chloride, are called **anions**, while ions with a positive charge, such as sodium, are called **cations**. In the written language of chemistry, the ionic form of an atom or molecule is represented by a superscript of + or − following the chemical formula. For example, the sodium ion is represented as Na^+ and the chloride ion is represented as Cl^-. For cations and anions that have two or more positive or negative charges, respectively, the appropriate number is placed before the + or – sign, as in sulfate, SO_4^{2-} or magnesium, Mg^{2+}. When salt dissolves in water, the electropositive hydrogen atoms of the water molecules surround the electronegative chloride ion, and the electronegative oxygen atoms of the water molecule surround the sodium ion. The sodium and chloride ions, in essence, become part of the fluid. As long as conditions remain constant, the sodium ions and chloride ions remain dissolved in solution.

States of Saturation

One final set of definitions completes our discussion of the dissolving power of water. The maximum concentration of a solute, including gases, that can be dissolved by a solution under a given set of conditions is called the **saturation concentration**. Two other states are possible: A solution may be **undersaturated** with respect to the solute, meaning the solution contains less of a substance than the saturation concentration; or the solution may be **supersaturated**, meaning the solution contains more of a substance than the saturation concentration.

Of course, the saturation concentration is not fixed; environmental factors such as temperature and pressure can change it. For example, at higher temperatures, the saturation concentration of salts in water increases. That is, water dissolves more salts at higher temperatures. Conversely, lowering the temperature reduces the saturation concentration. Thus, increases or decreases in temperature can cause a body of water to become undersaturated or supersaturated, respectively. States of undersaturation and supersaturation prove important to understanding dissolved gases in the ocean, too. However, gases behave differently in solution than do solids, as we shall see.

Electrostriction

As further testament to the magic of seawater, a curious thing happens when you dissolve NaCl in it: the volume of the solution decreases by about 3 percent (e.g., Pilson 2013). The reduction in volume of a solution when salts are added is called **electrostriction**, from electrical constriction. This reduction in volume results from the rearrangement of water molecules around solutes: positive hydrogens orient toward anions and the negative oxygen skews toward cations. In short, water and salts rearrange themselves into a tighter, more intimate space. Other salts cause electrostriction too. This property may help explain why seawater lacks the density maximum at 39.2°F of pure water (e.g., Pilson 2013).

The Periodic Table of the Ocean Elements

We can now examine the cast of characters—the elements—found in seawater. In 1997 Japanese oceanographer Yoshiyuki Nozaki (1947–2003) published an interesting electronic variation on the periodic table, one that included illustrations of the distribution of the elements in the water column. Nozaki's work inspired researchers at the Monterey Bay Aquarium Research Institute to produce an online version, which they called the **Periodic Table of the Elements in the Ocean** (PTEO). The PTEO provides a fun and useful visual tool for studying the ocean elements.

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7.7: Seawater Constituents

For this section, you may want to download a black-and-white periodic table or refer to the periodic table above. It helps to mark—and even color code—the following major categories of chemical constituents in seawater:

- **Major constituents**, the elements whose concentrations exceed 1 part per million in seawater
- **The trace elements**, or minor constituents, elements whose concentrations in seawater are less than 1 part per million, including elements that are important in biological reactions, the so-called biologically important nutrients
- **Dissolved organic matter (DOM)**, a heterogeneous group of very dilute, dissolved carbon–containing substances, and **particulate organic matter (POM)**, living and dead particles of organic matter
- **Dissolved gases**, gas-phase elements in seawater

The Major Constituents

The major constituents comprise a group of 11 elements that make up 99.9 percent (by weight) of all the elements dissolved in seawater. Put another way, if you evaporate all the water from seawater so all that remains is salt, 99.9 percent of that salt will be composed of these 11 elements.

In order of decreasing concentration, we find chlorine, sodium, magnesium, sulfur, calcium, potassium, carbon, bromine, boron, strontium, and fluorine. Of course, seawater is mostly water, so don't be misled. The dissolved salts make up only a small fraction of the total weight and volume of seawater, about 3.5 percent.

Perhaps most remarkably, these major constituents (except carbon) occur in identical proportions throughout the ocean, even though salinity may vary. Establishment of the **Principle of Constant Proportions**, as the relationship between major constituents is known, marked a key advance in chemical oceanography.

While a number of chemists worked on aspects of seawater chemistry from the late 1600s to the mid-1800s, three men in particular set in motion discoveries that would establish the foundations of chemical oceanography: Alexander Marcet (1770–1822), a Swiss-born chemist and physician; Georg Forchhammer (1794–1865), a chemist and geologist from Denmark; and William Dittmar (1833–1894), a German-born chemist who worked in Scotland. These men contributed techniques, sampling approaches, principles, and terminology that remain in use today. (See Wallace 1974—followed here—for extensive details of their contributions.)

Marcet (in 1819) was the first to suggest that seawater from different parts of the Atlantic Ocean and the Mediterranean Sea "contained the same ingredients" and in "very nearly the same proportions to each other," regardless of their salinity. In 1843 Forchhammer received several samples of Mediterranean seawater from a friend and set out to refine the methods of analysis. His painstaking work was summarized in a single publication, *On the Composition of Sea-water in the different parts of the Ocean* (Forchhammer 1865). Dittmar (1884) built on Forchhammer's findings in his work on samples collected during the Challenger Expedition. Dittmar's findings mirrored Forchhammer's, with several important improvements. He adopted Forchhammer's term "salinity" to describe total dissolved salts but modified it to the "parts of total salt in 1000 parts of sea water." Here he established a commonly used unit for salinity—parts per thousand. He confirmed that six elements comprised the greatest percentage of salts, and that those salts occurred in constant proportions in all depths of all oceans. Dittmar's result firmly established the Principle of Constant Proportions as a useful assumption when analyzing seawater.

The benefit of this principle comes when applied to the chemical analysis of seawater. If you know the concentration of just one of the major constituents, you know the concentrations of all of them (except carbon). Consider, for example, the color distribution of M&Ms (a very popular topic among math folks on the internet). According to StatsMedic (2023), M&Ms are produced in the following proportions: Brown (12.4%), Red (13.1%), Yellow (13.5%), Green (19.8%), Orange (20.5%), and Blue (20.7%). So if you had a bowl of M&Ms and wanted to know how many blue M&Ms were in the bowl, what might you do? Well, according to the Principle of Constant Proportions of M&Ms, you could count the number of brown M&Ms (the smallest number) to calculate the total number of M&Ms because

$$\textit{(Total brown M\&Ms)} / \textit{0.124} = \textit{Total number of M\&Ms}$$

(Eq. 10.1)

Once you know the total number of M&Ms, you only need multiply by the percentages to calculate the number of each color.

It's much simpler and much faster, which is why the Principle of Constant Proportions made such a splash with marine chemists. Determination of the salinity of a sample could be based on analysis of a single constituent. And it could be accomplished in hours instead of days.

Because nine other major constituents (except carbon) occur in a constant ratio—regardless of the salinity—major constituents are considered **conservative elements**; their ratios are conserved at all salinities. Most of the next group of elements, the minor constituents, obey no such rules.

The Trace Elements

Pilson (2013) confesses that

> *a great deal of time and material effort is required to achieve reliable results for some of the important elements . . . that are present at very low concentrations in the central water masses of the oceans. The real concentrations are so vanishingly small that the quantities present are easily swamped by contamination.*

Thus, we remain uncertain about the source–sink pathways of many of the minor constituents. Nevertheless, we can make some useful generalizations.

The minor constituents—elements whose concentrations are less than 1 part per million in the ocean—include elements too dilute to be considered major. Pilson (2013) lists some 63 minor constituents and their concentrations, excluding gases and radioactive compounds. An element's designation as "minor" should not mislead you. A good number of these elements prove vital to living things, and many trace the motions of water masses and other useful oceanographic processes. What unites them primarily are their low to extremely low concentrations in seawater.

Like major constituents, minor constituents originate from riverine, atmospheric, and subseafloor processes (Chapter 11). And like major constituents, their concentration and distribution in the ocean depend on the nature of their sources and sinks. For the most part, however, chemical oceanographers categorize minor constituents according to processes that remove them. On that basis the minor constituents can be divided into five types based on their vertical distribution in the water column (following Bruland and Lohan 2006).

Conservative-Type

Just like major constituents, some minor constituents exhibit conservative-type distributions; that is, their concentration in seawater varies proportionally with salinity. Metals such as cesium (Ce^+) and rubidium (Rb^+) exist as unreactive cations that spend a great deal of time in the ocean, 300,000 and 3 million years, respectively. Others, such as molybdenum and tungsten, play key roles in biological processes, but their high concentrations relative to their use by organisms make their concentrations largely invariable. Less than a dozen minor constituents are included in this category.

Scavenged-Type

As noted by Jeandel et al. (2015), "particles act as an essential regulator of ocean chemistry because they determine the residence time of many dissolved elements in seawater." Particles prove especially important for the removal of trace elements from the ocean. Jeandel and colleagues broadly distinguish two types of particles in the ocean: (1) **external particles**—those delivered via rivers, the atmosphere, the seafloor (shelf currents and hydrothermal vents), and even outer space (e.g., micrometeorites); and (2) **internal particles**, those formed within the water column via biological activities, aggregation of organic matter, or chemical precipitation. Dissolved trace elements interact with particles of both types, but here we focus on the removal of dissolved trace elements by sinking particles, a process called **scavenging**.

Scavenged elements easily attach to sinking particles, a process called **adsorption**. The attraction of trace elements to particles involves physical forces, or **physisorption**—the same weak forces that allow a gecko to climb a wall. It also involves chemical forces, or **chemisorption**, which pertains to chemical bonding between atoms and the surface of particles. Chemisorption occurs, for example, in the removal of harmful substances in water (or air) by activated carbon filters. Note that adsorption—the sticking to or adherence of dissolved elements to particles—differs from **absorption**, in which the dissolved elements become part of the

particle. It's kind of like the difference between hanging on to the outside of a cable car in San Francisco (adsorption) or getting inside it (absorption). It's not a perfect simile, but you get the idea.

Particles stick together, too, a process called **aggregation**. Thus, scavenging of trace elements by particles in the ocean is a three-part process: (1) adsorption of an element onto a particle; (2) aggregation; and (3) sinking of the particle to the seafloor.

Bruland and Lohan (2006) note that scavenged-type trace metals tend to occur in their greatest concentrations near their sources: the atmosphere, rivers, vents, or sediments. Aluminum, for example, shows its highest concentrations in the Atlantic Ocean and Mediterranean Sea due to a high input of atmospheric dust in these regions. Scavenged-type elements show their greatest depletion in older waters—those with less frequent atmospheric interaction. In the Pacific Ocean, for example, deep water remains out of contact with the atmosphere for hundreds of years, so scavenging can take place over a longer period of time. Pilson (2013) lists three dozen scavenged and "surface-depleted" minor constituents. However, he cautions that any of a number of geological or biological causes may generate a vertical distribution for a given constituent. As he puts it, "There is certainly much more to learn, and one wonders if there are more real surprises yet waiting."

Hybrid-Type

Hybrid-type trace elements occur where a minor constituent participates in more than one pathway in its removal from seawater. Iron, for example, may exhibit surface minima—where it is strongly utilized by phytoplankton (a nutrient-type distribution)—or surface maxima—where low phytoplankton activity and significant atmospheric deposition elevate its concentrations. In deep waters, iron concentrations tend to remain constant, unlike other nutrients. Variations in dissolved iron in the ocean appear to represent a balance of recycling of organic matter, which releases iron, and scavenging of iron by particles, which removes it.

Mixed-Type

Some elements exist in multiple forms in the ocean, a chemical process known as **speciation**. Germanium (the element, not the flower, which is spelled geranium) takes a form very much like dissolved silica; it forms a compound called germanic acid (H_4GeO_4). But it also binds with methyl groups (CH_3) to form what chemical oceanographers call the "Teflon of the sea," mono- and dimethylgermanium—$CH_3Ge(OH)_3$ and $(CH_3)_2Ge(OH)_2$, respectively. As germanic acid, germanium acts like a nutrient. It may be absorbed by phytoplankton and other plankton that form "shells." As methylated germanium, however, it's very stable, like a conservative minor constituent. Thus, the same element exhibits a **mixed-type distribution**, one that depends on the form of the element.

Biologically Important Nutrients

Biologically important nutrients, or simply nutrients, represent a group of dissolved substances necessary for the growth of photoautotrophs—photosynthetic organisms, such as phytoplankton, seaweeds, marine plants, and terrestrial plants. When oceanographers talk about nutrients, they aren't talking about the stuff that comes in a box of Wheaties or even the kind referred to by nutritionists. An oceanographer's nutrients are the dissolved stuff phytoplankton (and other photoautotrophs) absorb across their cell walls. Let's get this straight: they do not "eat" nutrients like Pac-People eat dots; they absorb them.

As many as 28 different nutrients may be required by phytoplankton (e.g., Moore et al. 2013; Supplemental). Elements required in greater quantities are generally referred to as **macronutrients**, while those needed in smaller amounts are called **micronutrients**. Reynolds (2006) defines macronutrients as those that exist at an abundance of greater than or equal to 1 percent of the ash-free dry mass of a cell. By this definition macronutrients include carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorus (P), and sulfur (S). Other authors, however, restrict the definition of macronutrients to those abundant elements that may limit the biomass of phytoplankton in the ocean, namely, phosphorus and nitrogen (e.g., Jones 2011). To this list some add silicon (e.g., Falkowski et al. 1998). Silica (SiO_2) is required for the growth of diatoms—who use it to manufacture their cell walls. Surprisingly cyanobacteria also take up silica, as recently discovered by Baines et al. (2012). The accumulation of silica by cyanobacteria has major implications for the global silicon cycle (Ikeda 2021).

Micronutrients include several trace metals, such as iron (Fe), manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), and boron (B), among others (e.g., Carrano et al. 2009; Twining and Baines 2013). Iron has received a lot of attention in recent decades for its role in limiting the biomass of phytoplankton in regions of the ocean that otherwise should be very productive. Micronutrients also include organic nutrients, such as thiamine, biotin, and vitamin B_{12}.

Given their use by phytoplankton, biologically important nutrients tend to be depleted in the upper ocean, where sunlight drives photosynthesis. Conversely, they tend to be highest in the deepest and oldest waters that remain out of sunlight, where photosynthesis doesn't occur.

DOM and POM

Greek philosopher-scientist Aristotle (385–323 BCE) was the first to report the presence of fatty substances on the sea surface, evidence for the presence of organic matter—biologically produced, carbon-containing molecules. Organic matter in the ocean broadly divides into two types: dissolved organic matter (DOM) and particulate organic matter (POM).

Operationally, DOM includes anything that passes through a 0.2 micrometer filter (e.g., Libes 2009). Technically, that includes small microbes and viruses—which are not dissolved—but that's why it's called an operational definition. POM includes anything alive or once living. As expressed somewhat tongue-in-cheek by Pilson (2013), POM can be "collected with harpoons . . . hook and line . . . dragging a net . . . or filtering," referring to the different sizes of living things—from blue whales to microbes—which make up POM.

DOM and POM mostly consist of carbon atoms. So oceanographers focus on measurements of dissolved organic carbon (DOC) or particulate organic carbon (POC) to estimate DOM or POM, respectively. By far, the greatest portion of organic matter in the ocean belongs to the DOC pool. Some 662 gigatons are reported (e.g., Hansell et al. 2009), slightly more than exists in terrestrial plants (e.g., Schlesinger and Barnhardt 2013). Libes (2009) reports an estimated 55 gigatons of POC in the ocean, 50 gigatons of which is **detritus**—particles of dead organic matter (think finely ground leaf litter). Note that this amount includes everything you think of when you think of marine organisms.

Most of the biomass of the ocean can be found in the small things. Biomass-wise, the largest organisms, such as whales, represent only a tiny fraction of the ocean's organic matter, around a tenth of a percent of the total POC (Smith 2007). Because DOM and POM play a significant role in primary productivity and marine food webs, we'll defer our discussion of them until later chapters.

Dissolved Gases

Have you ever shaken a can of soda and asked an unsuspecting person to open it for you? To their surprise and your amusement, the can erupts like a geyser, spraying soda everywhere.

Why do soft drinks fizz and froth when you open them after shaking? It's because they contain a gas—carbon dioxide—that has been dissolved in the liquid (consisting of about 90 percent water and a combination of sugar, flavors, sodium, phosphorus, and other ingredients). Soft drink manufacturers pump carbon dioxide gas into the liquid at cold temperatures and high pressures, effectively trapping the gas in the container and creating a supersaturated solution. When that pressure is released—when the tab or cap is opened—the reduced pressure allows the gas to come out of solution.

Shaking the bottle or can ahead of time accelerates the process because shaking disrupts the arrangement of the water molecules holding the gas in place. As Live Science puts it, shaking releases dissolved gases into the space above the liquid, increasing its pressure (Choi 2022). Carbon dioxide also reacts chemically with water, a process that affects everything from lakes to coral reefs. In fact, increases in the atmospheric concentration of carbon dioxide are changing the chemistry of the ocean, as we shall see. But first, let's take a look at some fundamental properties of gases in seawater. Feel free to pop your own favorite beverage while reading this section.

Factors Affecting Dissolved Gases

Three main physical or chemical factors affect the dissolution of gases in seawater: temperature, salinity, and pressure:

- The colder the water temperature, the greater the solubility of the gas.
- The lower the salinity (the fresher the water), the greater the solubility of the gas.
- The higher the pressure, the greater the solubility of the gas.

As the temperature of water decreases, the ability of the water to dissolve gases increases. Put another way, *the solubility of gases increases with decreasing temperature*. Conversely, as water temperature increases, less gas can be dissolved in a liquid. The solubility of gases decreases with increasing temperature. This relationship may seem at odds with what you learned previously about the solubility of solids in water. But the dissolution of gases in water works a bit differently from the dissolution of solids. Most gases (except for CO_2) do not separate into their individual elements, like NaCl does. Instead, the water molecules surround

the gas molecules, essentially trapping them in a net. At lower temperatures the water molecules are closer together and form a tighter net, and gas molecules cannot escape as easily. At higher temperatures water molecules are spaced farther apart, so the "mesh" of the water net expands, allowing more gas molecules to escape.

Higher salinity reduces the solubility of gases. That means that freshwater holds a greater concentration of gases than saltwater. In effect the water net is more crowded in saltwater; Na and Cl take up space and reduce the capacity of water to surround gas molecules. In oceanic regions with higher salinity—regions with high rates of evaporation relative to precipitation or where sea ice forms, causing rejection of the seawater's salts—the saturation concentration of dissolved gases may be lower. In regions with lower salinity—regions with high rates of precipitation relative to evaporation, in estuaries, or near the mouths of rivers—the saturation concentration of dissolved gases may be higher. However, temperature may counteract salinity effects. Colder temperatures in polar oceans reduce the effects of higher salinity in these waters, and warmer temperatures in estuaries may act against any increase in solubility as a result of fresher water.

Pressure affects the solubility of gases in water, as we might expect from our soft drink example above: *The higher the pressure, the greater the solubility of the gas*. So, the deeper you descend in the ocean, the greater the solubility of gases in seawater. In fact, every 33 feet (10 m) increases solubility by about 10 percent. Thus, seawater at the surface (100% saturation) may become undersaturated with oxygen and other gases at depth. So at 33 feet (10 m), the saturation concentration of a gas drops to 90 percent. At the same time, pressure acts to capture bubbles of air that are swirled downward by breaking waves. As a result, surface waters of the ocean are often supersaturated with gases, just like a soft drink.

Molecular interactions help explain why oxygen dissolves in water. As polar water molecules approach, the oxygen molecule's normally symmetrical electron cloud rearranges into an asymmetrical, weakly polar configuration—what is known as a **dipole**. As it does so, oxygen takes on the characteristics of a polar molecule. The positive and negative ends of the water molecule are now attracted to the negative and positive ends, respectively, of the oxygen dipole, and the oxygen molecule dissolves. Other nonpolar gases, like nitrogen, may also be dissolved in this way. Think of it as being like when you tell your parents your sibling made you do it. One molecule influences another molecule to do something it normally wouldn't.

The Air–Sea Interface

The boundary between the ocean and the atmosphere—where the sky and sea meet—is called the atmosphere–ocean interface, or simply the **air–sea interface**. It's a part of the ocean that few have heard of, yet it just might be the most important feature of our planet. Engel et al. (2017) call it "the ocean's vital skin," the **sea surface microlayer**, the thin film of water no deeper than 1 millimeter (the width of a pinhead). This interface acts as the gatekeeper for what enters the ocean from the atmosphere, and vice versa. A brief look at the role of this layer in gas exchange across the air–sea interface provides insights into the dynamic set of physical processes that control the concentration of dissolved substances in the ocean.

Gas Exchange

The simplest model of gas exchange across the air–sea interface (e.g., film theory; see Sarmiento and Gruber 2006; Liao and Wang 2013) assumes that transfer occurs as a result of simple **diffusion**—the movement of molecules across a boundary due to a concentration gradient (i.e., where the concentration of molecules across the boundary differs). For example, a drop of food coloring in a glass of water diffuses throughout the glass until the same concentration of dye exists everywhere in the water. If diffusion was the only process controlling the exchange of gases across the air–sea interface, then the concentration of gases in the ocean would be directly proportional to their concentration in the atmosphere (according to a relationship known as Henry's law). However, dissolved gases in the ocean, even near the surface, exhibit undersaturation or oversaturation relative to their atmospheric concentrations. In other words, most gases dissolved in the ocean are not in equilibrium with the atmosphere. That means other processes contribute to air–sea exchanges.

Anyone who has watched breaking waves at the shore or experienced them from beneath the surface as a swimmer or diver has likely noticed the effect of the waves on the water: They create foam, bubbles, and sea spray. Indeed, breaking waves in the open ocean also accelerate the exchange of gases across the air–sea interface. Waves break through the sea surface microlayer and allow gases to be transferred faster, both in and out of the atmosphere. Bubbles also penetrate the surface waters, where higher pressures compress and capture the gas molecules. The penetration and dissolution of bubbles of air caused by breaking waves is called **bubble injection**, a process that may lead to supersaturation.

Waves also contribute to **turbulence** in the upper ocean, the chaotic and irregular changes in the speed and direction of flowing water or air. Perhaps you've experienced turbulence in an aircraft or watched the turbulent chaotic spume of an incoming wave. Turbulence carries gases deeper and in more directions than simple diffusion. Bubble injection is an example of a turbulent process.

One way to think about turbulence is to consider the difference between pouring a dash of milk into a cup of coffee and letting it sit until the milk is distributed throughout the coffee or stirring the coffee to homogenize the mixture. Turbulence acts like a stir stick that transfers heat, particles, gases, and a whole host of other things throughout the ocean.

Dissolved Gases in Ocean Research

Research on seawater chemistry and dissolved gases in the ocean takes center stage for understanding a number of oceanographic processes, including the movements of water (e.g., using gases as tracers), the chemistry and biology of the seafloor (e.g., methane seeps), human impacts on marine life (e.g., dead zones), and ocean chemistry (e.g., ocean acidification, the increase of acidity in the ocean). Here we take a look at two gases: chlorofluorocarbons, used as tracers of water mass movements, and methane, a potential energy source and potent greenhouse gas. In later chapters we look more closely at research on carbon dioxide and oxygen, as a full understanding of these gases requires a bit more knowledge of the physics and biology of the ocean.

Chlorofluorocarbons (pronounced klor-oh-FLOOR-oh-car-buns), also known as CFCs, represent a class of gas molecules containing chlorine and fluorine (i.e., halogens) used widely as refrigerants and propellants from the 1930s through the 1980s. When carried high into the atmosphere, these gases break apart and destroy ozone (O_3), most of which is found in the **ozone layer**—a part of the **stratosphere**, which is the atmospheric layer above the one in which we live. Near the ground ozone can be harmful ("bad" ozone). In the stratosphere ozone absorbs DNA-damaging ultraviolet radiation (just like a good pair of sunglasses). So the ozone layer ("good" ozone) acts as a shield protecting life—including ocean life—from the harmful effects of ultraviolet radiation.

The reduction of the ozone layer occurs mostly in polar regions (most notably Antarctica), where cold temperatures and other atmospheric conditions favor the ozone-destroying reactions. The net result has been an **ozone hole**, a region where stratospheric ozone concentrations are greatly reduced. Because CFCs destroy the ozone layer, they were banned in 1987 under an international treaty called the Montreal Protocol on Substances That Deplete the Ozone Layer. Former UN Secretary-General Kofi Annan (1938–2018) called this global effort "the single most successful international environmental agreement to date" (Annan 2000, p. 56). Unfortunately, CFCs and their byproducts (especially chlorine) can remain in the atmosphere for hundreds of years. Thus, while most CFCs have been completely phased out and are no longer released into the atmosphere, their long lifetimes mean that the ozone hole will remain with us for several more decades. In 2022, the ozone hole reached its smallest maximum extent in decades (Gillespie 2022). A report released by the World Meteorological Organization in 2022 highlighted that "actions taken under the Montreal Protocol continued to decrease atmospheric abundances of controlled ozone-depleting substances" (WMO 2022).

Despite their negative impacts, CFCs offer an opportunity to study and better understand deep ocean circulation. CFCs act as a kind of time stamp for the origin and movements of water in the ocean's interior, a group of substances known as **ocean tracers**. When surface waters sink, the gases they contain are transported with them. Because these waters are in contact with the atmosphere, the soon-to-be-deep water takes on the properties of the atmosphere. As a result, deep water masses record the composition of the atmosphere at the time of their sinking. Dissolved gases, other dissolved substances, particulate matter, and even temperature and salinity can act as tracers. These tracers allow oceanographers to figure out when a particular mass of water formed and how it mixed with other water masses as it moved. As the Water Encyclopedia (2023) puts it, "Tracers serve as a 'dye' with which to follow the circulation of ocean waters."

The discovery of hydrothermal vents reinvigorated seafloor exploration and paved the way for the discovery of other chemosynthetic systems, such as **cold seeps**—places in the seafloor where methane and other energy-rich fluids leak through the sediments. Cold seeps provide an energy source for chemosynthetic ecosystems that is every bit as bizarre and wonderful as hydrothermal vents. In fact, some of these ecosystems may survive for hundreds—maybe even thousands—of years. There has been considerable speculation about the mining of the reserves of the methane associated with cold seeps. But the environmental consequences and wisdom of unleashing yet another carbon-emitting energy source remain to be determined.

Methane (CH_4), a little-heralded molecule composed of one carbon and four hydrogen atoms, exerts a tremendous influence on Earth's atmosphere and plays an important role in food webs and carbon cycling in lakes and the ocean. In the atmosphere methane acts as a greenhouse gas, the second-most potent after carbon dioxide.

Methane caught scientists by surprise when it was found in frozen form at the bottom of the ocean as **methane hydrates**, molecules of methane gas trapped in crystals of water ice that form at reduced temperatures and elevated pressures. Nearly all the methane and methane hydrates found in ocean sediments originate from the activities of **methanogens**, a type of microbe that converts organic matter into methane. Methanogens can be found in the water column and in sediments at the seabed surface (e.g., Max and Johnson 2016; Niu et al. 2018). Reeburgh (2007) estimates that methanogens living in seafloor sediments produce a billion tons of methane annually.

The primary interest in methane hydrates—though undoubtedly important in deep-sea ecology—lies with their vast potential as an energy source. **Natural gas hydrate**, or NGH, as it is known in the energy industry, represents potentially the largest reservoir of unconventional gas on our planet (Max 2018). Even if only 15 percent of the world's reserves can be economically extracted, there is enough NGH on the seafloor to meet global energy needs for the next 200 years or longer (Max and Johnson 2016).

As of 2019, Japan and China have successfully extracted deep-sea methane in experimental test wells, but no technology currently exists for commercial extraction of NGH from the seabed. Nevertheless, given the vast reserves, the energy industry views NGH as a "bridge" energy source, one that will enable countries to make the transition from fossil fuels to renewable sources. As Max and Johnson (2016) put it:

> *A completely renewable energy future may be in our future, but its timing is very uncertain. . . . Natural gas is the clean hydrocarbon fuel that will reach into the renewable energy future. Its continued availability at affordable prices becomes increasingly important as coal and oil power plants are retired and energy demand becomes increasingly filled by development of renewable or intermittent power sources.*

Clearly, oceanographers have a lot more to discover and learn about the ocean and its resources. It is a frontier ripe for exploration and adventure—and a lot closer to home than the moon or Mars.

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7.8: Chapter References

Annan, Kofi A. 2000. *"We the Peoples": The Role of the United Nations in the 21st Century*. New York: United Nations. https://digitallibrary.un.org/record/413745?ln=en

Baines, Stephen B., Benjamin S. Twining, Mark A. Brzezinski, Jeffrey W. Krause, Stefan Vogt, Dylan Assael, and Hannah McDaniel. 2012. "Significant Silicon Accumulation by Marine Picocyanobacteria." *Nature Geoscience* 5: 886–891. https://doi.org/10.1038/ngeo1641

Bruland, K. W., and M. C. Lohan. 2006. "Controls of Trace Metals in Seawater." In *The Oceans and Marine Geochemistry, Treatise on Geochemistry*, Vol. 6. Edited by H. Elderfield, 23–47. Oxford: Elsevier. https://www.elsevier.com/books/the-oceans-and-marine-geochemistry/elderfield/978-0-08-045101-5

Carrano, Carl J., Stephen Schellenberg, Shady A. Amin, David H. Green, and Fritjof C. Küpper. 2009. "Boron and Marine Life: A New Look at an Enigmatic Bioelement." *Marine Biotechnology* 11: 431–440. https://doi.org/10.1007/s10126-009-9191-4

Chatt, J. 1979. "Recommendations for the Naming of Elements of Atomic Numbers Greater than 100." *Pure and Applied Chemistry* 51: 381–384. https://doi.org/10.1351/pac197951020381

Choi, Charles Q. 2022. "Why Does Soda Fizz?" LiveScience. July 22, 2022. https://www.livescience.com/32492-why-does-soda-fizz.html

Dittmar, William. 1884. "Part I. Report on Researches into the Composition of Ocean-Water, collected by H.M.S. *Challenger*, during the years 1873-1876." In *Report on the scientific results of the voyage of H.M.S. Challenger during the years 1873-76. Physics and chemistry*, Vol. 1. Edited by Thomson, C. Wyville, and John Murray. London: Order of Her Majesty's Government. https://escholarship.org/uc/item/38p2q583

Djeghri, Nicolas, Philippe Pondaven, Fabienne Le Grand, Antoine Bideau, Nolwenn Duquesne, Maria Stockemreiter, Stephan Behl, Jessica Y-T Huang, Thomas Hansen, Sharon Patris, Gerda Ucharm, and Herwig Stibor. 2021. "High Trophic Plasticity in the Mixotrophic *Mastigias papua*-Symbiodiniaceae Holobiont: Implications for the Ecology of Zooxanthellate Jellyfishes." *Marine Ecology Progress Series* 666: 73–88. https://doi.org/10.3354/meps13707

Engel, Anja, Hermann W. Bange, Michael Cunliffe, Susannah M. Burrows, Gernot Friedrichs, Luisa Galgani, Hartmut Mermann, Norbert Hertkorn, Martin Johnson, Peter S. Liss, Patricia K. Quinn, Markus Schartau, Alexander Soloviev, Christian Stolle, Robert C. Upstill-Goddard, Manuela van Pinxerton, and Birthe Zänker. 2017. "The Ocean's Vital Skin: Toward an Integrated Understanding of the Sea Surface Microlayer." *Frontiers in Marine Science* 4: 165. https://doi.org/10.3389/fmars.2017.00165

Falkowski, Paul G., Richard T. Barber, and Victor Smetacek. 1998. "Biogeochemical Controls and Feedbacks on Ocean Primary Production." *Science* 281(5374): 200–206. https://doi.org/10.1126/science.281.5374.200

Forchammer, Georg. 1865. "IV. On the composition of sea-water in the different parts of the ocean." *Philosophical Transactions of the Royal Society* 155: 203–262. https://doi.org/10.1098/rstl.1865.0004

Gillespie, Alison. 2022. "Antarctic Ozone Hole Slightly Smaller in 2022." NOAA. October 26, 2022. https://www.noaa.gov/news-release/antarctic-ozone-hole-slightly-smaller-in-2022

Hansell, Dennis A., Craig A. Carlson, Daniel J. Repeta, and Reiner Schlitzer. 2009. "Dissolved Organic Matter in the Ocean: A Controversy Stimulates New Insights." *Oceanography* 22(4): 202–211. https://doi.org/10.5670/oceanog.2009.109

Ikeda, Takeshi. 2021. "Bacterial Biosilicification: A New Insight into the Global Silicon Cycle." *Bioscience, Biotechnology, and Biochemistry* 85(6): 1324–1331. https://doi.org/10.1093/bbb/zbab069

Jeandel, Catherine, Michiel Rutgers van der Loeff, Phoebe J. Lam, Matthieu Roy-Barman, Robert M. Sherrell, Sven Kretschmer, Chris German, and Frank Dehairs. 2015. "What Did We Learn about Ocean Particles Dynamics in the GEOSECS-JGOFS Era?" *Progress in Oceanography* 133: 6–16. https://doi.org/10.1016/j.pocean.2014.12.018

Jones, Ian S. F. 2011. "Contrasting Micro- and Macro-Nutrient Nourishment of the Ocean." *Marine Ecology Progress Series* 425: 281–296. https://doi.org/10.3354/meps08882

Liao, Qian, and Binbin Wang. 2013. “Near Surface Turbulence and Gas Exchange Across the Air-Sea Interface.” In *Topics in Oceanography*. Edited by Enrico Zambianchi. London: Intertech. https://doi.org/10.5772/56415

Libes, Susan M. 2009. *Introduction to Marine Biogeochemistry*, 2nd ed. Burlington: Academic Press. https://www.elsevier.com/books/introduction-to-marine-biogeochemistry/libes/978-0-12-088530-5

Max, Michael D., and Arthur H. Johnson. 2016. *Exploration and Production of Oceanic Natural Gas Hydrate*. Cham: Springer. https://doi.org/10.1007/978-3-030-00401-9_1

Monterey Bay Aquarium Research Institute. 2023. “Periodic Table of Elements in the Ocean.” Accessed March 14, 2023. https://www.mbari.org/know-your-ocean/periodic-table-of-elements-in-the-ocean/

Moore, C. M., M. M. Mills, K. R. Arrigo, I. Berman-Franks, L. Bopp, P. W. Boyd, E. D. Galbraith, R. J. Geider, C. Guieu, S. L. Jaccard, T. D. Jickells, J. La Roche, T. M. Lenton, N. M. Mahowald, E. Marañón, I. Marinov, J. K. Moore, T. Nakatsuka, A. Oschlies, M. A. Saito, T. F. Thingstad, A. Tsuda, and O. Ulloa. 2013. “Processes and Patterns of Oceanic Nutrient Limitation.” *Nature Geoscience* 6: 701–710. https://doi.org/10.1038/ngeo1765; Supplementary information

Niu, Mingyang, Wenyue Liang, and Fenping Wang. 2018. “Methane Biotransformation in the Ocean and Its Effects on Climate Change: A Review.” *Science China Earth Sciences* 61: 1697–1713. https://doi.org/10.1007/s11430-017-9299-4

Pilson, Michael E. Q. 2013. *An Introduction to the Chemistry of the Sea*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139047203

Pytkowicz, Ricardo Marcos. 1962. “Effect of Gravity on Distribution of Salts in Sea Water.” *Limnology and Oceanography* 7(3): 434–435. https://doi.org/10.4319/lo.1962.7.3.0434

Reeburgh, William S. 2007. “Oceanic Methane Biogeochemistry.” *Chemical Reviews* 107(2): 486–513. https://doi.org/10.1021/cr050362v

Reynolds, Collin S. 2006. *The Ecology of Phytoplankton*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511542145

Sarmiento, Jorge L., and Nicolas Gruber. 2006. *Ocean Biogeochemical Dynamics*. Princeton: Princeton University Press. https://press.princeton.edu/books/hardcover/9780691017075/ocean-biogeochemical-dynamics

Scerri, Eric. 2013. “Cracks in the Periodic Table.” *Scientific American*. June 1, 2013. https://www.scientificamerican.com/article/cracks-in-the-periodic-table/

Schlesinger, William H., and Emily S. Bernhardt. 2012. *Biogeochemistry: An Analysis of Global Change*. 3rd ed. Waltham: Academic Press. https://www.elsevier.com/books/biogeochemistry/schlesinger/978-0-12-385874-0

Scott, Alexander. 1887. “XVIII. On the Composition of Water by Volume.” *Proceedings of the Royal Society of London* 42(251–257): 396–400. https://doi.org/10.1098/rspl.1887.0090

Smith, Craig R. 2007. “Bigger Is Better: The Role of Whales as Detritus in Marine Ecosystems.” In *Whales, Whaling, and Ocean Ecosystems*. Edited by James A. Estes, Douglas P. Demaster, Daniel F. Doak, Terrie M. Williams, and Robert L. Brownell, Jr. 286–300. Berkeley: University of California Press. https://doi.org/10.1525/9780520933200-026

Statista. 2022. “Bottled Water—Worldwide.” March 2022. https://www.statista.com/outlook/cmo/non-alcoholic-drinks/bottled-water/worldwide

Stats Medic. 2023. “Color Distribution for Various Types of M&Ms.” Accessed January 18, 2023. https://www.statsmedic.com/m-m-distribution

Sutton, Jill, Michael J. Ellwood, William A. Maher, and Peter L. Croot. 2010. “Oceanic Distribution of Inorganic Germanium Relative to Silicon: Germanium Discrimination by Diatoms.” *Global Biogeochemical Cycles* 24(2): GB2017. https://doi.org/10.1029/2009GB003689

Twining, Benjamin S., and Stephen B. Baines. 2013. “The Trace Metal Composition of Marine Phytoplankton.” *Annual Review of Marine Science* 5: 191–215. https://doi.org/10.1146/annurev-marine-121211-172322

Wallace, William J. 1974. *The Development of the Chlorinity/Salinity Concept in Oceanography*. Amsterdam: Elsevier. https://www.google.com/books/edition/The_Development_of_the_Chlorinity_salini/1RR7ngEACAAJ

Water Encyclopedia. 2023. "Tracers of Ocean-Water Masses." *Water Encyclopedia*. Accessed January 18, 2023. http://www.waterencyclopedia.com/St-Ts/Tracers-of-Ocean-Water-Masses.html

World Meteorological Organization (WMO). 2022. "Executive Summary." *Scientific Assessment of Ozone Depletion: 2022*. GAW Report No. 278. Geneva: WMO. https://csl.noaa.gov/assessments/ozone/2022/

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CHAPTER OVERVIEW

8: The Water Cycle and Ocean Salinity

There's a fairy tale told to Norwegian school children about how the sea came to be salty. In this tale, a greedy man steals a magic (and lucrative) salt grinder from his poor brother and escapes in a ship with the salt grinder on board. The magic salt grinder requires a secret spell to stop it, but the greedy brother ran off too quickly to learn the spell. Soon the ever-churning salt grinder fills the ship with salt and the ship sinks. All hands are lost, including the greedy brother. But the salt grinder—still waiting for the secret code—carries on at the bottom of the ocean. Over the centuries, the grinder churned and churned and churned, spilling salt into the deep, dark ocean. It still churns to this day. And that's how the ocean became salty.

People have long been curious about salt and the salty nature of seawater. In fact, salts—at least the dried kind found on land—have occupied the attention of humans for millennia. According to Mark Kurlansky, author of *Salt: A World History* (2004), human use of salt began in an arid region of China around 6000 BCE. People gathered salt from a seasonally dry lake bed and stored it in pots with fish and soybeans, producing what came to be known in modern times as soy sauce. Next time you sit down to a meal with soy sauce, consider that you are partaking in a tradition more than 8,000 years old.

Native Americans apparently used salt for various purposes, too. A historical marker in Redondo Beach, California, commemorates the location where native people gathered to collect salts for cooking, food preservation, trading, and other uses. In fact, as the sign points out, there are times in human history when salt was more valuable than gold. (I have trouble imagining pirates demanding the location of a treasure chest of salt, but that's another story.)

Salt remains an integral part of modern human cuisine. On your next grocery store visit, stop by the spice aisle and check out the different varieties of sea salts. My favorite is Himalayan sea salt. When I eat it, I feel like I am on top of the world. (You know, Himalayas . . . Mount Everest . . . highest mountain in the world? Oh, never mind.)

But where do those salts come from? And how does their concentration change from place to place and time to time in the world ocean? The answers lie ahead.

8.1: A Useful and Simple Model
8.2: The Global Water Cycle
8.3: The Three States of Water
8.4: Water, the Dissolver of Rocks
8.5: Salinity over Long Timescales
8.6: Salinity over Short Timescales
8.7: Airborne Sources of Salts
8.8: Biological Sources and Sinks
8.9: Residence Time
8.10: Measuring Salinity
8.11: The Global Water Crisis
8.12: Chapter References

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8.1: A Useful and Simple Model

Before we explore the comings and goings of salt in the ocean, it's helpful to formalize a conceptual model introduced in Chapter 6, what I call the **reservoir model**. It helps us understand beach sand budgets, salinity, the water cycle, and a whole lot more.

The reservoir model has three features:

- a **reservoir**, a place where something is stored
- a **source**, a process that increases the mass or volume of a reservoir
- a **sink**, a process that decreases the mass or volume of a reservoir

A fish tank, a swimming pool, and the ocean are all places where water is stored; they are reservoirs. The atmosphere is a reservoir for various gases. The solid Earth contains reservoirs of fossil fuels (oil, coal, and natural gas), diamonds, and other kinds of rocks and minerals. Energy reservoirs exist too. Chemical energy is stored in food and wood. Heat energy is stored in the ocean, the atmosphere, and land surfaces. Even human systems feature reservoirs. Your refrigerator is a reservoir of food. Your bank account is a reservoir of money.

The money metaphor illustrates an important property: reservoirs are not static. Practically speaking, a single number represents your money reservoir, but this reservoir may be subdivided into smaller reservoirs, such as checking, savings, loans, or retirement funds. If your checking account is anything like mine, the balance changes almost daily. Reservoirs represent a snapshot of a quantity at one place in a given moment of time.

Reservoirs may grow in volume, shrink, or remain the same. And that's where the various sources and sinks come into play. Sources, also known as inputs, add to a reservoir. Sinks, also known as outputs, subtract from a reservoir. The volume of material, energy, or some other quantity in a reservoir at any moment in time may be described by the following simple mathematical formula:

$$Vt_{reservoir} = Vt_{sources} - Vt_{sinks}$$

(Eq. 11.1)

where $Vt_{reservoir}$ is the volume of the reservoir at time, t, $Vt_{sources}$ is the sum of all additions to the reservoir at time, t, and Vt_{sinks} is the sum of all subtractions from the reservoir at time, t.

Consider the implications of this formula. What happens to the reservoir volume when sources are greater than sinks? What happens when sinks are greater than sources? What happens when sources and sinks are equal?

When sources exceed sinks, the volume of a reservoir may grow. More is added than is taken away. When sinks exceed sources, the volume of a reservoir may contract. More is being removed than is being added. But when the rate of addition is the same as the rate of removal, then the size of the reservoir remains the same.

Note that even though a reservoir may not be changing in size, it can still have active sources and sinks. Imagine you are adding water to a bathtub from a faucet but you've left the drain partially open. If the source (water in) exceeds the sink (water out), the bathtub will fill. If the water drains faster than it's being added by the faucet, the volume of water will fall. What happens when the faucet and drain flow at equal speeds? The volume in the bathtub will not change. Just because a reservoir is not visibly changing, it doesn't mean nothing is happening. The sources and sinks of a reservoir may be quite active and maintain a steady volume.

Let's use this model to think about exchanges of water in the ocean, the main reservoir for water on Earth's surface. If we combine sources and sinks, we get a simple equation that looks like this:

- ***Volume of ocean water = sources – sinks***
- ***(Eq. 11.2)***

Now this model may seem obvious and not very useful. But when we start talking about phenomena such as sea level rise, this simple model proves useful. The most profound scientific ideas often start with simple models.

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8.2: The Global Water Cycle

To understand the nature of salt in the ocean, we must talk about water, the substance that dissolves the salt. The **global water cycle** represents a model of the movement of water between various reservoirs on Earth's surface. Over days to decades, the global water cycle drives variations in salinity throughout the world ocean. Over longer periods, other processes account for salinity variations.

The water cycle describes where water resides, the processes that move water, and the rate at which these exchanges occur. The water cycle serves as the main vehicle by which the hydrosphere interacts with the atmosphere, cryosphere, geosphere, and biosphere. It represents water's journey from the ocean to the atmosphere to the land and back to the ocean again. It also serves as the means by which salts (and a variety of other things) move from land to sea. Fundamentally, it explains why some parts of the ocean are saltier than others.

Earth's Water Reservoirs

Seven important reservoirs for water exist on our planet. The largest reservoir exists in Earth's interior, the geosphere—perhaps as much as 18 oceans' worth (Peslier et al. 2017). But most of Earth's interior water is chemically bound to rock and cycles over scales of millions of years (e.g., Bodnar et al. 2013). So it doesn't factor into our discussion here. The water we consider here can be found just beneath, upon, and above Earth's surface, **Earth's surface reservoirs**.

As you undoubtedly know, the ocean basins hold the most water on Earth's surface. This includes the parts of the world ocean that freeze over in winter as sea ice. It also means that most of the water on our planet is salty. Solid water constitutes the second-largest surface reservoir. Snow, ice, and glaciers are the most familiar forms. Beneath our feet we find the third-largest reservoir of water on our planet's surface—**groundwater**. This reservoir proves most critical to humans as it provides much of our drinking water. The land surface water reservoir ranks fourth. Freshwater lakes, rivers, streams, and ponds make up this reservoir.

While people don't usually think about it as a place with water, the atmosphere is the fifth most plentiful reservoir. Water vapor, an invisible gas, surrounds us and makes our air humid. **Clouds**, a visible form of suspended liquid or solid water (i.e., ice crystals), provide an endless form of entertainment on a summer day. My favorite clouds look like whales. What are your favorites?

And we can't forget about one other important reservoir: the water contained in living matter—the biosphere. The amount is small—0.0003 percent, according to one estimate (Bodnar et al. 2013)—but life manipulates water in ways that the physical world doesn't. Life influences rates of evaporation, the formation of clouds, the severity of floods, and the impacts of waves and tides on coastal erosion. Of course, life cannot exist without water, and the availability of water determines when and where life may flourish. The intersection of water and life figures prominently in discussions of the biology of the ocean and climate change, so we'll place the biosphere sixth on our reservoir list.

Rank	Reservoir	Volume (cubic miles)	Percentage	Residence Time
1	Ocean	328,680,477	96.89	3,100 years
2	Glaciers/Ice Caps	7,965,104	2.35	1,900 years
3	Groundwater	2,519,084	0.74	690 years
4	Land Water	49,662	0.15	2 years
5	Atmosphere	3,119	0.001	9.5 days
6	Biosphere	1,128	0.0003	248 days
Total	All	339,218,574		

Pathways of Exchange between Reservoirs

These reservoirs all connect to each other, so each represents a potential source or sink to the others. Movement of water in or out of a given reservoir defines the pathways and rates of flow, or **fluxes**, between reservoirs. But let's make one thing clear from the outset: the global water cycle is primarily driven by interactions between the ocean and the atmosphere. More water evaporates from the ocean and more rain falls into the ocean than anywhere else on Earth. In fact, the amount of rain that falls on the ocean equals about 71 percent of the rain that falls on Earth (e.g., Boldnar 2013). This should come as no surprise. The ocean covers 71 percent of the planet's surface after all. So naturally the ocean will be more involved in the water cycle than the land. I stress this point because most illustrations of the water cycle emphasize the land. Now you know it's the ocean where most of the global water cycle takes place.

Let's consider the ways water enters and leaves the ocean. **Precipitation**, the gravity-driven descent of liquid or solid water out of the sky, moves water from the atmosphere to the ocean. Gravity drives the flow of liquid water from rivers and streams (and everything they carry) into the ocean. Gravity also causes water to flow through soil and porous rocks, a process called **infiltration**. This water then flows underground through **aquifers**, porous subsurface sediments that serve as reservoirs of water. These ultimately drain to the ocean. Gravity makes glaciers flow downhill, where they may break off directly into the ocean, a process called **calving**. Seaborne chunks of glaciers—**icebergs**—eventually melt. Glaciers also release **meltwater**—water that orignates from frozen sources—to the ocean, a contribution that is rapidly increasing due to global warming. And each day humans discharge hundreds of billions of gallons of **wastewater** into the ocean—water into which human waste and chemicals from homes and businesses have been discharged. Globally, at least half of this wastewater enters the ocean untreated (Jones 2021). **Surface runoff**—water that flows over the land surface—originates from rain, snowmelt, and even human activities, such as landscape irrigation. This water often carries nutrients and chemicals that enter the ocean.

The main pathway by which water leaves the ocean is **evaporation**, the conversion of liquid water into water vapor. Though hard to observe (water vapor is invisible to our eyes), you may see water vapor from a warm surface (a lake or a field) condense when colder air passes over it, a phenomenon known as **evaporation fog**, or steam fog. Water also returns to the atmosphere via the process of **transpiration**, the uptake of water by roots and its subsequent evaporation through the stems, leaves, and flowers of plants. Globally, trees release an average of 39 percent of the precipitation they receive back to the atmosphere (Schlesinger and Jasechko 2014). Finally, small amounts of ocean water may be temporarily stored in sea ice, glaciers, coastal groundwater, and even Earth's crust. The water cycle has more twists and turns than a Los Angeles freeway.

The Water Cycle Is Solar- and Gravity- Powered

In the global view, heat from the Sun and gravity supply the energy that drives the water cycle. The transformation of liquid water to water vapor and its subsequent transport by winds (also solar- powered) distribute water across the planet. Precipitation of water onto elevated land surfaces supply the gravity-driven flows.

The transformations of water between its three physical states prove important for understanding how heat moves around our planet. An understanding of these transformations can help you understand a lot about the world ocean and your everyday life.

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8.3: The Three States of Water

In our everyday experience, heating or cooling something results in a straightforward change in its temperature. But for water, heating and cooling may bring about changes in its **physical state**; that is, whether it's a solid, liquid, or gas.

By definition, **solids** maintain their own form. **Liquids** take the shape of the containers in which they are held. **Gases** also take the shape of their container, but they will expand to fill the container, while liquids will not. A fourth state of matter, **plasma**, consists of free-moving electrons and ions. Plasmas occur primarily in the upper atmosphere and outer space, although lightning and **St. Elmo's fire**—an electrical discharge from the masts of ships—also qualify as plasmas. We won't deal with plasmas here.

As far as we know, water is the only substance on Earth to occur in all three physical states at the same time:

- **ice**, the solid form of water
- **liquid water**, simply referred to as water
- **water vapor**, the gaseous form of water

Each of these states plays an important role in Earth and ocean processes. The transformations between these states occur at specific temperatures. However, as we shall see, it's a little more complicated than heating water to its boiling point or cooling it to its freezing point.

Specific Heat: Heat We Can Sense

Water's enormous importance in global heat exchange comes from its ability to absorb a high amount of heat. In fact, water ranks first in heat-absorbing capability among all liquids at environmental temperatures.

Scientists define the heat-absorbing abilities of a substance as **specific heat**, the amount of heat required to change the temperature of a given mass of a substance by 1 degree Celsius (°C; scientists use the symbol ° as a shorthand for degrees). Because specific heat changes the temperature of a liquid, we sometimes refer to it as **sensible heat**, heat that can be detected by instruments (or touch). We use the Celsius scale here to make calculations simple. By definition, the specific heat of water is one calorie per gram per degree Celsius. (Note that "calorie" is spelled with a little c to differentiate it from "Calorie," used for food, which is 1,000 times greater but often also styled as lowercase). In an honest-to-goodness physics course, you would use official scientific units—the **International System of Units**, or **SI units**, also known as the **metric system**—in which case you would learn that the specific heat of water is 4.186 joules per gram per degree Celsius. But given that it's hard enough for nonmajors (and even beginning science majors) to grasp the math, we'll stick to calories. My apologies to the physicists.

To help you visualize specific heat, imagine a spoon holding one cubic centimeter of water—roughly a fifth of a teaspoon—which has a weight of one gram. Warming it (carefully) over a flame and recording its temperature with a thermometer, a temperature increase of 1°C would indicate that you have added one calorie of heat. Another degree increase, another calorie. For each degree of temperature rise, you've added one calorie.

If you cool your gram of water, you can watch the temperature fall. One calorie of heat will be lost for every 1°C drop in temperature. If you start with a gram of water at room temperature—22°C (72 degrees Fahrenheit, °F)—and remove one calorie, its temperature will be 21°C. Remove another calorie, and its temperature will be 20°C. The math follows easily if you understand what is happening: remove heat, lower the temperature; add heat, raise the temperature.

Latent Heat: "Hidden" Heat

Specific heat applies to changes in temperature that occur when liquid water gains or loses heat. But what about ice and water vapor? How do the solid and gaseous forms of water interact with heat?

Here's where water gets really interesting. While the freezing and boiling points of water are set at specific temperatures—0°C (32°F) and 100°C (212°F), respectively—water doesn't just instantaneously transform into a different state. Additional heat must be removed or added to "rearrange" water molecules into their solid or gaseous form. Because the heat involved in transforming water into its solid or gaseous state does not register as a change in temperature, these forms of heat are referred to as **latent heat**. The term "latent" means "hidden," so we can think of latent heat as a kind of "invisible" heat, undetectable with a thermometer.

Two kinds of latent heat must be considered: the **latent heat of fusion**—the heat required to transform liquid water to a solid and vice versa—and the **latent heat of vaporization**—the heat required to transform liquid water to water vapor and back again.

Before ice or water vapor can form, heat must be removed or added, respectively, to rearrange the water molecules into their new physical states, a solid or a gas.

What's important to remember is that to make ice—to turn liquid water into solid water—not only must you remove enough calories to lower the temperature to the freezing point, but once you reach freezing, you must remove even more calories of heat to change the liquid to a solid. Similarly, to boil water—to turn liquid water into water vapor—you must add enough heat to raise its temperature to the boiling point and then add even more heat to turn the liquid water into water vapor.

How much heat? A lot! The latent heat of fusion for water is 80 calories per gram. The latent heat of vaporization is even more extraordinary: 540 calories per gram. That's 5.4 times the amount of heat required to take the liquid temperature of water from 0°C to 100°C. That means you have to remove 80 calories of additional heat after reaching 0°C (32°F) to turn one gram of liquid water into ice. At the other end of the temperature scale, you would need to add 540 calories of additional heat once you reach the boiling point to turn one gram of liquid water into water vapor.

Let's return to our fifth of a teaspoon of room temperature water. With a temperature of 22°C, you would need to remove 22 calories of heat to lower its temperature to 0°C (32°F). But to turn it into ice, you would need to remove another 80 calories. So, in total, you would need to remove 22+80 calories, or 102 calories, to turn one gram of room temperature water into ice.

To go the other direction, you would need to add 78 calories to reach the boiling point (100 degrees minus 22 degrees is a difference of 78 degrees). Then, you'll need to add 540 more calories to transform that gram of water into water vapor. That's a total of 78+540 calories, or 618 calories, to turn one gram of room temperature water into ice.

Why is latent heat important? When tropical water vapor carried by winds condenses at higher latitudes, it releases heat, keeping temperate and polar regions warm. Latent heat proves important in the formation and intensification of storms and hurricanes. It's integral to the integrity of polar ice caps, which can absorb a tremendous amount of heat. Once gone, the heat that once went into melting ice goes directly into the atmosphere. Finally, latent heat cools your body. When your body heats up during exercise, you sweat. When those sweat molecules gain enough heat, they vaporize, carrying latent heat with them. Heat is transferred more effectively from your body to the surrounding air because of latent heat transfer during sweating. Pretty cool, huh?

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8.4: Water, the Dissolver of Rocks

We now return to the main topic of our chapter. In addition to moving water, precipitation and evaporation of water drive the movement of salts into the ocean. Precipitation delivers water to Earth's surface, where it dissolves the soluble parts of rocks—a process called **chemical weathering** (discussed in Chapter 6). Once dissolved, the salts go where the water flows. Eventually, rivers, streams, and underground flows deliver those salts to the ocean. Over time, without processes to remove them, the salts build up.

The best evidence that salts in the modern ocean originated from continental rocks comes from an analysis of their chemical composition. If we compare the elements in continental rocks, the dissolved elements in rivers, and the elements dissolved in seawater (i.e., the major constituents), we discover that they are virtually identical. Their concentrations vary, but their major constituents—Na, Cl, and others—are largely the same.

Dissolved Substance	**Concentration (µM)**	**Total**	**Total flux 10^{12} mol yr^{-1}**	
	Natural	**Human**		
Cl^-	162	71	233	8.70
Na^+	224	89	313	11.71
SO_4^{2-}	68	52	120	4.48
Mg^{2+}	138	12	150	5.62
Ca^{2+}	334	33	367	13.72
K^+	33	2	35	1.31
HCO_3^-	852	17	869	32.49
Source:* *Pilson 2013				

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8.5: Salinity over Long Timescales

Why don't salts build up in the ocean? Why isn't the ocean becoming saltier? Just how has ocean salinity changed over long timescales—centuries to millennia?

To understand the answers to these questions, we must go back in time. We begin in a period of geologic time known as the **Archean**, an eon that stretched from 4 to 2.5 billion years ago. Earth's first ocean—presumably freshwater—formed from outgassing of water vapor from the interior. Subsequent cooling of that water vapor brought torrential rains that covered Earth's basaltic crust. Higher elevations—probably volcanoes—stuck up like islands, but there were no continents. At some point, Earth's crust began to cool, and an early form of plate tectonics took hold. The sinking, melting, and reworking of Earth's oceanic crust gave rise to a smallish amount of continental crust. The first continent was born—**Ur**, named by geologist John Rogers in 1996. At a billion and a half years old, the relatively new Earth had one enormous ocean and one small continent (Rogers 1996).

While this was happening, water began to dissolve the soluble components of Earth's crust. Eventually, whatever was soluble became dissolved in the ocean, and the ocean became salty. Hydrothermal vents—known to be present at least 3.2 billion years ago—added and subtracted their share of minerals, mostly NaCl. Some research suggests that the early ocean may have been twice as salty as the current ocean (e.g., Knauth 2005). Other evidence points to an Archean ocean remarkably similar to our modern one (e.g., Marty et al. 2018). We'll have to wait for further studies to get a definitive answer.

Over time, through plate tectonic conversion of oceanic crust, other continents appeared: Arctica, Baltica, and Atlantica. About a billion years ago, they collided and formed a supercontinent called **Rodinia**. While this supercontinent-building was going on, parts of the coastal ocean were cut off. Seawater in the resultant isolated basins was trapped. The trapped water evaporated, the salts were left behind, and vast salt deposits called **evaporites** were formed.

Through tectonic uplift of the land, the evaporite deposits became permanent parts of the continents. At certain periods during Earth's history, tectonic and climatic conditions were such that huge deposits of evaporites were formed, called **mega-evaporites**. You can find these vast deposits of salt in places like Australia, Oman, Iran, Pakistan, and beneath the Gulf of Mexico. During periods of mega-evaporite formation, the oceans got less salty.

The latest episodes of salinity reduction appear to have occurred in the Mesozoic during the breakup of the supercontinent **Pangea** (~250 million years ago) and later when the ice caps formed (~35 million years ago). Prior to the Mesozoic, salinity values may have ranged as high as 50 parts per thousand (ppt). By the early Miocene (~23 million years ago), salinity values had fallen to 37 to 39 ppt (e.g., Hay et al. 2006). Eventually, the sources of salt into the ocean balanced out the sinks. The salinity of the world ocean was established at the value that it is today, about 35 ppt. Though the salinity of the world ocean continues to change (the plates haven't stopped moving, and sea level is rising due to melting of glaciers and ice caps), it's reasonable to assume that over time periods of a few million years, the salinity of the ocean is constant.

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8.6: Salinity over Short Timescales

At shorter timescales—weeks to decades—oceanographers have a much clearer picture of the factors that change salinity in the ocean. For much of the ocean, two processes dominate: precipitation and evaporation. Because these processes occur at the surface of the ocean, they have their greatest effect on **sea surface salinity**, designated as **SSS**.

Unlike changes over geologic timescales, changes in SSS don't involve addition or removal of salts. Salinity varies by addition or removal of water at the ocean's surface. Precipitation and evaporation dilute and concentrate, respectively, the salts in seawater. Within any span of time, the ocean may experience both precipitation and evaporation. For this reason, oceanographers (and meteorologists, as it turns out) express the change in SSS as the difference between these two processes, or

$$\Delta SSS = E - P$$

(Eq. 11.3)

where SSS is sea surface salinity, E is evaporation, and P is precipitation.

Now, here's where it gets interesting. We can imagine three different scenarios:

E > P

E < P, or

E = P.

What happens to SSS in each of these?

If E > P, then SSS will increase.

If E < P, then SSS will decrease.

If E = P, then SSS will remain the same.

From this analysis, we may predict that differences in rates of precipitation and evaporation control surface salinity at a given location in the ocean. Observational data support this prediction. Recently compiled data on ocean salinity measured from ships, buoys, Argo floats, and satellite sensors demonstrate that the "freshest" regions of the ocean occur where precipitation dominates—that is, where E < P. Evaporation dominates in the saltiest regions, where E > P.

Of course, freshwater runoff modifies ocean salinity as well. For example, the Amazon River—the world's largest river by volume of discharge at about 55 million gallons per second (e.g., Giffard et al. 2019)—lowers SSS to a distance some 100 miles out to sea. Meltwater from glaciers and ice caps can decrease SSS too, though these effects tend to be highly localized.

Seasonal changes in sea ice extent also modify SSS. When seawater freezes in fall and winter (at a temperature of about -2°C), the salts come out of solution as brine—super-salty seawater. This process, called **brine rejection**, increases SSS. Of course, when sea ice melts in spring and summer, it releases freshwater into the surrounding ocean, lowering SSS.

Hydrothermal vents play a role in salinity variations, though their effects are not well established. Circulation of water within the region beneath the seafloor—the subseafloor environment—removes some elements and adds others. Black smokers and white smokers provide visual evidence of precipitation of elements as the warmer vent fluids interact with the cooler surrounding seawater. Seafloor observatories (Chapter 4) have begun to reveal the extent to which hydrothermal vents contribute heat, salts, and gases to the water column. These new findings suggest a more dynamic and significant role for vents than once thought (e.g., Spietz et al. 2018; Seyfried et al. 2022; Evans et al. 2023).

Finally, SSS data over the past half century reveal trends associated with a warming climate. Because warming amplifies certain climate signals, wetter regions have been getting wetter and drier areas have been getting drier. Ocean salinities are decreasing and increasing, respectively, in response to these changes (e.g., Durack and Wijffels 2010).

Though we've focused on the surface here, changes in SSS affect the entire ocean. Increases in surface salinity cause an increase in seawater density. And if surface waters become more dense than the waters beneath them, the surface waters sink, in some cases, all the way to the bottom. These sinking motions contribute to the abyssal circulation of the ocean.

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8.7: Airborne Sources of Salts

Other processes can also contribute elements to the ocean. Transport of **aeolian dust**, wind-suspended particles of silt, clay, and microorganisms, contributes a small but significant percentage of the substances found in the ocean. These inputs prove especially important to biogeochemical and sedimentary processes in the open ocean, where terrestrial influences are minimal.

British naturalist Charles Darwin (1809–1882) was among the first to publish observations of dust while aboard ship off North Africa. He was also the first to note the presence of microorganisms—"infusoria"—in the material (Darwin 1846):

> *From the several recorded accounts it appears that the quantity of dust which falls on vessels in the open Atlantic is considerable . . . Lieut. Arlett found the water so discolored that the track left by his ship was visible for a long time. . . . Professor Eherenberg . . . finds that it is in considerable part composed of Infusoria, including no less than sixty-seven different forms.*

With the advent of Earth-observing satellites, we now know that billions of tons of dust take to the sky from the major deserts of the world, especially the Sahara Desert in Africa, the Gobi Desert in Mongolia and China, and the Chihuahan Desert in Mexico (e.g., Goudie and Middleton 2006; Rivera Rivera et al. 2009; Ginoux et al. 2012; Wu et al. 2020). Emissions from automobiles, industrial activities, wildfires, and fallout from nuclear testing also contribute contaminants and radioactive particles to the atmosphere, where they may ride with the wind before settling into the ocean.

Dust from the Sahara can influence the development of hurricanes (e.g., Dunion and Velden 2004; Shu and Wu 2009) Iron in Saharan dust may fertilize the Amazon rain forest (e.g., Bristow et al. 2010). Clouds of Saharan dust may even cause regional climate variability (e.g., Evan et al. 2016). Some studies suggest that aeolian iron may contribute to increased productivity of phytoplankton in iron-poor, low-latitude regions of the ocean (e.g., Conway and John 2014). We're just beginning to understand the ways in which aeolian dust affects processes in the Earth system (e.g., Tagliabue et al. 2017; Liu et al. 2022; Adebiyi et al. 2023).

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8.8: Biological Sources and Sinks

Numerous biological processes alter the concentration of substances in the ocean. The first involves microscopic drifting photosynthetic microbes, the **phytoplankton**, introduced in Chapter 4. In the presence of sufficient sunlight and appropriate biologically important nutrients, phytoplankton carry out **photosynthesis**, the light-driven manufacture of organic compounds from inorganic carbon.

Different types of photosynthesis exist, with different pathways for different elements—like oxygen. So we have to be specific when talking about photosynthesis in the ocean. Photosynthetic reactions that yield oxygen are called **oxygenic photosynthesis**—oxygen-yielding photosynthesis. Contrast that with **anoxygenic photosynthesis**, which does not yield oxygen. Both use carbon dioxide, but only oxygenic photosynthesis releases oxygen as a byproduct.

Organisms that carry out oxygenic or anoxygenic photosynthesis are **autotrophs**, organisms capable of using external energy sources to manufacture their own cellular components from inorganic materials. Through photosynthesis autotrophs turn inorganic carbon—namely carbon dioxide—into organic carbon, the stuff of which all life is made. To be classified as a true autotroph, an organism must get at least 50 percent of its cellular carbon from carbon dioxide, according to microbiologists (e.g., Schönheit et al. 2016).

The autotrophs with which you are most familiar are plants—the green, multicellular organisms with leaves, trunks, and roots that you eat, smoke, pluck, sit under, weave into clothing, and use to build houses. Phytoplankton are autotrophs too and carry out photosynthesis at rates roughly equivalent to land plants.

Hard as it may be to fathom, phytoplankton supply about half of the oxygen in the atmosphere. Put another way, every other breath you take comes from phytoplankton. Other photosynthetic oceanic autotrophs, such as seaweeds, seagrasses, mangroves, and corals (with their photosynthetic symbionts), also contribute to the production of oxygen, about 3 percent globally (e.g., Malone et al. 2017). Of course, they also transform dissolved inorganic carbon into organic carbon. Because all of these autotrophs use light energy, they may be referred to as **photoautotrophs**, organic matter–making organisms that use sunlight as an energy source.

Another type of autotroph is the chemosynthetic autotroph, or **chemoautotroph**. Like plants and phytoplankton, chemoautotrophs fix inorganic carbon into organic carbon. However, they don't require light, and they don't produce oxygen. Instead, chemoautotrophs use chemical energy, such as methane or hydrogen sulfide. This process, called **chemosynthesis**, removes these dissolved gases from the water column and uses them as an energy source. While we commonly associate chemosynthesis with hydrothermal vents, exploration of the seafloor in recent decades has revealed several types of chemosynthetic communities, including whale falls, wood falls, and cold seeps (e.g., Dubilier 2008).

In addition to photosynthesis and chemosynthesis, a third biological process changes the concentrations of gases in the ocean. **Respiration**, the metabolic breakdown of organic matter to obtain energy, occurs in all living organisms. Sparing you the details, respiration produces carbon dioxide as a byproduct. Knowing whether the ocean acts as a net sink or source for carbon dioxide hinges on our understanding of respiration in the ocean.

Oxygen may be affected by respiration too. **Aerobic respiration**—the most common form—consumes oxygen as part of the metabolic process. Thus, aerobic respiration acts as a source of carbon dioxide and a sink for oxygen. **Anaerobic respiration**—breakdown of organic matter in the absence of oxygen, which occurs primarily within the seafloor—releases carbon dioxide but has no effect on oxygen concentrations.

A fourth process involves removal of dissolved substances as organisms construct their cellular materials. In making their cell walls, different groups of phytoplankton may use silica or calcium carbonate. Australia's Great Barrier Reef is the ultimate expression of the way in which organisms used dissolved materials to build homes. Of course, the different varieties of mollusks, from clams and oysters to any of the prized varieties of seashells, represent sinks for dissolved elements. In truth, nearly every organism in the ocean at one time or another may serve as a source, sink, or both.

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8.9: Residence Time

Just like relatives who come to visit, it's useful to know how long a substance remains in a given reservoir. (Will they ever leave?) For that, we turn to calculations of **residence time**, the average time an element (or anything, really) spends in a reservoir. In essence, we're figuring out how long a given element spends in the ocean from the time it arrives by air or river to the time it leaves by way of a geological or biological process. Our reservoir model once again serves as a convenient way of understanding this idea.

Just like water enters your bathtub, hangs around while you splash and clean, then exits the tub via the drain, dissolved substances in the ocean have a residence time. Scientists define residence time as the amount of time a molecule spends in a reservoir. This concept has a wide variety of applications from engineering to medical to environmental. Residence time helps us understand the movements of various chemicals, drugs, or contaminants in human and biological systems.

A simple way to describe residence time mathematically is to consider what happens at steady state—that is, when the sources and sinks are in balance. In this case, we can define the average residence time (Rt) as:

Rt (years) = Amount of element (kilograms)/Rate of input or output (kilograms/years)

(Eq. 11.4)

According to the Periodic Table of Ocean Elements website (Chapter 10), the residence time of chloride in the ocean is about 87 million years. A given sodium molecule spends about 55 million years from source to sink. Other elements have shorter residence times. Iron, for example, spends from 200 to 500 years in the ocean before being cycled out.

This formula can be used to compute the residence time of water too. On average, a water molecule spends 3,100 years floating around in the world ocean reservoir before it's evaporated (Bodnar et al. 2013).

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8.10: Measuring Salinity

As noted in Chapter 10, chemical oceanographers were thrilled when they discovered that by using the Principle of Constant Proportions, they only had to measure one major constituent in the ocean to obtain the concentrations of the rest. But advances in the 20th century gave oceanographers a tool that provided an instantaneous readout of seawater salinity.

In 1729, Stephen Gray (1666–1736), a little-appreciated British chemist, discovered that electricity could flow through a wire, a property called **electrical conductivity**. By the 19th century, the power of that discovery would be fully harnessed. The Transatlantic Cable, completed in 1858, and the "wireless telegraph," such as the one used aboard the *Titanic*, serve as two historic applications of electrical conductivity. Another application was driven by a need to measure the salinity of water in boilers aboard ships. A buildup of salt deposits can damage boilers. To solve this problem, engineers developed the first **salinometers**, instruments for measuring salinity.

Driven by an interest to use salinometers in the ocean, American physicist Frank Wenner (1873–1954) and oceanographers Rear Admiral Edward "Iceberg" Smith (1889–1961) and Captain Floyd Soule (1901–1968) published in 1930 *Apparatus for the Determination aboard Ship of the Salinity of Sea Water by the Electrical Conductivity Method* (Wenner et al. 1930). In doing so, they set the stage for one of the most important measurements in the ocean today.

Salinometers, also known as conductivity meters, measure the "strength" of electrical conductivity—that is, how quickly a material conducts electricity. Because seawater contains charged molecules—cations and anions—it acts as a weak conductor of electricity. In a salinometer, electrical conductance is measured as the flow of electricity through a wire connected at each end to pieces of metal called **electrodes**. Because the electrodes are separated by a gap, no electricity will flow through the wire unless a conductor, such as seawater, is present in the gap. By submersing the electrodes in seawater, a current is generated that is proportional to the concentration of salts in the seawater: the greater the conductance, the greater the salinity.

But simply knowing that a solution conducts electricity doesn't get you very far. The key to making a salinometer useful lies in **calibration**, a method used to determine the quantitative relationship between conductivity and salinity. When you place a conductivity probe into a sample of seawater, you want to know that the number you read on the meter matches the real salinity of the sample. To do that, oceanographers calibrate their conductivity meters using solutions with a known salinity. Placing the conductivity meter into a solution with a known salinity permits the instrument to be adjusted so it displays and records an accurate salinity.

The most common solution used for calibration by oceanographers is something called **standard seawater**. It's obtained from the North Atlantic Ocean, modified to precise specifications, and sold by a single company. That single source ensures that oceanographers around the world can calibrate their instruments with identical seawater. Standard seawater has an accuracy of ±0.0003, meaning any one bottle of standard seawater may differ from others by ±0.0003.

For decades the salinity of the ocean was reported in parts per thousand. Thus, if a sample of water has a salinity of 10 ppt, it's made up of 990 parts water and 10 parts salt. Those units remain popular among some oceanographers and in other fields of study that require measurements of salinity. However, in 1978, oceanographers adopted the **practical salinity scale**, which reports salinity as a ratio of the conductivity of standard seawater to that of a precise concentration of potassium chloride (e.g., Millero et al. 2008). The practical salinity scale, unlike the traditional salinity scale, has no units. Thus, you can choose to report the average salinity of the ocean as 35 ppt, if you're old school, or 35, if you're new school.

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8.11: The Global Water Crisis

Despite the seeming abundance of water, as many as four billion people experience severe water shortages at least one month out of the year. From one to four billion people struggle to find water at any time of the year. At least 193 cities in 16 countries representing a third of the world's population lack sufficient water for drinking, agriculture, and industry (Mekonnen and Hoekstra 2016; He et al. 2021). Major cities such as Cape Town, South Africa; São Paolo, Brazil; and Chennai, India, face what has come to be known as **Day Zero**, the day that a city's municipal water supply runs dry. An assessment of water supply and demand in a dozen **megacities**—cities whose populations exceed 10 million—revealed that 11 of them currently use more water than they can supply (Ahmadi et al. 2020). The lack of water for billions of people across the globe has been called the **global water crisis**, a term that emerged in the 1990s (Bruns and Frick 2014).

"All Water Problems Are Local"

Though important, the notion of a global water shortage "is of little practical utility," according to Gleick and Palanniappan (2010). That's because supply and demand aren't matched on global scales (Gleick 2018). With few exceptions, humans obtain their water near a local source: the ground, a lake, a river, a reservoir. As Charles Fishman, author of *The Big Thirst: The Secret Life and Turbulent Future of Water* (2011), puts it, "All water problems are local."

The availability of water in a region depends on three major factors (following Gleick 2018):

- The operation of the water cycle—the relative rates of evaporation and precipitation that remove water from and add it to a reservoir.
- The demand for water—a complex function of population size, primary uses of water (e.g., household, agricultural, or industrial), social factors (e.g., landscape types, rural-to-urban transition), and economic factors (i.e., adoption of water reclamation and conservation technologies).
- The availability of technology for improving water use or supply.

Though highly simplified, this conceptual model of water supply helps frame the problems facing management of water resources.

Water Scarcity

The mismatch between supply and demand on a regional basis drives **water scarcity**—a lack of sufficient water in a region for any number of purposes (e.g., United Nations 2023). Shortages of water raise issues of **water security**, the ability of a community to protect access to sustainable quantities of water for practical and peaceful purposes (e.g., United Nations University 2013). In places where water scarcity is prolonged or severe, disputes over water—**water conflicts**—may occur.

Though other sociopolitical issues contribute to tensions between countries, states, or groups, scarcity has arguably led to an increase in water conflicts since the 1990s (e.g., Levy and Sidel 2011). Most disputes can be settled peacefully, but some—such as the conflicts in Syria and Yemen affecting tens of millions of people—underscore the ways in which water scarcity can ignite tensions and fuel violence (e.g., Gleick 2014). In such conflicts, water and water-generated energy supplies (i.e., dams) become centerpieces of military tactics for gaining an advantage over an enemy. Unfortunately, civilian populations suffer the most in these conflicts. Despite the challenges, there is hope for "peaceful sharing and management of water" in at least some parts of the world (e.g., Boretti and Rosa 2019; Angelakis et al., 2021; United Nations 2022).

Desalination: Freshwater from the Ocean

A full exploration of the ways in which governments and municipalities are grappling with water shortages is beyond the scope of our discussion here. But one strategy in particular has gained attention in recent decades. Because it involves salts and the ocean, I include it here.

With water supplies increasingly vulnerable to climate change, or where other water resources are scarce or limited, **desalination**—the removal of salts from seawater to produce freshwater—has emerged as one solution (e.g., Darre and Toor 2018; Eke et al. 2020). In extremely arid countries—such as Qatar, Kuwait, the United Arab Emirates, and Saudi Arabia—desalination provides more than half of the freshwater needs (e.g., Darwish et al. 2012; Mannan et al. 2019; Tariq et al. 2022).

More than 20,000 desalination plants—currently operational or under construction—exist in 181 countries around the world, including the United States (e.g., Eke et al. 2020). In fact, the US generates more than 11 percent of the freshwater produced

globally. Florida, California, and Texas account for most desalination (68 percent), but plants can be found in 32 other states as well (as of 2018; see Mickley 2018). California hosts a dozen existing and four proposed desalination plants (California Water Boards 2023b). The largest plant can be found in the US in Carlsbad, California, which supplies 400,000 San Diego County residents with about 50 million gallons of water daily (California Water Boards 2023a). Though not without controversy, two additional seawater desalination facilities are planned for Southern California: the West Basin Ocean Water Desalination Project (El Segundo) and the Doheny Ocean Desalination Project (Dana Point). On December 9, 2022, the California State Lands Commission approved a permit for construction of the Doheny plant. Once operational, the facility will supply five million gallons of water daily (South Coast Water District 2023).

Theoretically, the supply of water available for desalination is as big as the ocean. Unlike technologies that recycle wastewater, desalinated water is "new" water. It doesn't depend on evaporation and precipitation via the water cycle. It's also relatively climate-independent. Desalination can be maintained regardless of changes in climate as long as an energy source is available (e.g., Jones et al. 2021; Ghazi et al. 2022).

Desalination technologies generally fall into one of two categories: (1) **thermal-based desalination**, heating and evaporating seawater and recovering the water vapor; and (2) **membrane-based technologies**, using pressure to push seawater through a **semipermeable membrane**, a kind of filter which separates the salts from the water. Thermal technologies—the oldest form of desalination—work well in locations, such as North and East Africa and the Middle East (e.g., Xu et al. 2013; (Reif and Alhalabi 2015). Thermal-based desalination plants are often built adjacent to power plants to ensure a steady supply of energy. Membrane-based desalination plants have a lower energy requirement—though still high compared to conventional ways of obtaining water (e.g, Voutchkov 2018). This makes them more popular outside of the Middle East. The highest percentage of existing and planned desalination plants use membrane technologies (e.g, Eke et al. 2020).

Among membrane-based technologies, **reverse osmosis systems** (RO)—moving water against a concentration gradient (the opposite of osmosis)—are the most popular. In fact, RO systems exist for household, industrial, and military water purification. As described in Darre and Toor (2018), RO desalination plants typically require pretreatment of the intake seawater to remove particles, microbes, and other substances that may foul the membrane filter. The pretreated water is then pumped at high pressure through a membrane with pores large enough to permit water molecules to pass but too small for salts. The process results in production of both freshwater and brine.

A number of economic, technical, and environmental challenges complicate the acceptance of desalination as a competitive and sustainable source of water (e.g., Xu et al. 2013; Darre and Toor 2018). Its high energy requirements have raised concerns over costs in a future with rising energy prices. Plants may also produce greenhouse gas emissions in a world increasingly seeking to reduce them. Aende et al. (2020) note that the energy used by the Carlsbad desalination plant could power 20,000 homes. While solar-powered desalination plants hold promise, a number of factors, including intermittent availability of the Sun and seasonal and latitudinal variations in solar intensity, continue to hamper their implementation.

Disposal or reuse of **brine**—the salty syrup that remains once water has been extracted—has also been raised as a concern (e.g., Jones et al. 2021). In high-energy coastal environments, brine may be piped through diffusers, which help to mix and dilute it in the surrounding seawater. But this option is not available in low-energy environments, where toxins in the brine may harm marine organisms (e.g., Darre and Toor 2018; Delgado et al. 2020). In some cases, brine may be converted to rock salt and other products, but the volume of brine produced may exceed demand (e.g., Xu et al. 2013).

Finally, pumping seawater from the ocean may unintentionally remove large quantities of plankton and larvae that form the base of marine food webs. Prior to construction of the Carlsbad plant, scientists raised concerns about potential negative effects on the productivity of a nearby marine protected area (e.g., Darre and Toor 2018).

Future proposals for desalination plants will continue to raise concerns about cost effectiveness, energy demand, greenhouse gas contributions, brine disposal, and harm to the marine environment, especially in California. The Huntington Beach desalination plant—first proposed in 1998—met with considerable opposition from environmental groups, citizens, and taxpayer groups. They argued that the plant would raise water costs, displace Latine neighborhoods, and harm marine life (Symon 2020). Proponents argued that desalination is necessary to avert water shortages (Alvarado 2020). Ultimately, the Coastal Commission rejected the project in May 2022 (Becker 2022).

Despite the negative perceptions of desalination, some researchers argue that these challenges can be overcome. As renewable energy sources develop and brine disposal methods improve, the costs and environmental harm of desalination will be reduced (e.g., Pistocchi et al. 2020). Like any new technology, desalination will benefit from ongoing critical review and additional research to overcome its challenges (e.g., Darre and Toor 2018). However, like any technological fix, desalination may be a temporary solution. Ultimately, humans will need to make difficult choices about how we create a sustainable water supply in the 21st century (e.g., Pistocchi et al. 2020).

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8.12: Chapter References

Adebiyi, Adeyemi, Jasper F. Kok, Benjamin J. Murray, Claire L. Ryder, Jan-Berend W. Stuut, Ralph A. Kahn, Peter Knippertz, Paola Formenti, Natalie M. Mahowald, Carlos Pérez García-Pando, Martina Klose, Albert Ansmann, Bjørn H. Samset, AkinoriIto, Yves Balkanski, Claudia Di Biagio, Manolis N. Romanias, Yue Huang, and Jun Meng. 2023. "A Review of Coarse Mineral Dust in the Earth System." *Aeolian Research* 60: 100849. https://doi.org/10.1016/j.aeolia.2022.100849

Aende, Aondohemba, Jabbar Gardy, and Ali Hassanpour. 2020. "Seawater Desalination: A Review of Forward Osmosis Technique, Its Challenges, and Future Prospects." *Processes* 8(8): 901. https://doi.org/10.3390/pr8080901

Ahmadi, Mohammad Sadeq, Janez Sušnik, William Veerbeek, and Chris Zevenbergen. 2020. "Towards a Global Day Zero? Assessment of Current and Future Water Supply and Demand in 12 Rapidly Developing Megacities." *Sustainable Cities and Society* 61: 102295. https://doi.org/10.1016/j.scs.2020.102295

Alvarado, Gloria. 2020. "Desalination Plant in Orange County Will Help Ensure Clean Drinking Water." Calmatters. October 16, 2020. https://calmatters.org/commentary/my-turn/2020/10/desalination-plant-in-orange-county-will-help-ensure-clean-drinking-water/

Angelakis, Andreas N., Mohammad Valipour, Abdelkader T. Ahmed, Vasileios Tzanakakis, Nikolaos V. Paranychianakis, Jens Krasilnikoff, Renato Drusiani, Larry Mays, Fatma El Gohary, Demetris Koutsoyiannis, Saifullah Khan, and Luigi Joseph Del Giacco. 2021. "Water Conflicts: From Ancient to Modern Times and in the Future." *Sustainability* 13(8): 4237. https://doi.org/10.3390/su13084237

Becker, Rachel. 2022. "A Salty Dispute: California Coastal Commission Unanimously Rejects Desalination Plant." Calmatters. May 12, 2022. https://calmatters.org/environment/2022/05/california-desalination-plant-coastal-commission/

Bodnar, Robert J., Tristan Azbej, Stephen P. Becker, Claudia Cannatelli, András Fall, and Matthew J. Severs. 2013. "Whole Earth Geohydrologic Cycle, from the Clouds to the Core: The Distribution of Water in the Dynamic Earth System." In *The Web of Geological Sciences: Advances, Impacts, and Interactions*. Edited by Marion Bickford. Washington, DC: Geological Society of America. https://doi.org/10.1130/2013.2500(13)

Boretti, Alberto, and Lorenzo Rosa. 2019. "Reassessing the Projections of the World Water Development Report." *NPJ Clean Water* 2: 15. https://doi.org/10.1038/s41545-019-0039-9

Bristow, Charlie S., Karen A. Hudson-Edwards, and Adrian Chappell. 2010. "Fertilizing the Amazon and Equatorial Atlantic with West African Dust." *Geophysical Research Letters* 37(14): LI4807. https://doi.org/10.1029/2010GL043486

Bruns, Antje, and Fanny Frick. 2014. "The Notion of the Global Water Crisis and Urban Water Realities." In *The Global Water System in the Anthropocene*. Edited by A. Bhaduri, J. Bogardi, J. Leentvaar, and S. Marx, 415–426. Cham: Springer. https://doi.org/10.1007/978-3-319-07548-8_27

California Water Boards. 2023a. "Carlsbard Desalination Plant." California Water Boards. Accessed January 21, 2023. https://www.waterboards.ca.gov/sandiego/water_issues/programs/regulatory/carlsbad_desalination.html

———. 2023b. "Ocean Plan Requirements for Seawater Desalination Facilities." California Water Boards. Accessed January 21, 2023. https://www.waterboards.ca.gov/water_issues/programs/ocean/desalination/

Conway, Tim M., and Seth G. John. 2014. "Quantification of Dissolved Iron Sources to the North Atlantic Ocean." *Nature* 511: 212–215. https://doi.org/10.1038/nature13482

Darre, Natasha C., and Gurpal S. Toor. 2018. "Desalination of Water: A Review." *Current Pollution Reports* 4: 104–111. https://doi.org/10.1007/s40726-018-0085-9

Darwin, Charles. 1846. "An Account of the Fine Dust which Often Falls on Vessels in the Atlantic Ocean." *Journal of the Geological Society* 2: 26–30. https://doi.org/10.1144/GSL.JGS.1846.002.01-02.09

Darwish, M. A., Ali Darwish, and Amina Darwish. 2012. "Fifty Years of MSF Desalination in Kuwait and Sustainability Issues." *Desalination and Water Treatment* 29(1–3): 343–354. https://doi.org/10.5004/dwt.2011.2915

Delgado, William R., Timothy Beach, and Sheryl Luzzadder-Beach. 2020. “Solar Desalination: Cases, Synthesis, and Challenges.” *WIREs Water* 7(3): e1434. https://doi.org/10.1002/wat2.1434

Dubilier, Nicole, Claudia Bergin, and Christian Lott. “Symbiotic Diversity in Marine Animals: The Art of Harnessing Chemosynthesis.” *Nature Reviews Microbiology* 6: 725–740. https://doi.org/10.1038/nrmicro1992

Dunion, Jason P., and Christopher S. Velden. 2004. “The Impact of the Saharan Air Layer on Atlantic Tropical Cyclone Activity.” *Bulletin of the American Meteorological Society* 85(3): 353–366. https://doi.org/10.1175/BAMS-85-3-353

Durack, Paul J., and Susan E. Wijffels. 2010. “Fifty-Year Trends in Global Ocean Salinities and Their Relationship to Broad-Scale Warming.” *Journal of Climate* 23(16): 4342–4362. https://doi.org/10.1175/2010JCLI3377.1

Eke, Joyner, Ahmed Yusuf, Adewale Giwa, and Ahmed Sodiq. 2020. “The Global Status of Desalination: An Assessment of Current Desalination Technologies, Plants and Capacity.” *Desalination* 495: 114633. https://doi.org/10.1016/j.desal.2020.114633

Evan, Amato T., Cyrille Flamant, Marco Gaetani, and Françoise Guichard. 2016. “The Past, Present, and Future of African Dust.” *Nature* 531: 493–495. https://doi.org/10.1038/nature17149

Evans, Guy. N., William E. Seyfried Jr., and Chunyang Tan. 2023. “Nutrient Transition Metals in a Time Series of Hydrothermal Vent Fluids from Main Endeavour Field, Juan de Fuca Ridge, Pacific Ocean.” *Earth and Planetary Science Letters* 602: 117943. https://doi.org/10.1016/j.epsl.2022.117943

Fishman, Charles. 2011. *The Big Thirst: The Secret Life and Turbulent Future of Water*. New York: Free Press. https://www.simonandschuster.com/books/The-Big-Thirst/Charles-Fishman/9781439102084

Ghazi, Zeyad Moustafa, Syed Warisha Fatima Rizvi, Wafa Mohammad Shahid, Adil Muhammad Abdulhameed, Haleema Saleem, and Syed Javaid Zaidi. 2022. “An Overview of Water Desalination Systems Integrated with Renewable Energy Sources.” *Desalination* 542: 116063. https://doi.org/10.1016/j.desal.2022.116063

Giffard, Pierrick, William Llovel, Julien Jouanno, Guillaume Morvan, and Bertrand Decharme. 2019. “Contribution of the Amazon River Discharge to Regional Sea Level in the Tropical Atlantic Ocean.” *Water* 11(11): 2348. https://doi.org/10.3390/w11112348

Ginoux, Paul, Joseph M. Prospero, Thomas E. Gill, N. Christina Hsu, and Ming Zhao. 2012. “Global-Scale Attribution of Anthropogenic and Natural Dust Sources and Their Emission Rates Based on MODIS Deep Blue Aerosol Products.” *Review of Geophysics* 50(3): RG3005. https://doi.org/10.1029/2012RG000388

Gleick, Peter H. 2014. “Water, Drought, Climate Change, and Conflict in Syria.” *Weather, Climate, and Society* 6(3): 331–340. https://doi.org/10.1175/WCAS-D-13-00059.1

———. 2018. “Transitions to Freshwater Sustainability.” *PNAS* 115(36): 8863–8871. https://doi.org/10.1073/pnas.1808893115

Gleick, Peter H., and Meena Palaniappan. 2010. “Peak Water Limits to Freshwater Withdrawal and Use.” *PNAS* 107(25): 11155–11162. https://doi.org/10.1073/pnas.1004812107

Goudie, Andrew S., and Nicholas Middleton. 2006. *Desert Dust in the Global System*. Heidelberg: Springer Berlin. 288 pages. https://doi.org/10.1007/3-540-32355-4

Hay, William W., Areg Migdisov, Alexander N. Balukhovsky, Christopher N. Wold, Sascha, Flögel, and Emanuel Söding. 2006. “Evaporites and the Salinity of the Ocean during the Phanerozoic: Implications for Climate, Ocean Circulation, and Life.” *Paleogeography, Paleoclimatology, Paleoecology* 240(1–2): 3–46. https://doi.org/10.1016/j.palaeo.2006.03.044

He, Chunyang, Zhifeng Liu, Jianguo Wu, Zihang Fang, Jingwei Li, and Brett A. Bryan. 2021. “Future Global Urban Water Scarcity and Potential Solutions.” *Nature Communications* 12: 4667. https://doi.org/10.1038/s41467-021-25026-3

Jones, Edward R., Michelle T. H. van Vliet, Manzoor Qadir, and Marc F. P. Bierkens. 2021. “Country-Level and Gridded Estimates of Wastewater Production, Collection, Treatment, and Reuse.” *Earth System Science Data* 13: 237–254. https://doi.org/10.5194/essd-13-237-2021

Knauth, Paul. 2005. “Temperature and Salinity History of the Precambrian Ocean: Implications for the Course of Microbial Evolution.” *Paleogeography, Paleoclimatology, Paleoecology* 219(1–2): 53–69. https://doi.org/10.1016/j.palaeo.2004.10.014

Kurlansky, Mark. 2004. *Salt: A World History*. London: Penguin Books. https://www.penguinrandomhouse.com/books/286432/salt-by-mark-kurlansky/

Levy, Barry S., and Victor W. Sidel. 2011. "Water Rights and Water Fights: Preventing and Resolving Conflicts Before They Boil Over." *American Journal of Public Health* 101(5): 778–280. https://doi.org/10.2105%2FAJPH.2010.194670

Liu, Minxu, Hitoshi Matsui, Douglas S. Hamilton, Kara D. Lamb, Sagar D. Rathod, Joshua P. Schwarz, and Natalie M. Mahowald. 2022. "The Underappreciated Role of Anthropogenic Sources in Atmospheric Soluble Iron Flux to the Southern Ocean." *NPJ Climate and Atmospheric Science* 5: 28. https://doi.org/10.1038/s41612-022-00250-w

Mannan, Mehzabeen, Mohamed Alhaj, Abdel Nasser Mabrouk, and Sami G. Al-Ghamdi. 2019. "Examining the Life-Cycle Environmental Impacts of Desalination: A Case Study in the State of Qatar." *Desalination* 452: 238–246. https://doi.org/10.1016/j.desal.2018.11.017

Marty, Bernard, Guillaume Avice, David V. Bekaert, and Michael W. Broadley. 2018. "Salinity of the Archaean Oceans from Analysis of Fluid Inclusions in Quartz." *Comptes Rendus Geoscience* 350(4): 154–163. https://doi.org/10.1016/j.crte.2017.12.002

Mekonnen, Mesfin M., and Arjen Y. Hoekstra. 2016. "Four Billion People Facing Severe Water Scarcity." *Science Advances* 2(2): e1500323. https://doi.org/10.1126/sciadv.1500323

Mickley, Michael. 2018. *Updated and Extended Survey of US Municipal Desalination Plants*. Desalination and Water Purification Research and Development Program Report No. 207. Denver: US Department of the Interior. https://www.usbr.gov/research/dwpr/reportpdfs/report207.pdf

Millero, Frank J., Rainer Feistel, Daniel G. Wright, and Trevor J. McDougall. 2008. "The Composition of Standard Seawater and the Definition of the Reference-Composition Salinity Scale." *Deep Sea Research Part I: Oceanographic Research Papers* 55(1): 50–72. https://doi.org/10.1016/j.dsr.2007.10.001

Peslier, Anne H., Maria Schönbächler, Henner Busemann, and Shun-Ichiro Karato. 2017. "Water in the Earth's Interior: Distribution and Origin." *Space Science Reviews* 212: 743–810. https://doi.org/10.1007/s11214-017-0387-z

Pilson, Michael P. Q. 2013. *An Introduction to the Chemistry of the Sea*. 2nd ed. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139047203

Pistocchi, A., T. Bleninger, C. Breyer, U. Caldera, C. Dorati, D. Ganora, M. M. Millán, C. Paton, D. Poullis, F. Salas Herrero, M. Sapiano, R. Semiat, C. Sommariva, S. Yuece, and G. Zaragoza. 2020. "Can Seawater Desalination Be a Win-Win Fix to Our Water Cycle?" *Water Research* 182: 115906. https://doi.org/10.1016/j.watres.2020.115906

Reif, John H., and Wadee Alhalabi. 2015. "Solar-Thermal Powered Desalination: Its Significant Challenges and Potential." *Renewable and Sustainable Energy Reviews* 48: 152–165. https://doi.org/10.1016/j.rser.2015.03.065

Rivera Rivera, Nancy I., Thomas E. Gill, Kristi A. Gebhart, Jennifer L. Hand, Max P. Bleiweiss, and Rosa M. Fitzgerald. 2009. "Wind Modeling of Chihuahuan Desert Dust Outbreaks." *Atmospheric Environment* 43(2): 347–354. https://doi.org/10.1016/j.atmosenv.2008.09.069

Rogers, John J. W. 1996. "A History of Continents in the Past Three Billion Years." *Journal of Geology* 104(1): 91–107. https://doi.org/10.1086/629803

Schlesinger, William H., and Scott Jasechko. 2014. "Transpiration on the Global Water Cycle." *Agricultural and Forest Meteorology* 189–190: 115–117. https://doi.org/10.1016/j.agrformet.2014.01.011

Schönheit, Peter, Wolfgang Buckel, and William Martin. 2016. "On the Origin of Heterotrophy." *Trends in Microbiology* 24(1): P12–25. https://doi.org/10.1016/j.tim.2015.10.003

Seyfried, William E. Jr., Chunyang Tan, Xun Wang, Shijun Wu, Guy N. Evans, Laurence A. Coogan, Steven F. Mihály, and Marvin D. Lilley. 2022. "Time Series of Hydrothermal Vent Fluid Chemistry at Main Endeavour Field, Juan de Fuca Ridge: Remote Sampling Using the NEPTUNE Cabled Observatory." *Deep Sea Research Part I: Oceanographic Research Papers* 186: 103809. https://doi.org/10.1016/j.dsr.2022.103809

Shu, Shoujuan, and Liguang Wu. 2009. "Analysis of the Influence of Saharan Air Layer on Tropical Cyclone Intensity Using AIRS/Aqua Data." *Geophysical Research Letters* 36(9): L09809. https://doi.org/10.1029/2009GL037634

South Coast Water District. 2023. “Doheny Ocean Desalination Project.” South Coast Water District. Accessed January 21, 2023. https://www.scwd.org/about/district_projects/doheny_ocean_desalination_project/index.php

Spietz, Rachel L., David A. Butterfield, Nathaniel J. Buck, Benjamin I. Larson, William W. Chadwick Jr., Sharon L. Walker, Deborah S. Kelley, and Robert M. Morris. 2018. “Deep-Sea Volcanic Eruptions Create Unique Chemical and Biological Linkages Between the Subsurface Lithosphere and the Oceanic Hydrosphere.” *Oceanography* 31(1): 128–135. https://doi.org/10.5670/oceanog.2018.120

Symon, Evan. 2020. “Gov. Newsom Replaces Orange County Water Board Member Over Desalination Plant.” *California Globe*. October 22, 2020. https://californiaglobe.com/articles/gov-newsom-replaces-orange-county-water-board-member-over-desalination-plant/

Tagliabue, Alessandro, Andrew R. Bowie, Philip W. Boyd, Kristen N. Buck, Kenneth S. Johnson, and Mak A. Saito. 2017. “The Integral Role of Iron in Ocean Biogeochmeistry.” *Nature* 543: 51–59. https://doi.org/10.1038/nature21058

Tariq, Muhammad Atiq Ur, Rabeeah Alotaibi, Kumudu Kaushalya Weththasinghe, and Zohreh Rajabi. 2022. “A Detailed Perspective of Water Resource Management in a Dry and Water-Scarce Country: The Case in Kuwait.” *Frontiers of Environmental Science* 10: 1073834. https://doi.org/10.3389/fenvs.2022.1073834

United Nations. 2017. “Primary Production, Cycling of Nutrients, Surface Layer and Plankton.” In *The First Global Integrated Marine Assessment: World Ocean Assessment I*, 119–148. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108186148.009

———. 2022. *The United Nations World Water Development Report 2022: Groundwater: Making the Invisible Visible*. Paris: United Nations Educational, Scientific and Cultural Organization. https://unesdoc.unesco.org/ark:/48223/pf0000380721

———. 2023. “Water Scarcity.” Accessed January 20, 2023. https://www.unwater.org/water-facts/water-scarcity

United Nations University. 2013. *Water Security and the Global Water Agenda*. Hamilton: United Nations University. https://www.unwater.org/publications/water-security-and-global-water-agenda

Voutchkov, Nikolay. 2018. “Energy Use for Membrane Seawater Desalination—Current Status and Trends.” *Desalination* 431: 2–14. https://doi.org/10.1016/j.desal.2017.10.033

Wenner, Frank, Edward H. Smith, and Floyd M. Soule. 1930. “Apparatus for the Determination Aboard Ship of the Salinity of Sea Water by the Electrical Conductivity Method.” *Bureau of Standards Journal of Research* 5(3): 711–732. http://dx.doi.org/10.6028/jres.005.041

Wu, Mingxuan, Xiaohong Liu, Hongbin Yu, Hailong Wang, Yang Shi, Kang Yang, Anton Darmenov, Chenglai Wu, Zhien Wang, Tao Luo, Yan Feng, and Ziming Ke. 2020. “Understanding Processes that Control Dust Spatial Distributions with Global Climate Models and Satellite Observations.” *Atmospheric Chemistry and Physics* 20(22): 13835–13855. https://doi.org/10.5194/acp-20-13835-2020

Xu, Pei, Tzahi Y. Cath, Alexander P. Robertson, Martin Reinhard, Jacmes O. Leckie, and Jörg E. Drewes. 2013. “Critical Review of Desalination Concentrate Management, Treatment and Beneficial Use.” *Environmental Engineering Science* 30(8): 502–514. https://doi.org/10.1089/ees.2012.0348

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SECTION OVERVIEW

Voyage III Ocean Physics

9: The Sun and the Earth

9.1: Interesting Facts About the Sun
9.2: Electromagnetic Radiation
9.3: How the Sun Warms the Earth
9.4: Earth's Energy Imbalance
9.5: Chapter References

10: The Surface Circulation

10.1: Main Features
10.2: Boundary Currents
10.3: West Wind Drift Currents
10.4: Polar Ocean Currents
10.5: Understanding Ocean Motions
10.6: Ocean Currents Up Close
10.7: Monsoonal Circulation
10.8: Final Thoughts
10.9: Chapter References

11: The Seasons of the Sea

11.1: Sunrise, Sunset
11.2: Why Do Seasons Occur?
11.3: How Does Earth's Tilt Affect Surface Warming?
11.4: The Ocean Layer Cake
11.5: Measuring the Ocean's Layers
11.6: Visualizing Layers- The XZ Graph
11.7: The Seasons and the Thermoclines
11.8: The Importance of the Ocean's Seasonal Cycle
11.9: Chapter References

12: Atmospheric Circulation

12.1: Earth's Atmosphere
12.2: What Causes Winds?
12.3: Local and Regional Winds
12.4: Global Atmospheric Circulation
12.5: Final Thoughts
12.6: Chapter References

13: Ocean Waves

13.1: Energy in Motion
13.2: The Source of a Wave's Energy

13.3: The Geometry of Waves
13.4: Types of Waves
13.5: The Timing of Waves
13.6: The Speed of Waves
13.7: Wave Orbitals
13.8: Wind Stress- A Transfer of Energy
13.9: The Wind-Stressed Sea Surface
13.10: Factors Affecting Wave “Size”
13.11: The Beaufort Wind Force Scale
13.12: Dispersion of Waves
13.13: Deep- and Shallow-Water Waves
13.14: The Making of Surf
13.15: Chapter References

14: Ocean Tides and Sea Level Rise

14.1: The Tide-Causing Forces
14.2: The Tides Follow the Moon
14.3: Measuring and Predicting Tides
14.4: Classification of Tides
14.5: Tidal Height
14.6: Spring and Neap Tides
14.7: Practical Applications of Tide Knowledge
14.8: An Ever-Changing Sea Level
14.9: How Do We Measure Sea Level?
14.10: What Causes Sea Level Change
14.11: What Have We Learned About Global Sea Level Rise?
14.12: What Have We Learned About Local Sea Level Rise?
14.13: It’s Not Just Sea Level Rise
14.14: Chapter References

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CHAPTER OVERVIEW

9: The Sun and the Earth

Modern people cherish the Sun. On the few days when the Sun appears in Seattle, everyone—and I mean everyone—goes outside and occupies a patch of grass, a park bench, or any other sunny spot they can find. (You know it's true, Seattleites.) And surely, you can make a case that Southern Californians worship the Sun, what with their devotion to sunglasses, suntans, sunroofs, and sunny dispositions. College football teams (e.g., Arizona Sun Devils), brands of food (e.g., Sun Chips), and the most sacred day of the week—Sunday—are all named after the Sun. Even the cars we drive—the Solstice, Equinox, Eclipse, and Solara—refer to the Sun.

Our solar devotion has deep historical roots. Consider:

- The Polynesian word Maui refers to a god who captured the Sun for their people at Haleakala Crater on Maui, Hawaii, one of the best places in the world to view a sunrise (Westervelt 1910; Andersen 1995).
- The Incans and Aztecs worshiped the Sun, as evidenced in the temples at Qorikancha and Machu Picchu in Peru and the Pyramid of the Sun in the ancient city of Teotihuácan near Mexico City (e.g., Cowgill 2015).
- The Ise Grand Shrine complex in Ise, Japan, including Naikū and 91 nearby Shinto shrines devoted to Amaterasu-ōmikami, the goddess of the Sun, has existed since 4 BCE (e.g., Akima 1993).
- The Konark Sun Temple in Konark, India, built in the 13th century in honor of the sun god Surya, attracts hundreds of thousands of visitors each year (Behera 2005).
- A 68-foot-tall temple dedicated to Ra in Cairo marks the site of the ancient Egyptian city Heliopsis, the City of the Sun (Dobrowolska and Dobrowolski 2006).
- Stonehenge, now believed to be an ancient burial site, was built in alignment with the positions of the sunrise and sunset on the first day of summer in England (e.g., Pearson et al. 2009).
- At Mesa Verde, the Anasazi built a Sun Temple some 800 years ago, possibly as an astronomical observatory (e.g., Towers 2016).

But we must go deeper than this. Did you know that the Sun drives the motions of the ocean and atmosphere, creates our weather, and drives the production of food, lumber, medicines, and oxygen? Did you realize that every time you drive an internal combustion car, you unleash **ancient sunlight**, energy from the Sun that fell on Earth millions of years ago (e.g., Hartmann 2004)? Fossil fuels—sunlight captured by ancient plants and algae that were buried and transformed into coal, natural gas, and crude oil—drive the world's economies. The Sun powers our planet, feeds our hunger, and governs our daily lives. In many ways, our lives revolve around the Sun just as in ancient times.

But our modern relationship with the Sun has a dark side. Human activities have disrupted the natural processes by which the Sun makes Earth habitable for life by maintaining a narrow range of climate-comfortable temperatures. In unleashing ancient sunlight, we've unleashed carbon dioxide to our atmosphere—lots of it. As a result, our planet is warming. Human-caused warming has brought extreme weather, sea level rise, and the unraveling of ecosystems. How we deal with these threats in the next couple decades may well determine how and where we live.

If we are to live on this planet for centuries to come, then perhaps we owe it to ourselves and future generations to have a basic grasp of the Sun and how it provides energy to our planet and civilization. Find a sunny place and dive in.

9.1: Interesting Facts About the Sun

9.2: Electromagnetic Radiation

9.3: How the Sun Warms the Earth

9.4: Earth's Energy Imbalance

9.5: Chapter References

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9.1: Interesting Facts About the Sun

Our Sun, a star in the Milky Way galaxy, formed about 4.6 billion years ago. It began as a **protostar**, a whirl of gases—namely helium and hydrogen—that collapsed into a spinning ball. Increased temperature and pressure within the ball over the course of some 50 million years eventually ignited **hydrogen fusion**, a reaction that sustains the release of energy from the Sun even today. Under extreme gravitational forces, hydrogen atoms fuse into helium atoms, resulting in the release of enormous quantities of energy. The start of nuclear fusion represents the transition from protostar to full-fledged star (e.g., NASA 2023b). It is the moment when we may say, "Let there be sunlight, the sum of all wavelengths of light emitted by the Sun." From that moment on, light from the Sun—sunlight—filled space.

The Solar Wind

In addition to light, the Sun also emits charged particles—electrons, protons, and others—in a steady stream known as the **solar wind**. These particles interact with Earth's magnetic field and gases in Earth's atmosphere to create spectacular light shows, the **aurora borealis** and **aurora australis**, the northern and southern lights, respectively. **Coronal mass ejections** (CMEs)—intense outbursts of particles from the Sun—occasionally shift the lights toward the equator, offering opportunities for people living at lower latitudes to witness auroras (e.g., NASA 2019b).

CMEs can also produce dangerously strong **geomagnetic storms**, disruptions of Earth's magnetic field. In September 1859 the solar wind was so powerful it produced an aurora visible around the world. Electrical pulses from the event flickered through telegraph systems, shocking telegraph operators and setting their papers on fire (e.g., Muller 2014). While the damage that day was limited, scientists estimate that if such a storm were to occur today, the cost could reach trillions of dollars (Riley et al. 2018). NASA and other agencies monitor and forecast solar activity, what's known as **space weather**. Like atmospheric weather forecasts, space weather forecasts allow officials to inform civilian and military populations of possible disruptions to satellites, electrical power, computers, and other electrical devices during strong solar activity.

Classification of the Sun

Different stars in the Universe have different characteristics. When you look at stars in the sky, they may appear white, yellow, red, or blue. It's not an optical illusion. Different stars emit different colors of light. Astronomers can use these colors (and other properties) to classify stars—kind of like sorting your socks or dress shirts by color. **Star classification** serves as a kind of shorthand for describing the characteristics of a star. Based on the properties of the light and particles emitted, astronomers classify our Sun as a G2V star, a yellow dwarf star, and a main sequence star (NASA 2021). These classifications have great significance for astronomers, but for our purposes, the important point is that the Sun emits white-yellow light.

Of course, the Sun is not the only star in our neighborhood. Peer into the night sky and you will see thousands of twinkling stars. On a really dark night, far from the lights of industrial civilization, you might see as many as 4,500 stars. With a pair of binoculars or a telescope, you can see as many as a half a million stars and **galaxies**—collections of star systems bound together by gravity. Our own galaxy—the **Milky Way**—contains some 200 billion stars. And beyond the Milky Way, in the vast expanse of the Universe, lie perhaps as many as two trillion other galaxies, each with its own billions and billions of stars. It's said there are more stars in the Universe than grains of sand on the world's beaches. Of course, an accurate count of the number of stars in the Universe or grains of sand on Earth's beaches can never be known for sure. But it's fun to think about.

The Solar System

Around the time that our Sun lit up, gases and cosmic materials in nearby space coalesced into the celestial bodies orbiting the Sun, our **solar system**. The **rocky planets**—Mercury, Venus, Earth, and Mars—and the **gas planets**—Jupiter, Saturn, Uranus, and Neptune, formed around this time. So did the dwarf planet, Pluto, and hundreds of moons and asteroids. At the far reaches of the solar system, a collection of icy objects, the **Kuiper Belt** and the **Oort Cloud**, appeared as well. These icy bodies occasionally send traveling snowballs our way, the **comets** (NASA 2019a).

The dimensions of our Sun are impressive. It makes up 99.98 percent of all the matter in our solar system. It has a diameter that is 109 times the diameter of Earth. If the Sun were a hollow sphere, you could put 1.3 million Earth spheres inside of it. Of course, if you put Earth inside the Sun, you would experience heat like you've never felt before. The core of the Sun has a temperature of

about 27 million degrees Fahrenheit (F), about 15 million degrees Celsius (C); °F or °C, respectively. Out at its edge, it's cooler, only 10,000°F (5,500°C; e.g., NASA 2021).

People sometimes ask why the Sun looks so small if it's that big. Well, if you were 93 million miles away, you'd look small, too. This distance—the distance from the Earth to the Sun—represents an astronomer-designated unit called the **astronomical unit**, or AU. Earth, by definition, is one AU from the Sun. But because the Earth orbits the Sun in a slightly elliptical path, the Earth–Sun distance varies. In January, the Sun is slightly closer to Earth, at **perihelion**, about 0.98 AU (91.4 million miles). In July, it's slightly farther away, at **aphelion**, about 1.02 AU (94.5 million miles). On average, it works out to about 93 million miles (NASA 2001).

This brief introduction to the star of our solar system serves as a backdrop for the more important consideration of how the Sun—specifically, energy from the Sun—interacts with Earth and drives so many important Earth processes. Let's take a look now.

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9.2: Electromagnetic Radiation

Energy from the Sun comes to us in the form of **electromagnetic radiation**, a term that refers to all the types of radiant energy emanating from stars (e.g., the Sun). Scientists classify different types of electromagnetic radiation according to their **wavelengths**, the distance between the peaks of their waveform (just like sound waves). The arrangement of different types of electromagnetic radiation according to their wavelengths produces what is known as the **electromagnetic spectrum**, the range of all types of electromagnetic radiation. From longest to shortest, the electromagnetic spectrum consists of **radio waves** (the waves you listen to), **microwaves** (the waves you cook with), **infrared light** (used in night-vision gear), **visible light** (so named because you can see it), **ultraviolet light** (the reason you use sunscreen), **X-rays** (used by doctors and dentists), and **gamma rays** (used in medicine; e.g., NASA 2016b). In everyday usage regular folks just refer to the Sun's electromagnetic spectrum as sunlight, solar radiation, or solar energy. But the spectral divisions are useful, too, as we shall see.

Energy

Most people recognize that light is a form of energy. Few, however, appreciate what the word energy means. Formally, **energy** is defined as "the ability to do work"—crudely speaking, to move something (e.g., EIA 2023c). I like to think of energy as the stuff that makes things happen. It's a property of an object or system that can be used to generate a force of some kind and do work.

Broadly speaking, two kinds of energy exist: (1) **kinetic energy**, the energy of motion; and (2) **potential energy**, stored energy or energy inherent in an object in a gravitational field. Kinetic energy includes solar radiation (electromagnetic energy), the motion of objects (motion energy), sound waves (sound energy), electricity (electrical energy), and heat exchange (thermal energy). Potential energy may refer to energy stored in chemical bonds (chemical energy), energy stored in objects under tension (mechanical energy), radioactive materials (nuclear energy), or the force experienced by Humpty Dumpty on his epic fall (gravitational energy; EIA 2023a).

More important than the definition of energy is how it operates. Like Mystique of the X-People, energy can shape-shift. It can change from one form to another. Scientists express energy's ability to change forms in the well-known law of conservation of energy. In nontechnical terms, the **law of conservation of energy** states that energy can be neither created nor destroyed, but it can change forms. That means that one type of energy can become another type of energy—energy can transform. It's still the same energy; it's just in a different package (e.g., EIA 2023b).

Familiar examples will help you grasp this rather abstract concept. A log, the dried-out hunk of a trunk of a tree, was formed when the tree captured electromagnetic energy—sunlight. The tree turned the sun's energy into chemical bonds, the energy-containing stuff of which the tree is made. When you set the log ablaze, you transform its chemical energy into heat energy that provides warmth. A burning log also releases electromagnetic energy, the red-yellow-orange glow of its fire. And when you heat a marshmallow over a fire and eat it (with chocolate and graham crackers, of course), your body transforms their chemical energy into the kinetic energy of a laugh, a fist bump, or a romantic kiss. The story of energy is the story of its transformations.

Interactions of Light with Matter

Interactions between light (i.e., electromagnetic radiation) and matter (i.e., the atoms of which materials are composed) prove important for understanding transformations of energy. Fortunately, we need only master a few simple definitions to appreciate these interactions.

To understand light–matter interactions, it helps to think of light as **rays**, arrows that indicate the direction of a light wave. When a light ray encounters an object, many possible things may happen. But let's consider the four interactions that play a role in our understanding of how solar radiation heats our planet:

- **absorption**, the energy in the light ray is transferred to the object and becomes part of the object's energy
- **scattering**, the light ray interacts with the object and is sent in different directions
- **reflection**, the light ray bounces off the object at the same angle at which it arrived
- **transmission**, the light ray travels through an object and some or all of its energy comes out the opposite side from which it entered

Now, these definitions may not be picture perfect in the eyes of physicists, but they hopefully give you an understanding of the basic principles. (See also Ahrens and Henson for a good basic treatment of this topic.)

Temperature and Heat

When an object absorbs electromagnetic radiation, it gains energy. This causes its molecules to move more rapidly. In scientific terms, the kinetic energy of the molecules increases. We detect a gain in energy as a rise in **temperature**, loosely defined as the average kinetic energy of a system, substance, or object. Temperature provides a convenient way to compare the kinetic energy of systems, substances, and objects.

To be clear, temperature is not a measure of heat energy, total kinetic energy, or even the internal energy in a system or object. It's simply a convenient way to describe the jumpiness or sluggishness of the molecules in a system or object. By analogy, if kids in a bounce house are jumping all over the place, you might say their temperature is high. If the kids are barely moving, their temperature is low. The higher the temperature, the faster the molecules move, and vice versa. It's important to note that measurements of temperature are not the same as measurements of energy. An ice cube and an iceberg may have the same temperature, but the iceberg, by virtue of its much larger mass, contains considerably more energy.

Thermometers

A **thermometer**—a device used to measure temperature—provides a number for the average kinetic energy in an object or system. The level of fluid in a thermometer rises and falls according to the temperature. In a **digital thermometer**, a digital display corresponds to the expansion or contraction of a strip of metal or changes in its electrical conductivity as temperature changes.

The numbers displayed by a thermometer are completely arbitrary. In the **Celsius scale**—invented in 1742 by Swedish astronomer Anders Celsius (1701–1744)—the temperature of freezing water is set arbitrarily at 0°. In the **Fahrenheit scale**—invented in 1724 by physicist David Gabriel Fahrenheit (1686–1736)—the temperature of freezing water is set arbitrarily at 32°. The numbers for the freezing points of water were chosen by Mr. Celsius and Mr. Fahrenheit when they invented their thermometers. The same is true for the boiling points, 100°C and 212°F. These numbers were chosen by their inventors who for various reasons thought that they worked well for the range of temperatures that people who use the thermometers would encounter (e.g., Middleton 1966).

Thermometers work by heat exchange between the external environment and a fluid inside a tube. (Traditionally, the fluid was mercury; now most liquid thermometers contain alcohol.) When the external environment is hotter than the fluid inside the thermometer, heat energy flows from the environment to the fluid, and the fluid expands. The fluid expands because the molecules in the fluid are moving faster, and they take up more space in their motions. We see the fluid rise in the tube. When the external temperature is lower than the fluid inside the thermometer, heat energy flows from the fluid to the external environment; the fluid loses energy and the space between the molecules is reduced—the fluid contracts. We see the level of the fluid fall in the tube. Similar expansions and contractions—or changes in electrical conductivity—accompany heat exchange between the external environment and digital thermometers.

Regardless of the chosen scale, thermometers provide temperature measurements according to agreed-upon methods. They provide us with a means for determining the relative hotness or coolness of objects or systems. They ensure consistency and reproducibility in processes that depend on temperature control, such as cooking, the manufacture of steel, and a whole lot more.

Heat Transfer

Heat only exists when two objects or systems have different temperatures. Think of heat as energy in motion. When two objects or systems reach thermal equilibrium—when they have the same temperature—heat no longer exists (e.g., Ahrens and Henson 2018).

The increase in temperature that occurs when matter absorbs electromagnetic radiation represents one of three ways that heat can be transferred between objects or systems: (1) radiation, (2) conduction, and (3) convection. All three forms of heat transfer become important when we examine what happens when Earth's surface absorbs sunlight.

Radiation is the transfer of heat via electromagnetic energy. Radiation moves out in all directions from its source until it meets another object. That object may reflect the radiation, in which case no exchange of energy occurs; it may transmit the radiation, in which case the radiation travels right through it and no exchange of energy occurs; or it may absorb the energy, in which case the energy of the object (and its temperature) increases. If you've ever felt the hood of a black car on a sunny day, you've likely noticed that it's hotter than the surrounding air. That's because the metal of a car's hood absorbs electromagnetic radiation, increasing its temperature. When you touch the hot hood, heat energy is transferred to your finger, and you utter some variation of "ow" (depending on how much it hurts).

A car's hood also emits infrared radiation, electromagnetic energy at wavelengths beyond visible light. You do not detect this kind of radiation because, unlike visible light (which you can see), your eyes are not sensitive to infrared radiation. All objects, including humans, emit radiation in proportion to their temperature. Hotter objects emit shorter wavelengths, and cooler objects emit longer wavelengths. The relationship between temperature and the wavelength of maximum emission defines a principle known as **Wien's Law**. This law provides a quantitative formula for determining the peak emission wavelength from the temperature of an object. As temperature rises, the peak emission wavelength becomes shorter.

The infrared emission of objects, humans, and other forms of life makes them detectable using **night-vision technologies**. These devices have sensors that detect infrared radiation and electronics that turn the infrared signal into a color the user can see—usually green. They are very useful for seeing in the dark, but generally they are used for clandestine or military purposes.

Conduction occurs when the faster molecules of a higher-temperature object collide with the slower molecules of a lower-temperature object and exchange energy until all the molecules are moving at the same speed (i.e., until they have the same kinetic energy). Conduction is the transfer of heat energy through molecule-to-molecule collisions. Heat transfer by conduction requires contact between two objects. When you put a marshmallow on a metal skewer in a campfire, the end immersed in the fire gains energy and begins to transfer that energy via conduction along the length of the skewer. If you keep it in the fire long enough, the end you're holding will eventually get too hot and burn you. Skewers made of wood—a poor conductor of heat—protect your hand from burning. Kitchen utensils employ principles of heat conduction to prepare food and to protect chefs. Pans made of copper, aluminum, and carbon steel conduct heat faster than those made of cast iron or stainless steel. Fast-conducting pans are great for searing foods. At the other end of the pan, pot handles made of plastic or other non-conducting materials—or a good pair of cotton pot holders—limit heat conduction and prevent your hands from burning.

Convection involves heat transfer through the motions of fluids, such as air and water. When you heat air or water, you cause it to expand. This expansion lowers the density of the fluid. If the surrounding fluid is more dense, then the heated fluid will rise. This should be familiar to you as the principle behind heating and cooling in your home—heating devices (or their ducts) are generally on or near the floor because warm air rises. Air conditioners (or their ducts) are generally placed at the top of a window or in the ceiling because cold air sinks. The rising or sinking air transfers heat through its movements, which is called **convective heating**. Convection causes air or water to circulate—to move in a circular motion. On a global scale, convection is responsible for the large-scale motions of the atmosphere and the ocean—the global winds and ocean currents. (See Ahrens and Henson 2018.)

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9.3: How the Sun Warms the Earth

As we learned earlier, sunlight is a form of electromagnetic radiation. We most commonly observe it as visible light with wavelengths from 400 to 700 nanometers (10^{-9} meters, or 1 billionth of a meter). These wavelengths include the colors we see: violet, blue, green, yellow, orange, and red. To understand how the Sun warms the Earth, we also need to consider nonvisible forms of light—wavelengths shorter than 400 nanometers, namely ultraviolet radiation, and wavelengths longer than 700 nanometers, namely infrared light.

Because the gases in Earth's atmosphere absorb different wavelengths of electromagnetic radiation, some wavelengths of sunlight travel freely through Earth's atmosphere and others don't. The selectivity of the atmosphere to different wavelengths of sunlight is referred to as the **atmospheric window** (NWS 2023).Think of it as a kind of selective filter, blocking some wavelengths of light but not others. If you look closely at an illustration of Earth's atmospheric window, you will see that not all sunlight reaches Earth's surface and not all wavelengths of sunlight reach Earth's surface equally. Gamma rays and X-rays are mostly blocked by Earth's atmosphere. Ultraviolet, visible, and near-infrared wavelengths are transmitted through Earth's atmosphere. Mid- to far-infrared wavelengths are blocked. Short- to mid-wavelength radio waves are transmitted, while long-wavelength radio waves are blocked. The blocking (or transmitting) is due to different gases in Earth's atmosphere. The net effect is that about 20 percent of the Sun's energy is absorbed in the atmosphere and only about 50 percent reaches Earth's surface (e.g., Trenberth et al. 2009).

Other than radio waves, the atmosphere is most transparent (least opaque) to visible light (as to be expected given that our eyes evolved to detect this spectrum of light). In contrast, the part of the spectrum known as near infrared (700 to 5,000 nanometers) varies in its transmission through the atmosphere. And mid- to far-infrared wavelengths (5,000 to 350,000 nanometers) are nearly 100 percent blocked by the atmosphere.

Visible and mid- to far-infrared light are the operational parts of the electromagnetic spectrum where heating of our planet is concerned. To simplify the discussion, scientists divide these parts of the spectrum into two parts: **shortwave radiation**, which includes ultraviolet, visible, and near-infrared wavelengths; and **longwave radiation**, which includes the mid- to far-infrared wavelengths. Shortwave radiation is transmitted by Earth's atmosphere. Most longwave radiation is absorbed by Earth's atmosphere (e.g., NASA 2016a).

The Sun, like all stars, emits all forms of electromagnetic radiation. However, most of the radiation emitted by the Sun occurs in wavelengths between 300 and 2,500 nanometers. In fact, about half the radiation that reaches Earth's surface from the Sun consists of ultraviolet and visible wavelengths. The other half is near-infrared wavelengths. Thus, the sunlight that reaches Earth's surface can be classified as shortwave radiation. However, the Earth, like all objects that contain energy, also emits radiation. According to Wien's Law, the wavelengths of the emitted radiation depend on the temperature of the object: Hot objects emit short-wavelength radiation, while cool objects emit long-wavelength radiation. The superhot Sun emits mostly shortwave radiation, while the much cooler Earth emits longwave radiation. It's Earth's emission of longwave radiation and reabsorption of that radiation by gases in Earth's atmosphere that cause the atmosphere to warm.

The Greenhouse Effect

The filtering of solar radiation discussed above results from gases in our atmosphere. While nitrogen (70 percent) and oxygen (21 percent) make up the bulk of the gases, they absorb very little solar radiation. However, small concentrations of other atmospheric gases absorb significant quantities, especially longwave radiation. Four gases in particular are responsible for absorbing most of the longwave radiation emitted by Earth's surface: **carbon dioxide** (CO_2), **water vapor** (H_2O), **methane** (CH_4), and **nitrous oxide** (N_2O). The similarity of these gases to the function of a greenhouse (trapping heat) has earned them the nickname **greenhouse gases** (NASA 2023c). Scientists refer to the warming of Earth's surface by the greenhouse gases in the atmosphere as the **greenhouse effect**. (Watch 17-second animation by NASA.)

Operationally, Earth's atmosphere acts similarly to a greenhouse except that it doesn't prevent convection and confine heat like a greenhouse. Shortwave radiation—free to travel through Earth's atmosphere—reaches Earth's surface, where it is absorbed. Absorption of that radiation raises the temperature of Earth's surface. In turn, some of that energy is emitted by Earth's surface to the atmosphere as longwave radiation. In the atmosphere, that surface-emitted longwave radiation is absorbed by—you guessed it—greenhouse gases. As a result, they heat up. As they heat up, the greenhouse gases re-radiate some of their absorbed radiation. In

doing so, they warm the atmosphere and Earth's surface. In a sense, greenhouse gases recycle longwave radiation, acting as a reservoir of heat that keeps Earth's surface warm.

Lest you get the impression that the greenhouse effect is bad, know that the natural greenhouse effect is a good thing—even an essential thing. Because of the greenhouse effect, Earth experiences an average surface temperature of roughly 59°F (15°C). Without the greenhouse effect, Earth's average surface temperature would be 0°F (−18°C).

Atmospheric Scattering

While the greenhouse effect is the principal means by which Earth warms, other processes can diminish or enhance the amount of sunlight that reaches Earth's surface. When sunlight encounters the outermost part of Earth's atmosphere, it begins to interact with suspended particles and gases. Clouds (which are suspended water and ice), particles, and atmospheric gases may absorb, reflect, and scatter sunlight. Preferential scattering of blue wavelengths by atmospheric gases makes the sky appear blue. Similarly, scattering produces those gorgeous orange-red sunsets we often observe (e.g., NASA 2022).

But scattering can also limit the amount of sunlight that reaches Earth's surface. The most effective light-scattering agents in the atmosphere are **aerosols**, a group of solid or liquid particles less than a tenth the width of a human hair (less than 1 micrometer). Aerosols prove important in the formation of clouds—acting as **cloud condensation nuclei**—sites of condensation for water vapor. Aerosols—a form of air pollution—originate from a number of manmade and natural sources, including transportation (e.g., trains, planes, and automobiles), industrial activities (e.g., coal burning), agricultural practices (e.g., fertilizers), volcanoes (e.g., gas emissions), mineral dust (suspended by winds), ocean waves (e.g., sea foam), and even phytoplankton, which produce chemicals that act as cloud condensation nuclei (e.g., Boucher et al. 2013).

One type of aerosol—**black carbon**, formed from the incomplete combustion of fossil fuels—has received a lot of attention for its role in reducing the reflectivity of Arctic ice, causing it to melt faster (e.g., Hansen and Nazarenko 2004; Winiger et al. 2019). In the lower atmosphere, black carbon and aerosol pollution have severe health effects (e.g., Liu et al. 2018; Kusumaningtyas et al. 2018; Groma et al. 2022). On the other hand, aerosols in the upper atmosphere may actually be cooling Earth. Scientists estimate that cooling by as much as 0.9 to 1.98°F (0.5 to 1.1°C) has occurred because of atmospheric aerosols (e.g., Samset et al. 2018). Ironically, as efforts to reduce air pollution take hold, we can expect additional (and rapid) increases in Earth's surface temperature. Decreases in aerosol emissions during the pandemic were likely responsible for increases in surface temperatures in eastern China (e.g., Yang et al. 2020). Nevertheless, uncertainty remains over the role of aerosols in Earth's climate. Ongoing research and new approaches promise to improve our understanding in this important area of research (e.g., Li et al. 2022).

Albedo: The Reflectivity of Earth's Surface

Shortwave radiation traveling through Earth's atmosphere may also be reflected. Reflection changes the direction of a beam of light—similar to scattering (although it does not involve light–particle interactions). Reflection of sunlight by clouds, aerosols, particles, and Earth's surface reduces the energy heating Earth's surface. Reflection and backscattering (scattering in the opposite direction from which light rays arrive) reduce the sunlight reaching Earth's surface by about 30 percent. Add 20 percent absorption by clouds, particles, and atmospheric gases, and you can see why only about half the sunlight at the top of Earth's atmosphere makes its way to Earth's surface (e.g., Trenberth et al. 2009; Liang et al. 2019).

Of course, the amount of sunlight reflected from Earth's surface depends on the properties of its surface. Scientists define the reflectivity of Earth's surface by a property known as **albedo**—the ratio of reflected light to incoming light. Light-colored surfaces reflect a greater quantity of light than dark-colored surfaces. Thus, light-colored surfaces have a higher albedo than dark surfaces. Places with snow and ice have a high albedo and reflect more sunlight than the ocean or land, which have a low albedo. Urban areas have variable albedos, depending on the materials used to build them and the presence (or absence) of vegetation. For example, Downtown Los Angeles has a higher albedo than surrounding areas because it has less vegetation, which tends to absorb sunlight (e.g., Taha 1997; Vahmani and Ban-Weiss 2016).

Negative and Positive Feedback Loops

Processes internal to a system that modify how it responds to change are known as **feedback loops**. Feedback loops can slow down or speed up changes in a system. The Earth system and its seven subsystems (Chapter 1) exhibit numerous feedback loops. Of prime concern here are the ones that affect Earth's energy budget.

Feedback loops that reduce or reverse the impact of a change are known as **negative feedback loops**. The thermostat in your house provides a familiar example. When the house gets hot, the A/C kicks in. When the desired temperature is reached, the thermostat turns the A/C off. Negative feedback loops reduce extremes in a system. They help to maintain more constant and stable conditions. Scattering by atmospheric particles represents a negative feedback loop because combusion of fossil fuels produces particles that reflect shortwave radiation and reduce the warming effects of the resultant greenhouse gases. If we decrease our burning of fossil fuels, we'll produce fewer particles and Earth will warm as more shortwave radiation reaches Earth's surface. Of course, reduced concentrations of greenhouse gases (and the resultant cooling) will more than compensate for any increases in heating.

Changes that occur in a system that amplify or accelerate an effect are known as **positive feedback loops** (positive as in the same direction, not the "You're doing a great job" kind of positive feedback). During ice ages, when a greater proportion of Earth is covered with ice, more sunlight is reflected from Earth's surface. The increased albedo leads to even more cooling and more ice and even more cooling. Alternatively, losses of ice due to warming of Earth's surface lower Earth's albedo and allow more sunlight to be absorbed. Greater warming means even greater loss of ice and even more warming. This type of positive feedback worries climate scientists, as global warming will cause melting of the ice caps and greater warming.

At some point, feedback loops within a system (especially positive feedback loops) may cause it to spin out of control, so to speak. The system becomes unstable in its current state and reorganizes into a different form. Scientists refer to such events as **tipping points**, a change in the state of a system that is irreversible and unstoppable. A roller coaster makes a good example. As the car ascends to the highest point on the track—*click–clack*, *click–clack*, *click–clack*—you nervously anticipate what's ahead. You reach the top, your wits still about you, but then, there's that moment when the car crosses the point of no return. You've reached the tipping point. OMG! The entire coaster lets go and you scream at the top of your lungs, praying you're not about to die.

Climate scientists fear the Earth system has multiple irreversible tipping points (e.g., Heinze et al. 2021; Franzke et al. 2022). The predicted impacts will be severe: permanent loss of ice sheets, disruption of ocean circulation, and mass extinction of corals, among them. In the scientists' words, "the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute" (Lenton et al. 2019).

Earth's Temperature Is Rising

While atmospheric greenhouse gases occur naturally as a result of volcanic activity, decomposition of organic matter, evaporation of water, and oceanic exchanges (among others), these natural processes cannot account for the measurably significant rise in greenhouse gases since 1850. Human activities, especially the burning of fossil fuels (i.e., petroleum, natural gas, and coal) and **deforestation**, the removal of trees, have added greenhouse gases to the atmosphere.

For the 800,000 years prior to the industrial era (about 1850), atmospheric CO_2 never exceeded 300 parts per million (e.g., Lindsey 2022). Fast-forward 170 years, and the concentration of atmospheric greenhouse gases has risen to more than 400 parts per million, an increase of nearly 50 percent. On April 26, 2022, atmospheric CO_2 reached a record-setting 422.06 parts per million at the Mauna Loa Observatory in Hawaii (CO2.earth 2021). Atmospheric CO_2 has now reached its highest concentration in 23 million years (Cui et al. 2020).

What happens to Earth's surface temperature when the concentration of greenhouse gases in the atmosphere rises? As you might predict, the addition of greenhouse gases to the atmosphere increases the amount of radiation absorbed by greenhouse gases and re-emitted to Earth's surface. If more longwave radiation remains in our atmosphere, then it stands to reason that Earth's temperature will rise. That's exactly what we see. Climate scientists calculate that Earth has warmed by an average of nearly 2.0°F (1.1°C) over temperatures from 1850–1900 (IPCC 2021). That's the warmest Earth has been in 125,000 years (Tollefson 2021).

One way to visualize what happens as a result of an increase in atmospheric CO_2 is to consider what it's like on an ordinary day at the mall versus the mall during holidays. On an ordinary day, you can walk through the mall without bumping into people. On busy shopping days, you have to push and shove your way through crowds of people. Heat rays moving through a crowded greenhouse gas atmosphere take longer to travel into space and Earth's heat reservoir fills up.

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9.4: Earth's Energy Imbalance

Another way to understand the greenhouse effect is to look at the atmosphere, land, and ocean as reservoirs of heat. With increasing amounts of greenhouse gases, the sources of heat—the surface-emitted longwave radiation and its absorption and re-emission by greenhouse gases—exceed the sinks of heat—the escape of longwave radiation into outer space. As a result, the amount of heat in the reservoir increases—like water in a bathtub. In the language of the reservoir model introduced in Chapter 11, the sources (E_{in}) exceed the sinks (E_{out}), or

$$E_{in} > E_{out}$$

(Eq. 12.1)

This imbalance between the incoming radiation from the Sun (i.e., the source) and outgoing radiation from Earth's surface to space (i.e., the sink) is called **Earth's energy imbalance** (e.g., Hansen et al. 2005). Estimates of the energy imbalance indicate that nearly 1 watt of energy per square meter (1 joule per second per square meter of Earth's surface) remain in the Earth system versus what is leaving via outgoing radiation to space (e.g., Meyssignac et al. 2019; von Schuckman et al. 2020). In short, Earth is accumulating energy. According to the August 2021 report of the Intergovernmental Panel on Climate Change (better known as the IPCC):

- Every decade for the last four decades has been warmer than the one before. 2011–2020 was warmer than 2001–2010, which was warmer than 1991–2000, which was warmer than 1981–1990 (IPCC 2021).
- The last two decades (2001–2020) experienced the most rapid warming, about 1.8°F (1°C) higher than the period 1850–1900 (IPCC 2021).
- The highest temperature rise occurred over land, about 2.86°F (1.59°C); ocean temperatures rose 1.58°F (0.88°C; IPCC 2021).
- The Arctic is warming two to four times faster than the rest of the globe (e.g., AMAP 2021; IPCC 2021; Labe et al. 2020).

The rate of change of human-caused global warming is unlike anything observed in the past 2,000 years (IPCC 2021). Earth's average temperature has been rising at a rate of about 0.13°F (0.07°C) per decade since 1880. However, since 1981, that rate has more than doubled to 0.32°F (0.18°C) per decade (Lindsey and Dahlman 2023). It's getting warmer faster.

Global Warming vs. Global Climate Change

In Chapter 1, we noted that scientists have observed a change in Earth's climate (i.e., average weather conditions) over the past 150 years or so, what is known as global climate change. Global warming is one of the changes scientists have observed. Unfortunately, in the popular media, the terms global climate change and global warming are often used interchangeably. Let's make it clear: their meanings are distinct.

The increase in Earth's average temperature—global warming—results primarily from increases in human-generated atmospheric greenhouse gases (though other activities also contribute). The increase in Earth's energy alters the natural functioning of Earth's subsystems and causes climate to change. The cryosphere melts. The atmosphere gains heat and moisture. The ocean warms. Global warming is a part of Earth's changing climate, but many other weather- and climate-related phenomena—melting ice caps, extreme precipitation, droughts, more frequent and stronger hurricanes—also serve as examples of global climate change. The distinction between global warming and global climate change proves important for communicating the multiple changes that are happening as Earth warms. Global warming refers to a (specific) human-caused change. Global climate change refers to the myriad of weather and climate changes that occur as a result of global warming.

One other important note of clarification concerns the oft-remarked-upon (and mistaken) association of local changes with global ones. You may have heard someone comment during a cold-weather spell or snowstorm that global warming can't be happening because it's cold or snowing outside. Well, colder weather still happens in a warmer world. Global warming has not eliminated the seasonal cycle. Winter will still be colder than summer.

Temperature records reveal the trend expected in a warming world. The number of days of record heat exceeds the number of days of record cold. In the United States, record high temperatures occur twice as often as low temperature records (Meehl et al. 2009; Associated Press 2019). In Australia, that ratio is 12 to 1 (Lewis and King 2015). When you add it all up—across the entire globe—Earth is getting warmer. And we're the cause of it.

The Ocean's Temperature Is Rising

Because warming air temperatures affect us directly, you'd be forgiven if you hadn't thought about the effects of global warming on the ocean. But in fact, the effects of global warming on the ocean are perhaps more alarming than those on land. That's because the ocean has absorbed most of the heat that otherwise would have ended up in the atmosphere. A warming world ocean signals profound changes for the ocean and will literally change the world as we know it.

Science writers LuAnn Dahlman and Rebecca Lindsey refer to the ocean as Earth's "largest solar energy collector" (Lindsey and Dahlman 2020). As early as 1956, famed meteorologist Carl-Gustaf Rossby (1898–1957) postulated that "anomalies in heat probably can be stored and temporarily isolated in the sea" (Rossby 1959). In 2000, Sydney Levitus and colleagues published the first estimates of the amount of heat being absorbed by the upper ocean (to depths less than 9,842 feet, or 3,000 meters; Levitus et al. 2000). Their results confirmed Rossby's hypothesis: Most heat from global warming has gone into the ocean. Subsequent studies using observations from Argo floats and other newly available data substantiated the results more definitively: The world ocean has absorbed 93 percent of the excess heat associated with Earth's energy imbalance since 1971 (Levitus et al. 2012; Rhein et al. 2013; Meyssignac et al. 2019; Cheng et al. 2023).

Oceanographers refer to ocean-absorbed energy as **ocean heat content**, the amount of heat energy stored within the ocean (Cheng et al. 2017). Cheng et al. (2020) estimate that since 1960, ocean heat content across all depths of the world ocean has increased by 370 ± 81 zettajoules (1 zettajoule = 10^{21} joules). Now, I admit that it's difficult to wrap your head around joules much less zettajoules. But Levitus and colleagues (2012) calculated that if the excess heat in the upper 6,562 feet (2,000 meters) was instantaneously released—240 zettajoules since 1955 using their data—the atmosphere would warm by 65°F (36°C). For all depths of the world ocean—using the estimates of Cheng et al. 2020—that temperature comes close to 100°F (37.7°C). Of course, an instantaneous release of heat from the ocean to the atmosphere is impossible. Nevertheless, this calculation underscores the tremendous amount of heat added to the world ocean as a result of human-caused global warming.

Upper ocean heat content set new records in 2021 and 2022, the warmest in human history (Cheng et al. 2023). Not surprisingly, ocean surface temperatures in different locations also set records. In August 2020, the sea surface temperature at Scripps Pier in La Jolla, California, reached 79.5°F (26.4°C)—11.5°F above average (6.4°C)—beating a record set only two years previously (Anderson 2020). The long-term trend in ocean warming caused by climate change accounts for these temperatures (e.g., Fumo et al. 2020).

To conclude, the ocean stores tremendous quantities of heat. The good news is the presence of an ocean on our planet means that Earth's temperature has risen more slowly than it might have otherwise. The bad news is that even if we were to somehow stop greenhouse gas emissions today, it would take centuries for the ocean and atmosphere to return to normal. That's because the ocean circulates on timescales of centuries to millennia (Abram 2018; Cheng et al. 2020). So heat stored in the ocean will remain with our planet for a long time. Such a realization makes it ever more urgent that we act immediately to reduce greenhouse gas emissions and put Earth on a path toward a more sustainable and habitable future.

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9.5: Chapter References

Abram, Nerilie J. 2018. “Past Warming Events in the Arctic Linked to Shifting Winds in the Antarctic.” *Nature* 563: 630–631. https://doi.org/10.1038/d41586-018-07495-7

Ahrens, C. Donald, and Robert Henson. 2018. *Essentials of Meteorology: An Invitation to the Atmosphere*, 8th edition. Boston: Cengage. https://www.cengage.com/c/essentials-of-meteorology-8e-ahrens/9781305628458/

Akima, Toshio. 1993. “The Origins of the Grand Shrine of Ise and the Cult of the Sun Goddess Amaterasu Ōmikami.” *Japan Review* 4: 141–198. https://www.jstor.org/stable/25790929

AMAP. 2021. *Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers*. Tromsø: Arctic Monitoring and Assessment Programme (AMAP). https://www.amap.no/documents/doc/arctic-climate-change-update-2021-key-trends-and-impacts.-summary-for-policy-makers/3508

Andersen, Johannes Carl. 1995. *Myths and Legends of the Polynesians*. New York: Dover Publications. https://www.google.com/books/edition/Myths_and_Legends_of_the_Polynesians/vdnjpRcNdyIC?gbpv=0

Anderson, Erik. 2020. “Ocean Water Has Record Temperature Off San Diego Coast.” KPBS Midday Edition. August 26, 2020. https://www.kpbs.org/news/midday-edition/2020/08/26/ocean-has-record-temperature-san-diego-coast

Associated Press. 2019. “Record High US Temperatures Outpace Record Lows Two to One, Study Finds.” *The Guardian*. March 19, 2019. https://www.theguardian.com/environment/2019/mar/19/climate-change-temperatures-weather-us-news

Behera, Karuna Sagar. 2005. *Kobark: the black pagoda*. New Dehli: Ministry of Information and Broadcasting, Government of India, Patiala House. https://archive.org/details/konarkblackpagod00behe

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. K. Satheesh, S. Sherwood, B. Stevens and X. Y. Zhang. 2013. “Clouds and Aerosols.” In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Editing by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 571–657. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.016

Cheng, Lijing, John Abraham, Kevin E. Trenberth, John Fasullo, Tim Boyer, Michael E. Mann, Jiang Zhu, Fan Wang, Ricardo Locarnini, Yuanlong, Li, Bin Zhang, Fujiang Yu, Liying, Wan, Xigrong Chen, Licheng Feng, Xiangzhou Song, Yulong Liu, Franco Reseghetti, Simona Simoncelli, Vitor Gouretski, Genxin Chen, Alexey Mishonov, Jim Reagan, and Guancheng Li. 2023. “Another Year of Record Heat for the Oceans.” *Advances in Atmospheric Science*. January 11, 2023. Epub ahead of print. https://doi.org/10.1007/s00376-023-2385-2

Cheng, Lijing, John Abraham, Jiang Zhu, Kevin E. Trenberth, John Fasullo, Tim Boyer, Ricardo Locarnini, Bin Zhang, Fujiang Yu, Liyimg, Wan, Xingrong Chen, Xiangzhou Song, Yulong Liu, and Michael E. Mann. 2020. “Record-Setting Ocean Warmth Continued in 2019.” *Advances in Atmospheric Science* 37: 137–142. https://doi.org/10.1007/s00376-020-9283-7

Cheng, Lijing, Kevin E. Trenberth, John Fasullo, Tim Boyer, John Abraham, and Jiang Zhu. 2017. “Improved Estimates of Ocean Heat Content from 1960 to 2015.” *Science Advances* 3(3): e1601545. https://doi.org/10.1126/sciadv.1601545

Cowgill, George L. 2015. *Ancient Teotohuacan: Early Urbanism in Central Mexico*. Cambridge: Cambridge University Press. https://www.cambridge.org/us/academic/subjects/archaeology/archaeology-americas/ancient-teotihuacan-early-urbanism-central-mexico

Cui, Ying, Brian Schubert, and A. Hope Jahren. 2020. “A 23 M.Y. Record of Low Atmospheric CO_2.” *Geology* 48(9): 888–892. https://doi.org/10.1130/G47681.1

Dobrowolska, Agnieszka, and Jarosław Dobrowolski. 2006. *Heliopolis: Rebirth of the City of the Sun*. Cairo: American University Press. https://www.google.com/books/edition/Heliopolis/g1s80vojgmEC

EIA. 2023a. “Forms of Energy.” US Energy Information Administration. Accessed January 23, 2023. https://www.eia.gov/energyexplained/what-is-energy/forms-of-energy.php

———. 2023b. “Laws of Energy.” US Energy Information Administration. Accessed January 23, 2023. https://www.eia.gov/energyexplained/what-is-energy/laws-of-energy.php

———. 2023c. “What Is Energy?” US Energy Information Administration. Accessed January 23, 2023. https://www.eia.gov/energyexplained/what-is-energy/laws-of-energy.php

Franzke, Christian L. E., Alessio Ciullo, Elisaveth A. Gilmore, Denise Margaret Matias, Nidhi Nagabhatla, Anton Orlov, Shona K. Paterson, Jürgen Scheffran, and Jana Sillmann. 2022. “Perspectives on Tipping Points in Integrated Models of the Natural and Human Earth System: Cascading Effects and Telecoupling.” *Environmental Research Letters* 17(1): 015004. https://doi.org/10.1088/1748-9326/ac42fd

Fumo, James T., Melissa L. Carter, Reinhard E. Flick, Linda L. Rasmussen, Daniel L. Rudnick, and Sam F. Iacobellis. 2020. “Contextualizing Marine Heatwaves in the Southern California Bight Under Anthropogenic Climate Change.” *JGR Oceans* 125(5): e2019JC015674. https://doi.org/10.1029/2019JC015674

Groma, Veronika, Bálint Alföldy, Endre Börcsök, Ottó Czömpöly, Péter Füri, Annamária Horvánthné Kéri, Gabriella Kovács, Szabina Török, and János Osán. 2022. “Sources and Health Effects of Fine and Ultrafine Aerosol Particles in an Urban Environment.” *Atmospheric Pollution Research* 13(2): 101302. https://doi.org/10.1016/j.apr.2021.101302

Hansen, James, and Larissa Nazarenko. 2004. “Soot Climate Forcing via Snow and Ice Albedos.” *PNAS* 101(2): 423–428. https://doi.org/10.1073/pnas.2237157100

Hansen, James, Larissa Nazarenko, Reto Ruedy, Makiki Sato, Josh Willis, Anthoney Del Genio, Dorothy Kock, Andrew Lacis, Ken Lo, Surabi Menon, Tica Novakov, Judith Perlwitz, Gary Russel, Gavin A. Schmidt, and Nicholas Tausnev. 2005. “Earth’s Energy Imbalance: Confirmation and Implications.” *Science* 308(5727): 1431–1435. https://doi.org/10.1126/science.1110252

Hartmann, Thom. 2004. *The Last Hours of Ancient Sunlight: The Fate of the World and What We Can Do Before It’s Too Late*. New York: Three Rivers Press. https://www.penguinrandomhouse.ca/books/76441/the-last-hours-of-ancient-sunlight-revised-and-updated-third-edition-by-thom-hartmann/9781400051571

Heinze, Christoph, Thorsten Blenckner, Helena Martins, Dagmara Rusiecka, Ralf Döscher, Marion Gehlen, Nicolas Gruber, Elisabeth Holland, Øystein Hov, Fortunat Joos, John Brian Robin Matthews, Rolf Rødven, and Simon Wilson. 2021. “The Quiet Crossing of Ocean Tipping Points.” *PNAS* 118(9): e2008478118 https://doi.org/10.1073/pnas.2008478118

IPCC. 2021. “Summary for Policymakers.” In *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, 3−32. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/

Kusumaningtyas, Sheila Dewi Ayu, Edvin Aldrian, Trinah Wati, Dwi Atmoko, and Sunaryo Sunaryo. 2018. “The Recent State of Ambient Air Quality in Jakarta.” *Aerosol and Air Quality Research* 18(9): 2343–2354. https://doi.org/10.4209/aaqr.2017.10.0391

Labe, Zachary. 2020. “Warm Arctic, Cold Siberia Pattern: Role of Full Arctic Amplification Versus Sea Ice Loss Alone.” *Geophysical Research Letters* 47(17): e2020GL088583. https://doi.org/10.1029/2020GL088583

Lenton, Timothy M., Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen, and Hans Joachim Schellnhuber. 2019. “Climate Tipping Points—Too Risky to Bet Against.” *Nature* 575: 592–595. https://doi.org/10.1038/d41586-019-03595-0

Lewis, Sophie, and Andrew D. King. 2015. “Dramatically Increased Rate of Observed Hot Record Breaking in Recent Australian Temperatures.” *Geophysical Research Letters* 42(18):7776–7784. https://doi.org/10.1002/2015GL065793

Levitus, Sydney, John I. Antonov, Timothy P. Boyer, and Cathy Stephens. 2000. “Warming of the World Ocean.” *Science* 287(5461): 2225–2229. https://doi.org/10.1126/science.287.5461.2225

Levitus, S., J. I. Antonov, T. P. Boyer, O. K. Baranova, H. E. Garcia, R. A. Locarnini, A. V. Mishonov, J. R. Reagan, D. Seidov, E. S. Yarosh, and M. M. Zweng. 2012. “World Ocean Heat Content and Thermosteric Sea Level Change (0–2000 m), 1955–2010.” *Geophysical Research Letters* 39(10): L10603. https://doi.org/10.1029/2012GL051106

Li, Jing, Barbara E. Carlson, Yuk L. Yung, Daren Lv, James Hansen, Joyce E. Penner, Hong Liao, V. Ramaswarmy, Ralph A. Kahn, Peng Zhang, Oleg Dubovik, Aijun Ding, Andrew A. Lacis, Lu Zhang, and Yueming Dong. 2022. "Scattering and Absorbing Aerosols in the Climate System." *Nature Reviews Earth & Environment* 3: 363–379. https://doi.org/10.1038/s43017-022-00296-7

Liang, Shunlin, Dongdong Wang, Tao He, and Yunyue He. 2019. "Remote Sensing of Earth's Energy Budget: Synthesis and Review." *International Journal of Digital Earth* 12(7): 737–780. https://doi.org/10.1080/17538947.2019.1597189

Lindsey, Rebecca. 2022. "Climate Change: Atmospheric Carbon Dioxide." NOAA Climate. June 23, 2022. https://www.climate.gov/news-feature...carbon-dioxide

Lindsey, Rebecca, and Luann Dahlman. 2020. "Climate Change: Ocean Heat Content." NOAA Climate. August 17, 2020. https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

———. 2023. "Climate Change: Global Temperature." NOAA Climate. January 18, 2023. https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

Liu, Wenling, Ziping Xu, and Tianan Yang. 2018. "Health Effects of Air Pollution in China." *International Journal of Environmental Research and Public Health* 15(7): 1471. https://doi.org/10.3390%2Fijerph15071471

Meehl, Gerald A., Claudia Tebaldi, Guy Walton, David Easterling, and Larry McDaniel. 2009. "Relative Increase of Record High Maximum Temperatures Compared to Record Low Minimum Temperatures in the US." *Geophysical Research Letters* 36(23): L23701. https://doi.org/10.1029/2009GL040736

Meyssignac, Benoit, Tim Boyer, Zhongxiang Zhao, Maria Z. Hakuba, Felix W. Landerer, Detlef Stammer, Armin Köhl, Seiji Kato, Tristan L'Ecuyer, Michael Ablain, John Patrick Abraham, Alejandro Blazquez, Anny Cazenave, John A. Church, Rebecca Cowley, Lijing Cheng, Catia M. Domingues, Donata Giglio, Viktor Gouretski, Masayoshi Ishii, Gregory C. Johnson, Rachel E. Killick, David Legler, William Llovel, John Lyman, Matthew Dudley Palmer, Steve Piotrowicz, Sarah G. Purkey, Dean Roemmich, Rémy Roca1, Abhishek Savita, Karina von Schuckmann, Sabrina Speich, Graeme Stephens, Gongjie Wang, Susan Elisabeth Wijffels, and Nathalie Zilberman. 2019. "Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance." *Frontiers in Marine Science* 6: 432. https://doi.org/10.3389/fmars.2019.00432

Middleton, W. E. Knowles. 1966. *A History of the Thermometer and Its Use in Meteorology*. Baltimore: John Hopkins University Press. https://www.google.com/books/edition/A_History_of_the_Thermometer_and_Its_Use/PApRAAAAMAAJ

Muller, C. 2014. "The Carrington Solar Flares of 1859: Consequences on Life." *Origins of Life and Evolution of Biospheres* 44: 185–195. https://doi.org/10.1007/s11084-014-9368-3

NASA. 2001. "Earth at Perihelion." NASA Solar System Exploration. January 3, 2001. https://science.nasa.gov/science-news/science-at-nasa/2001/ast04jan_1

———. 2016a. "The Earth's Radiation Budget." NASA Science. Accessed January 23, 2023. https://science.nasa.gov/ems/13_radiationbudget

———. 2016b. "Introduction to the Electromagnetic Spectrum." NASA Science. Accessed January 23, 2023. https://science.nasa.gov/ems/01_intro

———. 2019a. "Oort Cloud." NASA Solar System Exploration. December 19, 2019. https://solarsystem.nasa.gov/solar-system/oort-cloud/overview/

———. 2019b. "The Solar Wind Across Our Solar System." NASA Solar System Exploration. Accessed January 23, 2023. https://solarsystem.nasa.gov/resources/2288/the-solar-wind-across-our-solar-system/

———. 2021. "Our Sun." NASA Solar System Exploration. Accessed January 23, 2023. https://solarsystem.nasa.gov/solar-system/sun/in-depth/

———. 2022. "Why Is the Sky Blue?" NASA Science Space Place. August 29, 2022. https://spaceplace.nasa.gov/blue-sky/en/

climate_resources/240/the-greenhouse-effect-simplified/

———. 2023a. "The Greenhouse Effect, Simplified." NASA Global Climate Change. Accessed January 23, 2023. https://climate.nasa.gov/

———. 2023b. “Stars.” NASA Science. Accessed March 14, 2023. https://science.nasa.gov/astrophysics/focus-areas/how-do-stars-form-and-evolve

———. 2023c. “What Is the Greenhouse Effect?” NASA Global Climate Change. Accessed January 23, 2023. https://climate.nasa.gov/faq/19/what-is-the-greenhouse-effect/

NWS. 2023. “The Atmospheric Window.” National Weather Service. Accessed January 23, 2023. https://www.weather.gov/jetstream/absorb

Pearson, Mike Parker, Andrew Chamberlain, Many Jay, Peter Marshall, Josh Pollard, Colin Richards, Julian Thomas, Chris Tilley, and Kate Welham. 2009. “Who Was Buried at Stonehenge?” *Antiquity* 83(319): 23–39. https://doi.org/10.1017/S0003598X00098069

Rhein, Monika, Stephen R. Rintoul, Shigeru Aoki, Edmo Campos, Don Chambers, Richard A. Feely, Sergey Gulev, Gregory C. Johnson, Simon A. Josey, Andrey Kostianoy, Cecilie Mauritzen, Dean Roemmich, Lynee D. Talley, and Fan Wan. 2013. “Observations: Ocean.” In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 255–315. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/ar5/wg1/

Riley, Pete, Dan Baker, Ying D. Liu, Pekka Verronen, Howard, Singer, and Manuel Güdel. 2018. “Extreme Space Weather Events: From Cradle to Grave.” *Space Science Reviews* 214: 21. https://doi.org/10.1007/s11214-017-0456-3

Rossby, Carl-Gustaf. 1959. “Current Problems in Meteorology.” In *The Atmosphere and Sea in Motion: Scientific Contributions to the Rossby Memorial Volume*. Edited by Burt Bolin. New York: Rockefeller Institute Press. https://books.rupress.org/catalog/book/atmosphere-and-sea-motion

Samset, B. H., M. Sand, C. J. Smith, S. E. Bauer, P. M. Forster, J. S. Fuglestvedt, S. Osprey, and C.-F. Schleussner. 2018. “Climate Impacts from a Removal of Anthropogenic Aerosol Emissions.” *Geophysical Research Letters* 45(2): 1020–1029. https://doi.org/10.1002/2017GL076079

Scripps Institution of Oceanography (@scripps_ocean). “Today’s surface reading of 76.5 F is a daily record, and yesterday’s 79.5 F is a tie for the warmest water temp off the Scripps Pier since readings began in 1916.” August 24, 2020. https://twitter.com/Scripps_Ocean/status/1298030487479316480

Taha, Haider. 1997. “Urban Climates and Heat Islands: Albedo, Evapotranspiration, and Anthropogenic Heat.” *Energy and Buildings* 25(2): 99–103. https://doi.org/10.1016/S0378-7788(96)00999-1

Tollefson, Jeff. 2021. “IPCC Climate Report: Earth Is Warmer Than It’s Been in 125,000 Years.” *Nature* 596: 171–172. https://doi.org/10.1038/d41586-021-02179-1

Towers, Sherry. 2016. “Astronomical Alignments of the Sun Temple Site in Mesa Verde National Park.” *arXiv*: 1610.07462. https://doi.org/10.48550/arXiv.1610.07463

Trenberth, Kevin E., John T. Fasullo, and Jeffrey Keihl. 2009. “Earth’s Global Energy Budget.” *Bulletin of the American Meteorological Society* 90(3): 311–324. https://doi.org/10.1175/2008BAMS2634.1

Vahmani, P., and G. A. Ban-Weiss. 2016. “Impact of Remotely Sensed Albedo and Vfraction on Simulation of Urban Climate in WRF-Urban Canopy Model: A Case Study of the Urban Heat Island in Los Angeles.” *JGR Atmospheres* 121(4): 1511–1531. https://doi.org/10.1002/2015JD023718

von Schuckmann, Karina, Lijing Cheng, Matthew D. Palmer, James Hansen, Caterina Tassone, Valentin Aich, Susheel Adusumilli, Hugo Beltrami, Tim Boyer, Francisco José Cuesta-Valero, Damien Desbruyères, Catia Domingues, Almudena García-García, Pierre Gentine, John Gilson, Maximilian Gorfer, Leopold Haimberger, Masayoshi Ishii, Gregory C. Johnson, Rachel Killick, Brian A. King, Gottfried Kirchengast, Nicolas Kolodziejczyk, John Lyman, Ben Marzeion, Michael Mayer, Maeva Monier, Didier Paolo Monselesan, Sarah Purkey, Dean Roemmich, Axel Schweiger, Sonia I. Seneviratne, Andrew Shepherd, Donald A. Slater, Andrea K. Steiner, Fiammetta Straneo, Mary-Louise Timmermans, and Susan E. Wijffels. 2020. “Heat Stored in the Earth System: Where Does the Energy Go?” *Earth System Science Data* 12: 2013–2041. https://doi.org/10.5194/essd-12-2013-2020

Westervelt, W. D. 1910. *Legends of Ma-Ui—A Demigod of Polynesia and of His Mother Hina*. Honolulu: The Hawaiian Gazette Co., Ltd. https://www.gutenberg.org/files/32601/32601-h/32601-h.htm

Winiger, P., T. E. Barrett, R. J. Sheesley, L. Huang, S. Sharma, L. A. Barrie, K. E. Yttri, N. Evangeliou, S. Eckhardt, A. Stohl, Z. Klimont, C. Heyes, I. P. Semiletov, O. V. Dudarev, A. Charkin, N. Shakova, H. Holmstrand, A. Andersson, and Ö. Gustafsson. 2019. "Source Apportionment of Circum-Arctic Atmospheric Black Carbon from Isotopes and Modeling." *Science Advances* 5(2): eaau8052. https://doi.org/10.1126/sciadv.aau8052

Yang, Yang, Lili Ren, Huimin Li, Hailong Wang, Pinya Wang, Lei Chen, Xu Yue, and Hong Liai. 2020. "Fast Climate Responses to Aerosol Emission Reductions During the COVID-19 Pandemic." *Geophysical Research Letters* 47(19): e2020GL089788. https://doi.org/10.1029/2020GL089788

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CHAPTER OVERVIEW

10: The Surface Circulation

Though oceanographers and sailors give names to the surface currents that flow beside coastlines and along the equator—part of what's known as the **surface circulation**—these are not, in fact, the only currents in the world ocean. An arguably more important, albeit weaker and slower, set of currents churn in the abyssal ocean—the **deep circulation**. Traditionally, oceanographers have treated surface and deep circulation as two independent systems. However, in recent decades, they have increasingly recognized that these are part of one global ocean circulation system—the **world ocean circulation**, what physical oceanographers formally refer to as the **meridional** (muh-RID-ee-un-ul) **overturning circulation**, or MOC (e.g., Knauss and Garfield 2017).

While the emphasis on a world ocean circulation remains important, students of oceanography find it easier to tackle each part separately. Like Dr. Dolittle's famous two-headed beast, the pushmi-pullyu, the world ocean circulation operates as a single system simultaneously driven by processes at the surface and within the deep. They're parts of the same beast—the world ocean circulation. Nevertheless, in the interest of preventing your head from being pushed and pulled in two directions, the surface and deep circulation are presented here in separate chapters.

10.1: Main Features
10.2: Boundary Currents
10.3: West Wind Drift Currents
10.4: Polar Ocean Currents
10.5: Understanding Ocean Motions
10.6: Ocean Currents Up Close
10.7: Monsoonal Circulation
10.8: Final Thoughts
10.9: Chapter References

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10.1: Main Features

In this chapter, we largely follow the terminology and definitions adopted by Talley et al. (2011). Additional references are cited where helpful.

The surface circulation crosses the ocean like a vast network of oceanic rivers. However, unlike rivers, the currents that make up the surface circulation in each basin form an ensemble of currents known as **oceanic gyres**, or simply gyres. The word comes from the Greek word *gyros*, translated as "circle or ring." It describes a system of currents that rotate around a common center like spokes on a wheel. The centers of the oceanic gyres can be found in two general locations in the world ocean: the **subtropical gyres**, straddling the Tropic of Cancer and the Tropic of Capricorn; and the **subpolar gyres**, adjacent to the Arctic and Antarctic Circles. Their boundaries are fluid and may change seasonally, but these two gyre archetypes—subtropical and subpolar—help us simplify the complex patterns of the surface circulation and allow us to make some broad generalizations.

I should also note that oceanographers refer to currents that move along lines of latitude—east to west or west to east—as **zonal currents**. The equatorial currents and the west wind drift currents represent examples of zonal currents in a gyre. Currents that move along lines of longitude—toward the poles or the equator—are referred to as **meridional currents**. The California Current along the West Coast of the US and the Gulf Stream along the East Coast represent meridional currents in a gyre. Look for other examples in Figure 17.10.

Subtropical Gyres

As pointed out by Roemmich et al. (2016), most people in the world live under weather patterns influenced by the subtropical gyres. Five major subtropical gyres occupy the three major ocean basins: the **North Pacific Gyre** (NPG), **South Pacific Gyre** (SPG), **North Atlantic Gyre** (NAG), **South Atlantic Gyre** (SAG), and the **South Indian Gyre** (SIG)—one for each major ocean basin except the North Indian. Squeezed and shortened by the presence of the Indian subcontinent, the North Indian Ocean basin lacks a true gyre, but in its place lives a fascinating system of currents that change direction seasonally (see below). Note that the gyres in the Northern Hemisphere rotate clockwise, while the Southern Hemisphere gyres rotate counterclockwise. These rotations result, of course, from the Coriolis force (introduced in Chapter 15).

Polar and Subpolar Gyres

Polar gyres exist only in the Arctic Ocean whose waters reach the very highest latitudes of the world ocean. Here we find the **Beaufort Gyre** (BG) in the Beaufort Sea—named after Irish hydrographer Sir Francis Beaufort (1774–1857). This gyre spins clockwise in the Arctic Basin (when viewed from above).

Subpolar gyres occur at latitudes above 60°. Generally, landmasses restrict their size in the Northern Hemisphere, while in the Southern Hemisphere, the Antarctic Circumpolar Current (described below) sweeps such a broad path that its gyres are confined to a few locations nestled against Antarctica.

Like their subtropical counterparts, subpolar gyres are named and feature zonal and meridional currents that mark their boundaries. They don't rotate consistently because at these smaller scales, the momentum of the currents that feed them and the shape of the land that surrounds them govern their behavior. Nevertheless, they exert an important influence on regional oceanographic and meteorological conditions.

Notable in the North Pacific are the **Alaskan Gyre** (AG), where we find the northward-flowing coastal-hugging Alaska Current; and the **Western Subarctic Gyre** (WSAG), fed by the East Kamchatka and Oyashio Currents. In the Southern Ocean, two subpolar gyres can be found. The **Ross Gyre** (RG) acts as a gatekeeper for warm-water exchanges between the Antarctic Circumpolar Current and the Ross Sea—a broad, shallow sea located at the "mouth" of the elephant head–shaped continent. It occupies a region roughly between East and West Antarctica (e.g., Dotto et al. 2018). Across the "trunk" of the West Antarctic peninsula lies the Weddell Sea and the **Weddell Gyre** (WG), a site of bottom water formation thought to be critically important to world ocean circulation and climate change (e.g., Vernet et al. 2019).

Equatorial Currents

In all three major basins—Atlantic, Pacific, and Indian—currents flow along the equator from east to west in a complex of currents known as the **equatorial currents**. Occupying the tropical regions of our planet, this set of currents receives the most intense solar

radiation. As their waters move from east to west, they warm up. By the time they travel the full width of the basin, their waters reach their highest temperatures. Indeed, the warmest waters in the world ocean can generally be found at the western terminus of the equatorial currents, places such as the Caribbean Sea and coastal Brazil, the Philippine Sea and Indonesian Seas, and north of Madagascar off the coast of Somalia, where modern-day pirates skulk.

The principal equatorial currents include the **North Equatorial Current** (NEC), the **South Equatorial Current** (SEC), the **North Equatorial Countercurrent** (NECC), the **South Equatorial Countercurrent** (SECC), and the **Equatorial Undercurrent** (EUC) in the Pacific, Atlantic, and Indian Oceans. Note that in the Pacific Ocean, the **Equatorial Undercurrent** is also known as the Cromwell Current, named after the man who discovered it, Scripps oceanographer Townsend Cromwell (1922–1958). In the Pacific Ocean, the South Equatorial Current exists as a broad, westward-flowing current that flows along the equator in both hemispheres. The South Equatorial Countercurrent develops seasonally as an eastward flow in the western part of the basin (e.g., Chen and Qiu 2004). In the Atlantic Ocean, the South Equatorial Current develops two additional branches: the **North South Equatorial Current** (NSEC) and the **Central South Equatorial Current** (CSEC). In the Indian Ocean, the South Equatorial Current and Equatorial Undercurrent only develop seasonally (e.g., Phillips et al. 2021).

Equatorial currents move waters from the eastern sides of ocean basins to their western sides. Indeed, oceanographers use the terms eastern and western to distinguish the eastern and western halves of ocean basins. For example, the US West Coast lies along the eastern North Pacific while the US East Coast lies along the western North Atlantic. It can get a bit confusing, but it helps to remember that eastern refers to the right-hand side of the basin while western refers to the left-hand side. Just remember western US (left-hand side of the continent) and eastern US (right-hand side of the continent) and apply the same reasoning to figure out which side of an ocean basin you're on.

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10.2: Boundary Currents

The continental borders of the eastern and western halves of ocean basins define a set of important surface currents known as the **boundary currents**. Coined by American meteorologist Jule Gregory Charney (1917–1981; Charney 1955), "boundary current" has come to define the types of currents found at the edges—eastern and western—of the ocean basins. The **western boundary currents** flow along the east coasts of continents, while **eastern boundary currents** flow along the west coasts. The western and eastern boundaries refer to the ocean basins, not the continents. The western edge of an ocean basin is the eastern edge of a continent, and vice versa. Boundary currents represent the veins and arteries of the gyre circulation. They carry cold water toward the equator and warm water toward the poles. Western boundary currents move warm water poleward, while eastern boundary currents move colder water toward the equator. In this way, they act as the main transporters of heat in the world ocean and play an important role in atmospheric heat transport in the Northern Hemisphere (e.g., Palter 2015).

Whereas western boundary currents might be considered the *mas macho* of ocean currents—strong, fast, and intense—eastern boundary currents tend to be more chill—slow, broad, and diffuse. Western boundary currents gain their strength from global wind patterns and the Coriolis force, while eastern boundary currents profit from regional winds that blow seasonally along their length. Coastlines adjacent to western boundary currents experience warmer ocean temperatures and higher humidity. Eastern boundary current coastlines cope with colder water temperatures and abundant fog. Both boundary currents can enhance biological productivity and support active global and regional fisheries (e.g., Palomares and Pauly 2019).

Western Boundary Currents

Five major western boundary currents can be found in the subtropical gyres: the **Kuroshio Current** (KURO; pronounced cur-o-shee-o, with no syllable emphasized, as is common in Japanese), the **Gulf Stream** (GUST), the **East Australian Current** (EAUC), the **Brazil Current** (BC), and the **Agulhas Current** (AGUC). Several minor western boundary currents can be found at various locations—tropical, subtropical, and subpolar—around the world ocean. These minor currents exert considerable and important influence over local and, in some cases, global oceanographic processes. They may not be main arteries, but they feed important "organs" of the world ocean circulation.

Western boundary currents move volumes of water exceeding those of the world's largest rivers. Two western boundary currents—the Kuroshio Current and the Gulf Stream—exhibit flows up to 140 Sverdrups (Sv, a unit equal to 1 million m^3/second). That's some 70 times greater than the Amazon River with a mean flow of 0.2 Sverdrups. In South Florida, where I grew up, the Gulf Stream approaches within a few miles of the coast, where it's clearly visible against the eastern horizon. Standing on the beach, you can watch the massive undulating ripples of the current moving at speeds up to 4 knots (4.6 mph). Ships struggle against the flow, and scuba divers caught in the current haven't got a chance. Many a planned reef dive ends up as a drift dive when the Gulf Stream is running close to shore.

In satellite images, western boundary currents appear like rivers winding back and forth along the edge of coastal seas. Their fluid "banks" meander, that is, they move in a snake-like motion. Occasionally, one of these meanders turns back on itself and pinches off, forming unusually large and coherent mesoscale eddies called **rings**. Think of them as giant, slow-moving whirlpools (minus the ship-endangering suction effect as seen in *Pirates of the Caribbean: At World's End*; Verbinski 2007). Rings can be found throughout the world ocean, but they are best known in the Kuroshio and Gulf Stream where they have been studied for decades.

Oceanographers recognize two types of rings: **cold-core rings** that trap cold oceanic water inside a donut of warm boundary current water, and **warm-core rings**, which are the opposite—warm water trapped inside a ring of cold water. Rings are common to both currents but most prevalent in the Gulf Stream, which produces an average of 33 cold-core rings and 26 warm-core rings annually (e.g., Silver et al. 2021). Their structure differs markedly. Cold-core rings spin outward toward the middle of the gyre in a cyclonic rotation (counterclockwise in the Northern Hemisphere), while warm-core rings spin toward land in an anticyclonic rotation (e.g., The Ring Group 1981; Olson 1991; Faghmous et al. 2015; Gangopadhyay et al. 2020). The interior of cold-core rings traps nutrient-rich water that promotes phytoplankton blooms (e.g., Conway et al. 2018). Warm-core rings generate deep mixing that entrains nutrients and also supports blooms equal to or greater than those of cold-core rings (e.g., Dufois et al. 2016). Phytoplankton, of course, provide a food source in what is otherwise an oceanic desert—the central regions of the oceanic gyres. These features provide an excellent example of the interactions among the physics, chemistry, and biology of the ocean (e.g., McGillicuddy 2016; Gaube and McGillicuddy 2017; Xu et al. 2019).

The energy in eddies can also contribute to a recirculation of water within the main flow, known as a **recirculation gyre**. When averaged over time and space, these recirculation gyres appear as persistent features of a western boundary current and act to increase the volume of its flow. Both the Kuroshio and Gulf Stream current systems exhibit permanent recirculation gyres that loop back and reconnect downstream (e.g., Imawaki et al. 2013). Along the way, they interact with other currents and water masses. Ultimately, they feed modified water back into the main flow. Understanding recirculation in western boundary currents proves important for estimating heat transport from the tropics to the poles and for projections of the effects of climate change on ocean circulation (e.g., Delman and Lee 2021).

Eastern Boundary Currents

Five major eastern boundary currents can be found in the world ocean: the **California Current System** (CACS); the **Peru–Chile Current** (PECH), also known as the Peru Current or the Humboldt Current (HUMC); the **Canary Current** (CANC); the **Benguela Current** (BENC); and the longest boundary current—at more than 3,400 miles (approximately 5,500 km)—the poleward-flowing (instead of the usual equatorward-flowing) **Leeuwin Current** (LEEC; pronounced LOO-win). Now, scholars of boundary currents and alert students may note that most websites and textbooks still refer to the **West Australian Current** (WAUC) as the eastern boundary current in the South Indian Ocean. However, some decades ago, oceanographers recognized that a warm-water, southward-flowing current occurred along the West Australian coast. They named it for the first ship that explored the area in 1622—the *Leeuwin*, the Dutch word for lioness (Cressell and Golding 1980). No longer classified as an eastern boundary current, the West Australia Current refers to the broad northward flow of water in the eastern half of the South Indian Ocean. Update your charts.

Like western boundary currents, eastern boundary currents gain at least part of their strength from the gyre-scale wind patterns and the Coriolis force. But they also draw energy from seasonal winds that cause **upwelling**, the upward movement of subsurface waters toward the surface (e.g., Talley et al. 2011). If you look at eastern boundary currents in satellite images, you can often see jets of cold, blue water streaming along their paths. These pockets of cold water, drawn from depths between 164 and 984 feet (50–300 m), also bring with them an abundant supply of biologically important nutrients. In the days following an upwelling event, a green tint will begin to appear in the upwelled waters as phytoplankton divide and proliferate. Soon, meandering filaments of green take over the scene as the phytoplankton bloom reaches its peak. Eastern boundary currents are some of the most productive waters on the planet, supporting some 20 percent of the world's coastal fisheries (e.g., Kämpf and Chapman 2016).

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10.3: West Wind Drift Currents

The currents that flow along the northern boundary (in the Northern Hemisphere) or southern boundary (in the Southern Hemisphere) of the subtropical gyres move water left to right—that is, from west to east, or zonally, just like the equatorial currents. Some oceanographers refer to these eastward-flowing currents as the **west wind drift currents**, after the winds that generate them—the westerlies (e.g., Talley et al. 2011, 308). This terminology has not gained widespread use, but it provides a convenient means for students to distinguish the four parts of a subtropical gyre, so I've adopted it here.

The westerlies blow in broad bands west to east at middle latitudes in each hemisphere. These winds drive the northern and southern limbs of the subtropical gyres in the Northern and Southern Hemispheres, respectively. In the Northern Hemisphere, the broad, slow-moving west wind drift currents flow at middle latitudes—around 40°N in the North Pacific and 50°N in the North Atlantic. They transport warm water zonally across the basin, where the currents encounter the North American or Eurasian continents. In the Southern Hemisphere, the west wind drift currents interact with the Antarctic Circumpolar Current (discussed below).

The principal west wind drift currents include the **North Pacific Current** (NPC), the **North Atlantic Current** (NAC), the **South Pacific Current** (SPC), the **South Atlantic Current** (SAC), and the **South Indian Current** (SIC). Until recently, the South Pacific Current, South Atlantic Current, and the South Indian Current were thought to be part of the Antarctic Circumpolar Current. Oceanographers now recognize these as distinct currents flowing along the southern boundaries of their respective gyes (e.g., Talley et al. 2011).

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10.4: Polar Ocean Currents

The polar oceans occupy unique positions in the world ocean circulation. Both contribute mightily to the deep circulation, but their role in the surface circulation has gained increased attention as the linkages between the surface and deep circulation become better understood.

Central to the surface and deep circulation is the **Antarctic Circumpolar Current**, or ACC. The Antarctic Circumpolar Current occupies the southernmost limb of all three subtropical gyres in the Southern Hemisphere. From this vantage point, it controls flows of surface and deep water into the major ocean basins and influences their properties (as we shall see in Chapter 18). In this way, the Antarctic Circumpolar Current acts as the Grand Mix Master of the world ocean. Like a DJ, it samples, blends, and invents unique combinations of water masses that it distributes throughout the ocean. (Cue DJ Spooky, who actually visited Antarctica and composed a musical work in tribute to this extraordinary continent.)

The Arctic Ocean basin—first observed by Norwegian oceanographer Fridtjof Nansen (1861–1930)—hosts two wind- and buoyancy-driven current systems that deserve our attention for their role in sea ice dynamics, climate change, and the general circulation of the Atlantic Ocean. Along the eastern (southward-flowing) extension of the Beaufort Gyre, we find the **Transpolar Drift Stream** (TPD). This current flows off the Siberian Shelf and transports water and sea ice into the Norwegian, Greenland, and Iceland Seas. Dramatic warming and changes in sea ice and freshwater flows in this region have generated concern among polar oceanographers for disruptions to Arctic ecosystems, Arctic peoples, and global climate (e.g., Proshutinsky et al. 2015; Timmermans and Marshall 2020). An ice-free, summertime Arctic has major implications for maritime, political, and military interests. The **Transpolar Sea Route**, a hypothesized shipping lane from the Atlantic to the Pacific across the Arctic Ocean, may become a reality by the 2040s (e.g., Bennett et al. 2020; Crawford et al. 2021).

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10.5: Understanding Ocean Motions

Before taking a closer look at individual currents, it's helpful to learn a little about the planetary, atmospheric, and oceanic factors that generate flows in the ocean. While this is a bit of an advanced topic—and one which students of physical oceanography learn about in great detail—a brief summary for the introductory students provides insights into the machinery that makes the ocean move.

Ekman Transport

Fridtjof Nansen was a Norwegian explorer and oceanographer. He was also a great humanitarian and helped half a million former prisoners of World War I repatriate in countries around the world. For this he was awarded the Nobel Peace Prize in 1922, the only oceanographer ever to receive a Nobel Prize. Nansen's contributions remain relevant today. He invented the Nansen bottle (still in use for water sampling) and the Nansen closing net, a zooplankton net that opens and closes at depth (still sold today). He is also known for having built a round-bottom ship, the *Fram*, that could not be crushed if the ocean froze around it. It's here where we pick up his story.

Nansen dreamed of being the first person to reach the North Pole. He had already achieved fame as the first person to cross the interior of Greenland on skis. But instead of crossing the frozen ocean on skis, he came up with the idea of letting a ship, the *Fram*, freeze into the sea ice, the movements of which would take him across the North Pole. It was a great idea, in theory. Alas, it was not to be. The drift of the ice and the motions of the underlying currents did not favor a journey over the pole. The *Fram* only made it to 84°4'N. Still determined to make the pole, Nansen set off on dogsled with the athletic Hjalmer Johansen (1867–1913), shipmate and fellow explorer. They made it as far as 86°13.6'N, the farthest north of any men at the time. Rugged ice and lack of food forced them to head west to Franz Josef Land. Conditions forced them to spend the winter in a small hut, where polar bears, walrus, and seals kept them fed. The following June, they were found and rescued by British explorer Frederick Jackson (1860–1938).

Among Nansen's many valuable contributions to our knowledge of Arctic waters, one in particular changed our understanding of ocean circulation. While adrift in the *Fram*, he noted something curious about the interaction of the wind with the ice. The ice appeared to move to the right of the direction of the wind, which he hypothesized was due to Earth's rotation (Nansen 1902, 369). That conclusion, however, would require mathematical proof.

He mentioned this observation to Norwegian meteorologist and oceanographer Vilhelm Bjerknes (1862–1951), who handed the problem to a Swedish graduate student, V. Walfrid Ekman (1874–1954). The son of a physical oceanographer and well versed in mathematics, Ekman had no trouble deriving the solution (Eliassen 1982; Jenkins and Bye 2006). The rotation of the Earth and the associated Coriolis force explained the drift of the ice to the right of the wind in the Northern Hemisphere. What's more, the right-directed surface layer dragged the layer beneath it, causing it to move and also deviate to the right, as did the layer beneath that one, and so on. Ekman likened the effect to a spiral staircase. He published his results in 1902 (in Norwegian) and 1905 (in English), and the phenomenon came to be known as the **Ekman spiral**. Soon it became apparent that the Ekman spiral could explain other water motions as well. And, indeed, the motions of the ocean as driven by the wind-generated Ekman spiral underlie the surface circulation of the world ocean.

The Ekman spiral can be best envisioned as a spiral stack of books. In the Northern Hemisphere, as the wind blows over the surface layer of the ocean—the top book—it slowly moves forward and turns, adopting an angle of 20°–45° to the right of the wind. (In the Southern Hemisphere, the angle is to the left of the wind.) Due to friction, the surface layer drags the layer underneath it—the second book in the stack—and that layer begins to move and turn, adopting an even greater angle relative to the direction of the wind. It also moves more slowly than the surface layer, which moves more slowly than the wind, because the transfer of momentum is never 100 percent efficient. Each successive layer moves a bit more to the right and a bit more slowly. At some point, water layers may even move in the opposite direction of the wind. At the **Ekman depth**—defined as the depth where the current flow is 37 percent of the surface current flow and in a direction 180° opposite the direction of the wind—the Ekman spiral runs out of steam, so to speak, and the motion ceases. You've reached the bottom book.

If we take the average direction of all the water layers from the surface to the Ekman depth, we find that the average direction of water movement is 90° to the right of the wind. So the net transport of water, the net motion caused by a blowing wind, is 90° to the right (or left) of the wind (depending on the hemisphere). The 90° net movement of the ocean by the wind-driven Ekman spiral

is called **Ekman transport**. By way of example, consider that a sustained 20 mph wind will generate a surface current of less than 0.05 mph, or about 236 feet per hour. Slow. That surface current moves in a direction that is 45° to the right of the wind. At depths of roughly 330–500 feet (100–150 m), the much, much slower current moves in the opposite direction—at an angle of 180° to the wind. If we take the average speed and direction of all the layers between the surface and 500 feet (150 m), we find that the net water movement is 90° to the direction of the wind.

Geostrophic Flow

The importance of Ekman transport becomes clear when you consider the effects of the global surface winds on the ocean. You may recall that trade winds blow generally east to west in a region about 20° north and south of the equator. At the same time, the westerlies blow west to east at middle latitudes (30° to 60°). If you consider the flows of water generated by Ekman transport (i.e., 90° to the right or left of the wind, depending on the hemisphere), you might predict that the trade winds will move water toward the poles and the westerlies will move water toward the equator. In theory, water should pile up in the center of the gyres.

Though humans can't discern changes in the height of the sea surface, satellites can. Indeed, scientists using satellite altimeters observe hills of water—from 3 to 6 feet (0.9–1.8 m) high—in the central gyres. You might say that the ocean surface resembles the bumpy appearance of a *pan de muerto* (Mexican bread of the dead)—albeit one stretched over thousands of miles. The bumps represent changes in **sea surface height**, the changes in elevation of the sea surface. Measurements of sea surface height produce maps of **sea surface topography**—the shape of the sea surface.

As discussed in Chapter 4, satellite altimeters send out a pulse of microwave energy and measure quite precisely the time it takes for that pulse to return to the satellite. In principle satellite altimeters work just like sonar or the laser rangefinders used in golfing, construction, or the military. Knowing the speed of the microwave pulse and dividing the time of pulse and return by two (because the pulse goes down and back up, traveling twice the distance), computers aboard the satellite can calculate the height of the sea surface relative to the height of the satellite. These highly sophisticated instruments can actually detect variations in sea surface height on the order of a few millimeters, which is pretty impressive considering they're being done in space. Satellite altimetry reveals a great deal about the circulation of the ocean, tides, climate change, El Niño and La Niña, and even the seafloor, because the ridges and trenches and seamounts create bumps and wiggles on the sea surface.

The increased elevation of the sea surface in the center of the gyres creates a pressure imbalance at the surface of the ocean. Just like water poured on a tabletop tends to spread out, the ocean surface tries to remain level. Pressure imbalances, or pressure gradients—differences in pressure between two locations—in the ocean cause currents, just like pressure gradients in the atmosphere cause winds. Where elevations exist, water begins to flow downhill. But the flow of water is subject to the Coriolis force, just like any current in the ocean. As a result, the water will turn to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Though initially water moves uphill by Ekman transport, it begins to flow back down as a result of the pressure gradient. And as it moves downhill, it is deflected toward the right or left. Eventually, the pressure gradient force and the Coriolis force come in to balance with each other. As a result, the balanced current flows at right angles to the directions of the pressure gradient and the Coriolis force and flows around the sea surface elevation. This balanced current is called a **geostrophic current**, one under the influence of Earth's rotation.

The rotation of geostrophic ocean currents around the sea surface elevations in gyres is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The balance between the wind-driven pressure gradient (caused by Ekman transport) and the Coriolis force explains this pattern. Put another way, the major ocean currents are geostrophic. The geostrophic balance provides a satisfactory explanation for the broad surface circulation patterns that we observe in the world ocean.

Western Intensification

Now, there's one more physical explanation required to explain a difference observed in the surface currents. Don't worry, it's a short explanation, and it doesn't even require you to think.

Along the western boundaries of the gyres—that is, on the western sides of the ocean basins—the surface currents move much more quickly than currents along the eastern sides of the ocean basins. As mentioned earlier, western boundary currents are faster, narrower, and more energetic than eastern boundary currents, which are slower, wider, and less energetic. The difference is explained by something called **western intensification**, which is caused by latitudinal differences in the Coriolis force. That's it.

That’s the explanation. The Coriolis force, which governs the behavior of geostrophic currents, gets stronger from the equator to the poles. The result is a narrowing and intensification of western boundary currents.

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10.6: Ocean Currents Up Close

Now that we know something about the overall patterns of currents and the forces that generate those patterns, let's take a look at some specific examples of individual current systems, especially those that play important roles in human affairs.

The Kuroshio Current: Where Sushi Is Born

Along the western edge of the North Pacific near the equator, the North Equatorial Current splits into southward and northward flows. The southward flow forms the lesser-known **Mindanao Current** (MINC), which originates in the vicinity of the second-largest island in the Philippines, Mindanao, the Land of Promise (Jhian 2016). The northward flow becomes the well-known Kuroshio Current, or "black current" (presumably for its dark blue waters). The Kuroshio officially starts along the coast of Taiwan, then flows north along the coast of southern Japan and splits eastward as the Kuroshio Extension. Off the island of Hokkaido, the Kuroshio meets the southward-flowing **Oyashio Current** (OYAC) (o-ya-shee-o; "parental tide"), forming a massive confluence of currents that flow toward the northwest. Though ranked as the second-largest western boundary current in the ocean, the Kuroshio's influence over people and cultures is unmatched. Its highly productive waters boast dozens of commercially important species and provide a spawning grounds and nursery for Pacific bluefin tuna (Oshima et al. 2017; Ashida et al. 2022). The warm waters of the Kuroshio even allow coral reefs to grow along the coast of Japan, the northernmost coral reefs in the world. But the Kuroshio's use as a "highway" connecting islands and mainland all along its length—the Kuroshio Road, as it is called—has inspired exchanges of resources and cultures since ancient times. As Hyun (2018) expresses it: "The sea in which the Kuroshio Current flows is not just a geographical unit but also an integration of trajectories for those who live and have lived in the area." The Kuroshio maritime culture extends well beyond Japan. You could even argue that sushi's popularity in the US has brought the Kuroshio culture to our shores as well.

The Gulf Stream: The Ocean's First Freeway

Along the East Coast of the United States lies a familiar western boundary current—the Gulf Stream. To the early Spanish explorers, this fast-moving current seemed to flow out of the Gulf of Mexico, which indeed it does. Naturally it was first known as *la Corriente del Golfo*, the Spanish term for Gulf Stream. Had the Gulf Stream been any old current, it would have remained unremarkable in human history. But Spanish sailors in the 1500s soon learned to use the current to quicken their journey home. They managed to keep this knowledge secret for a few decades, but soon other seafaring peoples, especially whalers, fishers, and merchant sailors, learned to use the current to their advantage. In this way the Gulf Stream became known as the most favorable route from the New World to the Old World (e.g., Gaskell 1972; MacLeish 1989; Ulanski 2008).

Historically, the Gulf Stream was first noted in 1513 by Spanish explorer Juan Ponce de Leon (1474–1521) and his skilled navigator, Antonio de Alaminos (1475–1520; Pillsbury 1891). It was first accurately charted in 1733 by British captain and tobacco merchant Walter Hoxton (1699–1741). Though his chart was largely ignored, he clearly understood important details about the Gulf Stream and rightfully deserves credit for the first description (Richardson 1982). Be that as it may, American Founder and inventor Benjamin Franklin (1706–1790) receives popular credit as the first person to systematically chart the Gulf Stream. Franklin served from 1753 to 1774 as the deputy postmaster general for North America (under British rule), and while visiting London in 1768 as part of these duties, he heard complaints about the longer delivery times for westbound (from Britain to the US) versus eastbound mail (US to Britain). Chatting about this problem with his cousin Timothy Folger, a Nantucket whaling captain, Franklin learned that whalers were quite familiar with the current. Folger sketched an outline of the strong current on a chart, and the rest is history, as they say. Franklin published three versions of the chart in 1769, 1780, and 1786. The first two printings were limited to avoid giving away secrets to the British, who were at war with the US from 1775 to 1783 (Lacouture 1995). The 1783 version, the most inaccurate of the three, remained the most popular until the 1978 discovery of the first version in Bibliothèque Nationale in Paris by oceanographer Philip Richardson (Richardson 1980).

Other Western Boundary Currents

While the Kuroshio and Gulf Stream are the poster children of western boundary currents for oceanographers (at least in the Northern Hemisphere), among the movie-watching public, the most famous western boundary current has to be the East Australian Current, the EAC, as depicted in the Disney film *Finding Nemo* (Stanton and Unkrich 2003). This western boundary current in the South Pacific flows southward along the east coast of Australia (hence its name) and serves as a kind of superhighway for marine

life, including fish and sea turtles. Unfortunately, and I really hate to break this to you, there's no evidence that clownfish hitch rides on the backs of sea turtles on the EAC.

In the South Atlantic, the Brazil Current flows sluggishly southward until it meets the **Malvinas Current** (MC; also known as the Falkland Current) off the coasts of Uruguay and Argentina in a region known as the Brazil–Malvinas Confluence (e.g., Artana et al. 2019). This meeting of warm and cold water generates considerable dynamic complexity and a high productivity that supports one of the largest squid fisheries in the world (Alberto et al. 2020).

The California Current System: The Kelp Highway

Near and dear to those of us living on the West Coast of the United States is the eastern boundary current known as the California Current (sorry, Oregon and Washington). This shallow flow of water (surface to 1,000 ft) starts off the coast of British Columbia, Canada (around 48°N) and winds its way south past the tip of Baja and into equatorial waters. Around 15°N to 20°N, it joins the North Equatorial Current. The California Current varies seasonally, with its strongest flows during the upwelling season (July–August, when northerly winds are strongest) and weakest flows (sometimes no flow) during the winter. In general, the main flow of the current can be found offshore about 124 to 186 miles (200 to 300 km).

Most authors describe the California Current and similar eastern boundary currents as wide currents, on the order of 600 miles (1,000 km). Talley et al. (2011) describe the California Current and eastern boundary currents in general as relatively narrow, on the order of 60 miles (100 kilometers). They restrict their definition of eastern boundary currents to the intensified equatorward flows created by Ekman transport and upwelling (narrow in width) versus the general equatorward flow of the eastern Pacific (wide). Indeed, the narrower region defined by Talley corresponds to the "transition zone" identified by Lynn and Simpson (1987), which they describe as the "core" of the California Current.

Indeed, the California Current is best described as a system of currents, and most authors refer to the boundary current of the eastern North Pacific as the California Current System (CCS). In fact, we find several named currents along the coast of California. From the shores of Orange County to the ocean side of the Channel Islands, we are more likely to see mean flows of water to the north rather than to the south. The true California Current flows outside of the Channel Islands. Because of the bathymetry of the California Borderland with its associated islands and the topography of the transverse mountain ranges of Southern California (San Gabriel and San Bernardino), which generate coastal atmospheric eddies, the current splits at the southern end of the Channel Islands. The main branch continues southward but another branch does a U-turn and flows northward along the coastlines of San Diego, Orange County, and Los Angeles. That northerly coastal flow is called the **California Countercurrent**. It is strongest in the fall and winter, when the California Current is weakest. Where the California Countercurrent flows north of Point Conception (just north of Santa Barbara)—along the West Coast to about 48°N—it is called the **Davidson Current**. This current was named after the British-born, American-raised geographer George Davidson (1825–1911), who, among other accomplishments, mapped the Pacific Coast, built the first West Coast astronomical observatory, and served for 17 years as president of the California Academy of Sciences (Lewis 1954). Underneath the Davidson Current is another northward-flowing current, the **California Undercurrent**, which flows at an average depth of about 656 feet (200 meters). The California Undercurrent can be traced from the eastern equatorial Pacific to the northernmost boundary of the California Current. Like other currents in the California Current System, it varies seasonally, reaching peak flows in the fall and winter. Who would expect anything different from a current named after California? We're complicated.

Before we leave the California Current System, we need to pay homage to one of the reasons why the coastal waters of California, Oregon, and Washington support thriving communities of marine life: upwelling. When a northerly wind blows, Ekman transport drives surface waters offshore. The movement of surface water offshore sucks cold, nutrient-rich waters from 328 to 984 feet (100 to 300 meters) to the surface. In satellite images of ocean color, you can see the cold surface waters flowing like paint off the coastline. These upwelled waters bring abundant, dissolved, biologically important nutrients to waters that were previously lacking in them. The result: phytoplankton blooms all along the coast soon after upwelling occurs. Such images beautifully illustrate the link between a physical event—wind-driven upwelling—and a biological event—proliferation of phytoplankton in the presence of upwelled nutrients.

Upwelling also provides habitable temperatures and nutrients for marine seaweeds, such as the giant kelp, the largest seaweed in the world, reaching a length of nearly 200 feet (60 m; e.g., Schiel and Foster 2015). Kelps and similar seaweeds prefer colder waters, which upwelling and the southerly flow of the California Current System help to maintain. The "forests" they create and

their tremendous productivity—the giant kelp can grow more than one foot (0.35 m) per day (e.g., Stewart et al. 2009)—attracts hundreds of species of marine organisms. Their abundance along the Pacific Rim coastline has led some anthropologists to speculate that humans migrated to the Americas from Northeast Asia by watercraft some 16,000 years ago. The so-called **kelp highway**—an ice-free, coastal corridor from Japan to Mexico—would have provided plenty of food, fur, and other materials to sustain their journey (e.g., Erlandson et al. 2015). The kelp highway offers an intriguing and perhaps more accessible alternative to the more commonly accepted land-bridge route, fraught with glaciers.

Other Eastern Boundary Currents

The eastern boundary currents of other ocean basins exhibit features similar to the California Current System—seasonal flows that reverse, jets and eddies, and upwelling-driven productivity. The South Pacific basin is home to the famous Peru-Chile Current—also known as the Humboldt Current, named after Prussian explorer and biogeographer Alexander von Humboldt (1769–1859). This eastern boundary current and its upwellings drive the Peruvian anchoveta fishery, one of the most productive in the world (e.g., Bakun and Weeks 2008). In the North Atlantic basin, the Portugal–Canary Current System bathes the coastlines of Portugal and North Africa. The South Atlantic harbors the Benguela Current, an eastern boundary current that traces its northerly path along the western shores of South Africa. Shipwrecks litter the northern section of the current along coastal Namibia, earning this region the nickname of **Skeleton Coast**. The cold waters of the current and hot desert air generate dangerous fogs here. In the South Indian basin, the Leeuwin Current joins a complex of other currents along the western and southern shores of Australia. Unlike other eastern boundary currents, the Leeuwin Current is generally nutrient-poor and lacks upwelling, though the potential exists for enhanced productivity due to eddies that spin off the current (Waite et al. 2007).

Currents and Winds along the Equator

At the southern terminus of the California Current in the North Pacific, we find the beginnings of the North Equatorial Current, a broad, westward-flowing surface current generally found between latitudes 10°N and 30°N. The North Equatorial Current forms the lower limb of the North Pacific Gyre. The North Equatorial Current is strongly influenced by processes associated with the convergence of trade winds at the Intertropical Convergence Zone (ITCZ). It also interacts with the eastward-flowing Equatorial Countercurrent—sometimes divided into the North and South Equatorial Countercurrents—whose existence is associated with the dynamics of the ITCZ. Of course, this is where the world famous El Niño and La Niña occur. Though not well understood, both El Niño and La Niña affect the flow of the North Equatorial Current, which in turn affects the flow of the Kuroshio and Mindanao (e.g., Wang et al. 2020). This in turn influences fisheries and weather in these regions. One thing leads to another. And while we're here, I have to mention the South Equatorial Current, which you might think (and others have claimed) exists in the Southern Hemisphere. Due to the larger surface area of land in the Northern Hemisphere and larger surface area of ocean in the Southern Hemisphere, the trade winds and ITCZ shift northward, so that the westward-flowing South Equatorial Current flows from about 30°S to 5°N. (Yes, that means part of the South Equatorial Current actually flows into the Northern Hemisphere.)

West Wind Currents: The Weather-Makers

Along the northern boundaries of the North Pacific and North Atlantic subtropical gyres, we find the North Pacific Current and North Atlantic Current, respectively. Though complicated, their flows—highly dependent on the boundary currents to which they connect—exert a great influence on weather patterns in the US and Europe.

From its starting point off the Grand Banks of Newfoundland, the North Atlantic Current immediately splits into two branches. One branch dips southward along the eastern edge of the Gulf Stream Recirculation Gyre, then swings eastward across the Azores, where it is known as the **Azores Current**. A northerly branch takes a bit of a sightseeing tour along the edge of the continental shelf off Newfoundland. This branch swings northeast and northward, following the contours of Flemish Cap, which you may remember from the book *The Perfect Storm* (Junger 2009). Here it acts as a western boundary current along the coast of Newfoundland. This branch splits off the coast of Ireland. A northerly flow becomes the **Norwegian Current**, and a southerly flow moves along the Bay of Biscay toward Portugal. Finally, another branch of the North Atlantic Current follows the traditional route of westerly flows. This branch heads almost due east from the Grand Banks until it reaches the coast of Portugal, where it joins water from its northerly sister branch and a bit of flow from the Azores Current. Together these flows contribute to the surface waters of the Mediterranean Sea as they enter through the Straits of Gibraltar. Suffice it to say that the North Atlantic Current takes more turns than a trip to Grandma's house at Thanksgiving.

The twists and turns of the North Atlantic Current aside, there's a larger principle at work here that gets to the heart of one of the reasons why ocean currents are so important: they affect large-scale weather patterns. Broadly speaking, we can think of the North Atlantic Current as a distribution pipeline for the Gulf Stream. The flows of the North Atlantic Current distribute water, heat, dissolved substances, life, and manmade materials from the Gulf Stream to the east, north, and northeast. The northerly flows of the North Atlantic Current bring warm water farther north than in any other ocean basin. The citizens of the United Kingdom—and much of Europe—owe their damp but temperate weather to the western boundary portion of the North Atlantic Current, which heats air masses moving eastward with the polar jet stream (e.g., Palter 2015).

Another key aspect of the multidirectional flows of the North Atlantic Current is their impact on the circulation of the deep ocean. The flows of the North Atlantic Current influence the formation of deep water masses that are formed in the subarctic North Atlantic. These masses sink and spread throughout the world ocean. The North Atlantic Deep Water may play a role in abrupt climate change, a hypothesis that gained notoriety (albeit in a nonscientific fashion) from the movie *The Day after Tomorrow* (Emmerich 2004). The take-home message here is that surface currents interact with the atmosphere, and these interactions influence Earth's weather and climate. Temporal and spatial variability in surface currents, especially in their energy and mass transport, contribute to temporal and spatial variability in weather and climate. The atmosphere and ocean form a linked system: as one goes, the other goes. A great deal of scientific effort is being spent to understand how the atmosphere and ocean interact.

The same message—coupled air–sea interactions—applies to the North Pacific Ocean. You can blame the weather along the West Coast of the United States—and the Midwest, for that matter—on conditions in the North Pacific Ocean. Just as the Gulf Stream feeds the North Atlantic Current, so too the Kuroshio Current feeds the North Pacific Current. And so temporal and spatial variability in the Kuroshio and the Kuroshio Extension, and their contributions to variability in the North Pacific Current, will influence weather and climate in the western United States (Schulte and Lee 2017). Pretty amazing, huh?

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10.7: Monsoonal Circulation

The Encyclopedia Britannica calls the Indian Ocean "the smallest, geologically youngest, and physically most complex of the world's three major oceans." To that I would add that the Indian Ocean is the least known scientifically, a cruel irony given that it's the one on which humans have sailed since sailing became a thing. Our lack of knowledge of the Indian Ocean strikes home for a more urgent reason: the Indian Ocean strongly influences weather and climate patterns around the world. It connects with the Pacific Ocean through a well-known ocean choke point, the **Indonesian Throughflow**, that acts as a kind of control valve for exchanges of waters between the Pacific, Indian, and even the Atlantic Oceans. And scientists now recognize that the Indian Ocean spawns the **Madden–Julian Oscillation**, an intraseasonal (i.e., within a season), eastward-traveling, globe-trotting atmospheric "wave" that influences weather. As described by Gottschalck (2014):

The MJO can modulate the timing and strength of the monsoons, influence tropical cyclone numbers and strength in nearly all ocean basins, and result in jet stream changes that can lead to cold air outbreaks, extreme heat events, and flooding rains over the United States and North America.

At a time when we need as much knowledge about the climate system as we can muster, our incomplete knowledge of the Indian Ocean remains a hindrance. We cannot protect what we don't understand.

Be that as it may, there is one phenomenon of the Indian Ocean that we understand fairly well: the seasonally reversing wind pattern known as the *mausin* (alternatively, *mausam*) in Arabic, better known as the **monsoon** in English (e.g., Tripati 2017). Characterized by strong winds from the southwest in summer and strong northeast winds in winter, the monsoon brings seasonal changes in rainfall. Given that agricultural productivity in this region feeds a third of the world's population, the monsoon rains are literally a matter of life and death for billions of people (McPhaden et al. 2009). The monsoon winds also bring seasonal changes in ocean currents. In fact, like the winds, the currents in the Indian Ocean change direction in accordance with the seasonally changing winds.

Left Wind, Right Wind, Left Wind

Since the time of the Harappan Civilization, which spanned 3300 to 1700 BCE in the Indus Valley in modern-day Pakistan (e.g., Shinde 2016), people have known about monsoon weather. This should come as no surprise: the monsoon brings seasonal changes in rainfall, and the tens of thousands of people living in cities in this region at that time depended on the rains to produce their food. It appears that by at least 1 CE and perhaps as early as 2500 BCE, Indian Ocean sailors used the monsoon winds to carry out trading voyages (e.g., Tripati 2017). Whether headed east across the Bay of Bengal and Andaman Sea to Indonesia or west across the Arabian Sea to Africa or the Middle East, these early sailors timed their voyages to coincide with the prevailing winds.

During the summer season, heating of the Indian subcontinent results in a kind of giant sea breeze. Hot air rises above the subcontinent, and cooler air from the ocean rushes in to take its place. Because of the Coriolis force, the predominant direction of these winds is from the southwest. This tropical ocean air holds vast amounts of water vapor. So as it rises above the subcontinent and cools, that water vapor is released as torrential rain. The combination of southwest winds and heavy rains characterizes the summer monsoon, also known as the southwest monsoon.

In the winter the situation reverses. The warmer ocean water (as compared to land) generates a circulation similar to a land breeze (albeit a continental-sized one). Winds blow now from the northeast, from the land to the ocean. The winter monsoon, or northeast monsoon, brings dry weather to the Indian subcontinent and beyond.

These seasonally reversing winds meant that sailors could venture from India to the west toward Africa and the Middle East during the winter (northeast) monsoon and return under favorable winds during the summer (southwest) monsoon. Though scholars still debate the timing of the origins of monsoonal sailing, a considerable body of archaeological and cultural evidence appears to support the earlier dates. It makes for a fascinating study and a rich opportunity to learn about the cultural and economic development of India.

Monsoonal Currents

Changes in wind direction cause changes in ocean currents. During the winter monsoon (November–March), the wind patterns in the equatorial Indian Ocean resemble those in the equatorial Atlantic and Pacific. Winds north of the equator blow from the

northeast and winds south of the equator blow from the southeast—a typical trade wind pattern. In this case the currents in the tropical Indian Ocean move toward the west.

Now, the geography of the Indian Ocean and the nature of the currents cause some crossing of the equator by these equatorial currents, but by and large they behave similarly to the equatorial currents in the other ocean basins. A westward-flowing North Equatorial Current is present, though it also goes by the name **Northeast Monsoon Current**. (Do you ever wonder if these currents are in some kind of witness protection program with all their different names?) A South Equatorial Current and Equatorial Countercurrent also exist.

Things get weird in the summer. The onset of the summer monsoon (June–October) winds blowing from the southwest cause a complete reversal of the ocean currents. The North Equatorial Current and the Equatorial Countercurrent disappear and become the **Southwest Monsoon Current**—with current speeds in excess of 2 knots (strong for a current). This strong eastward-flowing current sends branches into the Arabian Sea and Bay of Bengal as well. The South Equatorial Current crawls up the northern coast of Africa and southeastern Arabia, where it's called the Somali Current.

Though our tidy description here makes it all seem quite simple, the circulation of the Indian Ocean is—like some people—complicated. For a deeper look into the details of this circulation, consult Phillips et al. (2021).

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10.8: Final Thoughts

Since humans first ventured into the sea on primitive boats, the surface currents have carried us in search of new opportunities. Even now, the surface currents serve as convenient ocean highways for a myriad of human industries. Unfortunately, the surface currents also carry with them the debris of humanity. As we learned in Chapter 6, “The ocean is downhill from everywhere” (Moore 2023). Indeed, anything tossed onto the ground—even thousands of miles from the ocean—will under the power of winds or moving water make its way into the ocean. Pollutants and toxins, too, released in one part of the ocean make their way to other parts, near and far. It’s an extraordinary journey with a lesson for humans: What happens in one part of the ocean can affect the entire ocean. In other words, what happens *here* doesn’t always stay *here*. Our wastes and byproducts of modern industrial civilization—no matter where they originate—reach all parts of the ocean and every shore.

The world ocean circulation lies at the heart of the concept of a world ocean discussed in Chapter 1: it’s all one ocean. Waters that flow across the surface of the ocean lose buoyancy in polar regions and sink to the abyss. Winds and other mixing processes pull these waters back to the surface. Surface waters that sink in one part of the ocean—say, off the coast of Greenland in the North Atlantic—may travel southward toward the Antarctic, bend eastward below the southern tip of Africa, and be pulled to the surface of the South Pacific a thousand years later. For better or for worse, we are all connected to the same world ocean system.

Our understanding of the surface circulation provides a context for appreciating the interconnectedness of the ocean. To the extent that the ocean connects our activities and our lives, we should always remember it’s all one ocean, our world ocean.

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10.9: Chapter References

Alberto, María Luz Torres, Nicolás Bodnariuk, Marcela Ivanovic, Martín Saraceno, and Eduardo Marcelo Acha. 2020. “Dynamics of the Confluence of Malvinas and Brazil Currents, and a Southern Patagonian Spawning Ground, Explain Recruitment Fluctuations of the Main Stock of *Illex argentinus*.” *Fisheries Oceanography* 30(2): 127–141. https://doi.org/10.1111/fog.12507

Artana, Camila, Christine Provost, Jean-Michel Lellouche, Marie-Hélène Rio, Ramiro Ferrari, Nathalie Sennéchael. 2019. “The Malvinas Current at the Confluence With the Brazil Current: Inferences From 25 Years of Mercator Ocean Reanalysis.” *Journal of Geophysical Research Oceans* 124(10): 7178-7200. https://doi.org/10.1029/2019JC015289

Ashida, Hiroshi, Tamaki Shimose, Yumi Okochi, Yosuke Tanaka, and Sho Tanaka. 2022. “Reproductive Dynamics of Pacific Bluefin Tuna (*Thunnus orientalis*) Off the Nansei Islands, Southern Japan.” *Fisheries Research* 249: 106256. https://doi.org/10.1016/j.fishres.2022.106256

Bakun, Andrew, and Scarla J. Weeks. 2008. “The Marine Ecosystem off Peru: What Are the Secrets of Its Fishery Productivity and What Might Its Future Hold?” *Progress in Oceanography* 79(2–4): 290–299. https://doi.org/10.1016/j.pocean.2008.10.027

Bennett, Mia M., Scott R. Stephenson, Kang Yang, Michael T. Bravo, and Bert De Jongheg. 2020. “The Opening of the Transpolar Sea Route: Logistical, Geopolitical, Environmental, and Socioeconomic Impacts.” *Marine Policy* 121: 104178. https://doi.org/10.1016/j.marpol.2020.104178

Charney, J. G. 1955. “The Gulf Stream as an Inertial Boundary Layer.” *Proceedings of the National Academy of Sciences* 41(10): 731–740. https://doi.org/10.1073/pnas.41.10.731

Chen, Shuiming, and Bo Qiu. 2004. “Seasonal Variability of the South Equatorial Countercurrent.” *Journal of Geophysical Research Oceans* 109: C08003. https://doi.org/10.1029/2003JC002243

Chereskin, T. K. 1995. “Direct Evidence for an Ekman Balance in the California Current.” *Journal of Geophysical Research* 100(C9): 18,261–18,269). https://doi.org/10.1029/95JC02182

Conway, Tim, Jaime B. Palter, and Gregory F. de Souza. “Gulf Stream Rings as a Source of Iron to the North Atlantic Subtropical Gyre .” 2018. *Nature Geoscience* 11: 594–598. https://doi.org/10.1038/s41561-018-0162-0

Crawford, Alex, Julienne Stroeve, Abigail Smith, and Alexandra Jahn. 2021. “Arctic Open-Water Periods Are Projected to Lengthen Dramatically by 2100.” *Communications Earth & Environment* 2: 109. https://doi.org/10.1038/s43247-021-00183-x

Cresswell, G. R., and T. J. Golding. 1980. “Observations of a South-Flowing Current in the Southeastern Indian Ocean.” *Deep Sea Research Part A. Oceanographic Research Papers* 27(6): 449–466. https://doi.org/10.1016/0198-0149(80)90055-2

Delman, Andrews, and Tong Lee. 2021. “Global Contributions of Mesoscale Dynamics to Meridional Heat Transport.” *Ocean Science* 17(4): 1031–1052. https://doi.org/10.5194/os-17-1031-2021

Dotto, Tiago S., Alberto Naveira Garabato, Sheldon Bacon, Michel Tsamados, Paul R. Holland, Jack Hooley, Eleanor Frajka-Williams, Andy Ridout, and Michael P. Meredith. 2018. “Variability of the Ross Gyre, Southern Ocean: Drivers and Responses Revealed by Satellite Altimetry.” *Geophysical Research Letters* 45(12): 6195–6204. https://doi.org/10.1029/2018GL078607

Dufois, François, Nick J. Hardman-Mountford, Jim Greenwood, Anthony J. Richardson, Ming Feng, and Richard J. Matear. 2016. “Anticyclonic Eddies Are More Productive Than Cyclonic Eddies in Subtropical Gyres Because of Winter Mixing.” *Science Advances* 2(5): e1600282. https://doi.org/10.1126/sciadv.1600282

Eliassen, Arnt. 1982. “Vilhelm Bjerknes and His Students.” *Annual Review of Fluid Mechanics* 14: 1–11. https://doi.org/10.1146/annurev.fl.14.010182.000245

Emmerich, Roland. 2004. *The Day After Tomorrow*. 20th Century Fox. 123 minutes. Film. https://www.imdb.com/title/tt0319262/

Erlandson, Jon M., Todd J. Braje, Kristina M. Gill, and Michael H. Graham. 2015. “Ecology of the Kelp Highway: Did Marine Resources Facilitate Human Dispersal From Northeast Asia to the Americas?” *Journal of Island and Coastal Archaeology* 10(3): 392–411. https://doi.org/10.1080/15564894.2014.1001923

Faghmous, James H., Ivy Frenger, Yuanshun Yao, Robert Warmka, Aron Lindell, and Vipin Kumar. 2015. “A Daily Global Mesoscale Ocean Eddy Dataset from Satellite Altimetry.” *Scientific Data* 2: 150028. https://doi.org/10.1038/sdata.2015.28

Gangopadhyay, Avijit, Glen Gawarkiewicz, E. Nishchitha S. Silva, Adrienne M. Silver, M. Monim, and Jenifer Clark. 2020. “A Census of the Warm-Core Rings of the Gulf Stream: 1980–2017.” *JGR Oceans* 125(8): e2019JC016033. https://doi.org/10.1029/2019JC016033

Gaskel, Thomas Frohock. 1973. *The Gulf Stream*. London: Cassell. https://archive.org/details/gulfstream00gask

Gaube, Peter, and Dennis McGillicuddy. 2017. “The Influence of Gulf Stream Eddies and Meanders on Near-Surface Chlorophyll.” *Deep Sea Research Part I: Oceanographic Research Papers*. 122: 1–16. https://doi.org/10.1016/j.dsr.2017.02.006

Gaube, Peter, Camrin D. Braun, Gareth L. Lawson, Dennis J. McGillicuddy Jr., Alice Della Penna, Gregory B. Skomal, Chris Fischer, and Simon R. Thorrold. 2018. “Mesoscale Eddies Influence the Movements of Mature Female White Sharks in the Gulf Stream and Sargasso Sea.” *Scientific Reports* 8: 7363. https://doi.org/10.1038/s41598-018-25565-8

Gottschalk, Jon. 2014. “What Is the MJO, and Why Do We Care?” NOAA Climate. December 31, 2014. https://www.climate.gov/news-features/blogs/enso/what-mjo-and-why-do-we-care

Guzman, Hector M., Catalina G. Gomez, Alex Hearn, and Scott A. Eckert. 2018. “Longest Recorded Trans-Pacific Migration of a Whale Shark (*Rhincodon typus*).” *Marine Biodiversity Records* 11: 8. https://doi.org/10.1186/s41200-018-0143-4

Imawaki, Shiro, Amy S. Bower, Lisa Beal, and Bo Qiu. 2013. “Western Boundary Currents.” In *Ocean Circulation and Climate: A 21st Century Perspective*. Edited by Gerold Siedler, Stephen M. Griffies, John Gould, and John A. Church, 305–338. Oxford: Elsevier. https://doi.org/10.1016/B978-0-12-391851-2.00013-1

Jenkins, Alistair D., and John A. T. Bye. 2006. “Some Aspects of the Work of V. W. Ekman.” *Polar Record* 42(1): 15–22. https://doi.org/10.1017/S0032247405004845

Junger, Sebastian. 2009. *A Perfect Storm*. New York: W.W. Norton. https://wwnorton.com/books/The-Perfect-Storm/about-the-book/product-details

Kämpf, Jochen, and Piers Chapman. 2016. *Upwelling Systems of the World*. Cham: Springer. https://doi.org/10.1007/978-3-319-42524-5

Knauss, John A., and Newell Garfield. 2017. *Introduction to Physical Oceanography*, 3rd ed. Long Grove: Waveland Press. https://www.waveland.com/browse.php?t=504

Lacouture, Captain John. 1995. “The Gulf Charts of Benjamin Franklin and Timothy Folger.” *Historic Nantucket* 44(2): 82–86. https://nha.org/research/nantucket-history/historic-nantucket-magazine/maritime-mementos/

Lewis, Oscar. 1954. *George Davidson: Pioneer West Coast Scientist*. Berkeley: University of California Press. https://www.google.com/books/edition/_/cfTOJI1b8Z8C

Lynn, Ronald J., and James J. Simpson. 1987. “The California Current System: The Seasonal Variability of Its Physical Characteristics.” *Journal of Geophysical Research Oceans* 92(C12): 12947–12966. https://doi.org/10.1029/JC092iC12p12947

MacLeish, William H. 1989. *The Gulf Stream: Encounters with the Blue God*. Boston: Houghton Mifflin. https://archive.org/details/gulfstreamencoun00macl

McGillicuddy, Dennis J., Jr. 2016. “Mechanisms of Physical-Biological-Biogeochemical Interaction at the Oceanic Mesoscale.” *Annual Review of Marine Science* 8: 125–159. https://doi.org/10.1146/annurev-marine-010814-015606

McPhaden, M. J., G. Meyers, K. Ando, Y. Matsumoto, V. S. N. Murty, M. Ravichandran, F. Syamsudin, J. Vialard, L. Yu, and W. Yu. 2009. “RAMA: The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction.” *Bulletin of the American Meteorological Society* 90(4): 459–480. https://doi.org/10.1175/2008BAMS2608.1

Moore, Charles. 2023. “Captain Charles Moore.” *Captain Charles Moore*. Accessed January 28, 2023. http://www.captain-charles-moore.org/

Nansen, Fridtjof. 1902. “The Oceanography of the North Polar Basin. C. The Deviation of the Wind Drift Caused by the Deflecting Force Arising from the Earth’s Rotation.” In *The Norwegian North Polar Expedition 1883–1896: Scientific Results*, Vol.

III. 369–381. London: Longmanns, Green & Co. https://www.nb.no/items/ccc15a48b5c7a62ec602fa94d4cb37b7?page=389

Ohshimo, Seiji, Atsushi Tawa, Tomoko Ota, Satoru Nishimoto, Taiki Ishihara, Mikio Watai, Keisuke Satoh, Toshiyuki Tanable, and Osamu Abe. 2017. "Horizontal Distribution and Habitat of Pacific Bluefin Tuna, *Thunnus orientalis*, Larvae in the Waters Around Japan." *Bulletin of Marine Science* 93(3): 769–787. https://doi.org/10.5343/bms.2016.1094

Olson, Donald B. 1991. "Rings in the Ocean." *Annual Review of Earth and Planetary Sciences* 19: 283–311. https://doi.org/10.1146/annurev.ea.19.050191.001435

Palomares, Maria-Lourdes D., and Daniel Pauly. 2019. "Coastal Fisheries: The Past, Present, and Possible Futures." In *Coasts and Estuaries: The Future*. Edited by Eric Wolanski, John W. Day, Michael Elliott, and Ramesh Ramachandran, 569–576. https://doi.org/10.1016/B978-0-12-814003-1.00032-0

Palter, Jaime B. 2015. "The Role of the Gulf Stream in European Climate." *Annual Review of Marine Science* 7: 113–337. https://doi.org/10.1146/annurev-marine-010814-015656

Phillips, Helen E., Amit Tandon, Ryo Furue, Raleigh Hood, Caroline C. Ummenhofer, Jessica A. Benthuysen, Viviane Menezes, Shijian Hu, Ben Webber, Alejandra Sanchez-Franks, Deepak Cherian, Emily Shroyer, Ming Feng, Hemantha Wijesekera, Abhisek Chatterjee, Lisan Yu, Juliet Hermes, Raghu Murtugudde, Tomoki Tozuka, Danielle Su, Arvind Singh, Luca Centurioni, Satya Prakash, and Jerry Wiggert. 2021. "Progress in Understanding of Indian Ocean Circulation, Variability, Air–Sea Exchange, and Impacts on Biogeochemistry." *Ocean Science* 17:(6): 1677–1751. https://doi.org/10.5194/os-17-1677-2021

Proshutinsky, Andrey, Dmitry Dukhovskoy, Mary-Louise Timmermans, Richard Krishfield, and Jonathan L. Bamber. 2015. "Arctic Circulation Regimes." *Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences* 373(2052): 20140160 https://doi.org/10.1098/rsta.2014.0160

Richardson, Philip L. 1980. "The Benjamin Franklin and Timothy Folger Charts of the Gulf Stream." In *Oceanography: The Past*. Proceedings of the Third International Congress on the History of Oceanography, held September 22-26, 1980, at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. Edited by Mary Sears and Daniel Merriman, 703–717. New York: Springer. https://doi.org/10.1007/978-1-4613-8090-0_64

———. 1982. "Walter Hoxton's 1735 Description of the Gulf Stream." *Journal of Marine Research* 40: 597–603. https://peabody.yale.edu/explore/publications/journal-marine-research

Ring Group. 1981. "Gulf Stream Cold-Core Rings: Their Physics, Chemistry, and Biology." *Science* 212(4499): 1091–1100. https://www.jstor.org/stable/1685370

Roemmich, Dean, John Gilson, Philip Sutton, and Nathalie Zilberman. 2016. "Multidecadal Change of the South Pacific Gyre Circulation" *Journal of Physical Oceanography* 46(6): 1871–1883. https://doi.org/10.1175/JPO-D-15-0237.1

Rudnick, D. L. 2003. "Observations of Momentum Transfer in the Upper Ocean: Did Ekman Get It Right?" In *Near-Boundary Processes and Their Parameterization, Proceedings of the 13th 'Aha Huliko'a Hawaiian Winter Workshop*. Edited by P. Müller and D. Henderson, 163-170. Honolulu: University of Hawaii. http://www.soest.hawaii.edu/PubServices/2003pdfs/TOC2003.html

Schiel, David R., and Michael S. Foster. 2015. *The Biology and Ecology of Giant Kelp Forests*. Oakland: University of California Press. https://www.ucpress.edu/book/9780520278868/the-biology-and-ecology-of-giant-kelp-forests

Schulte, Justin A., and Sukyoung Lee. 2017. "Strengthening North Pacific Influences on United States Temperature Variability." *Scientific Reports* 7: 124. https://doi.org/10.1038/s41598-017-00175-y

Shinde, Vasant. 2016. "Current Perspectives on the Harappan Civilization." In *A Companion to South Asia in the Past*. Edited by Gwen Robbins Shugg and Subhash R. Walimbe, 127–144. West Sussex: Wiley Blackwell. https://doi.org/10.1002/9781119055280.ch9

Silver, Adrienne, Avijit Gangopadhyay, Glen Gawarkiewicz, E. Nishchita S. Silva, and Jenifer Clark. 2021. "Interannual and Seasonal Asymmetries in Gulf Stream Ring Formations from 1980 to 2019." *Scientific Reports* 11: 2207. https://doi.org/10.1038/s41598-021-81827-y

Stanton, Andrew, and Lee Unkrich. 2003. *Finding Nemo*. Walt Disney Pictures. Film. 100 minutes. https://www.imdb.com/title/tt0266543/

Stewart, H. L., J. P. Fram, D. C. Reed, S. L. Williams, M. A. Brzezinski, S. MacIntyre, and B. Gaylord. 2009. "Differences in Growth, Morphology, and Tissue Carbon and Nitrogen of *Macrocystis pyrifera* within and at the Outer Edge of a Giant Kelp Forest in California, USA." *Marine Ecology Progress Series* 375: 101–112. https://doi.org/10.3354/meps07752

Talley, Lynne D., George L. Pickard, William J. Emery, and James H. Swift. 2011. *Descriptive Physical Oceanography, An Introduction*, 6th ed. London: Elsevier. https://doi.org/10.1016/C2009-0-24322-4

Timmermans, Mary-Louise, and John Marshall. 2020. "Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate." *JGR Oceans* 125(4): e2018JC014378. https://doi.org/10.1029/2018JC014378

Tripati, Sila. 2017. "Early Users of Monsoon Winds for Navigation." *Current Science* 113(8): 1618–1623. https://www.jstor.org/stable/26494327

Ulanski, Stan L. 2008. *The Gulf Stream: Tiny Plankton, Giant Bluefin, and the Amazing Story of the Powerful River in the Atlantic*. Chapel Hill: University of North Carolina Press. https://uncpress.org/book/9780807871577/the-gulf-stream/. See also https://archive.org/details/isbn_9780807832172

Verbinski, Gore. 2007. *Pirates of the Caribbean: At World's End*. Walt Disney Pictures and Jerry Bruckheimer Film. 169 minutes. https://www.imdb.com/title/tt0449088/

Vernet, M., W. Geibert, M. Hoppema, P. J. Brown, C. Haas, H. H. Hellmer, W. Jokat, L. Jullion, M. Mazloff, D. C. E. Bakker, J. A. Brearley, P. Croot, T. Hattermann, J. Hauck, C.-D. Hillenbrand, C. J. M. Hoppe, O. Huhn, B. P. Koch, O. J. Lechtenfeld, M. P. Meredith, A. C. Naveira Garabato, E.-M. Nöthig, I. Peeken, M. M. Rutgers van der Loeff, S. Schmidtko, M. Schröder, V. H. Strass, S. Torres-Valdés, and A. Verdy. 2019. "The Weddell Gyre, Southern Ocean: Present Knowledge and Future Challenges." *Review of Geophysics* 57(3): 623–708. https://doi.org/10.1029/2018RG000604

Waite, A. M., P. A. Thompson, S. Pesanta, M. Feng, L. E. Beckley, C. M. Domingues, D. Gaughan, C. E. Hansona, C. M. Hollh, T. Koslow, M. Meuleners, J. P . Montoya, T. Moore, B. A. Muhling, H. Paterson, S. Rennie, J. Strzelecki, and L. Twomey. 2007. "The Leeuwin Current and Its Eddies: An Introductory Overview." *Deep Sea Research Part II: Topical Studies in Oceanography* 54(8–10): 789–796. https://doi.org/10.1016/j.dsr2.2006.12.008

Wang, Xin, Bo Tong, Dongxiao Wang, and Lei Yang. 2020. "Variations of the North Equatorial Current Bifurcation and the SSH in the Western Pacific Associated with El Niño Flavors." *Journal of Geophysical Research Oceans* 125(1): e2019JC015733. https://doi.org/10.1029/2019JC015733

Xu, Guangjun, Changming Dong, Yu Liu, Peter Gaube, and Jingsong Yang. 2019. "Chlorophyll Rings around Ocean Eddies in the North Pacific." *Scientific Reports* 9: 2056. https://doi.org/10.1038/s41598-018-38457-8

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CHAPTER OVERVIEW

11: The Seasons of the Sea

We now turn our attention to changes in sunlight incident on Earth's surface that occur as a result of Earth's orbit around the Sun, what we know as the **seasons**. These seasonal changes in solar radiation have a profound effect on nature and human activities. The seasonal cycle represents one of the most dynamic and important processes on Earth. The term "season" originated from French and Latin words meaning "to sow or plant." People in ancient times depended on the planting and harvesting of crops for survival, as they do in modern times. Seasons marked the times when certain farming activities had to be completed. Time off from school during summer—the so-called summer break—arose from the need for young people to help with the planting and harvesting of crops. While fewer modern-day students work on farms than in times past, the tradition of summer break continues to this day. (Aren't we lucky?)

In the modern age, winter, spring, summer, and fall have special significance in our lives for the clothes we wear, the activities we do, the foods we eat, and the holidays we celebrate. We look forward to the changing seasons. Winter brings snowboarding, spring means Coachella, summer ushers in days at the beach, and fall allows you to dress up like a ghoul. Each new season brings an opportunity to look forward to something, a chance to say, "Next season, I'm going to . . . "

The ocean has its seasons, too, its own Valentine's Days, Earth Days, Fourth of Julys, and Halloweens. As the seasons bring changes in the intensity and duration of sunlight, the ocean's surface cools or warms. Sea ice forms or melts. Plant and animal life diminish or flourish. Like the changing colors of foliage on land, so do the seasons bring changing colors of the ocean, too. In Southern California, the seasonal cycle brings gray whales in winter. It draws beach-nesting grunion fish to our shores in spring, puts forth dazzling tide pool life in summer, and lights the nighttime surf in a blue glow in fall.

In many ways, the seasons of the sea illustrate the most spectacular story of the ocean and its interconnections with life and our planet. Your understanding of the reasons for the seasons provides not only a framework for how the ocean works as a system but also an awareness of its many moods. Each season drives profound shifts in the physics, chemistry, biology, and ultimately the geology of our planet. By the end of this chapter, you'll have a better appreciation for how and why.

11.1: Sunrise, Sunset

11.2: Why Do Seasons Occur?

11.3: How Does Earth's Tilt Affect Surface Warming?

11.4: The Ocean Layer Cake

11.5: Measuring the Ocean's Layers

11.6: Visualizing Layers- The XZ Graph

11.7: The Seasons and the Thermoclines

11.8: The Importance of the Ocean's Seasonal Cycle

11.9: Chapter References

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11.1: Sunrise, Sunset

Two very important and obvious-if-you-think-about-them phenomena mark the seasons. First, the time of the sunrise and the time of the sunset change daily. Unless you arrived on Planet Earth only recently, the nights of your entire life have gotten longer during certain times of the year and shorter during other times. Now, some people will say that the days get shorter in the winter and longer in the summer. But it's really more accurate to say that **daylength**, defined as the lighted portion of the day, changes over the seasons. In actuality daylength increases from the first day of winter until the first day of summer. From the first day of summer to the first day of winter, the daylength hours diminish.

Second, the point on the eastern horizon where the Sun comes up and the point on the western horizon where it goes down change every day. (You knew that, right?) These points actually have a name: the **sunrise point**, the location on the eastern horizon where the Sun rises, and the **sunset point**, the location on the western horizon where the Sun sets. The reason for the change in the sunrise and sunset points has to do with the path of the Sun as it crosses the sky. As it moves from the sunrise point to the sunset point, the Sun traces an arc—the **solar path**. And the solar path changes daily. Now, the solar path might not be something that you've ever taken notice of, but you've likely noticed changes in the sunrise and sunset points. Have you ever been nearly blinded by the rising or setting sun while driving along an east–west highway? That happens because the sunrise or sunset points fall in a direct line with the road you're on. You've fallen victim to the seasonally changing solar path.

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11.2: Why Do Seasons Occur?

Day and night length and sunrise and sunset points change because of Earth's position as it orbits the Sun. To understand Earth's orbit, we need to review a few astronomy terms and concepts. But before we start, let's clear up one very common misconception about the seasons.

Earth's tilt (explained below) causes the seasons. As you learned in Chapter 12, the Sun heats Earth's surface (with shortwave radiation). Earth's surface, in turn, heats our atmosphere (with longwave radiation). Because Earth is tilted with respect to the incoming solar radiation, some places receive more intense sunlight than others. Some times of the year, a given location will receive direct sunlight. Other times of the year, it will receive less direct sunlight. The result is intense heating some times of the year and less intense heating effect other times of the year. Those changes in heating we know as the seasons.

Much of this chapter is devoted to exploring the details of the seasonal cycle so don't worry if it's not clear to you just yet. But if the tilt model of Earth's season doesn't satisfy you, ask yourself this: Why does the Northern Hemisphere enjoy summer in June while folks in the Southern Hemisphere experience winter in June. Let's find out why.

Earth's Rotation

As I'm sure you know by now, Earth turns like a disco ball in outer space, in what is called **Earth's rotation**. The imaginary line around which it rotates is called Earth's axis of rotation, or simply **Earth's axis**. Grab a spherical piece of fruit—an orange works nicely—and carefully jab a pencil through the middle of it. (Styrofoam balls work for this too, but not everyone keeps Styrofoam balls in their house.) Hold the top end of the pencil–orange physical model of Earth so that the pencil is vertical. Then twirl the orange. Voilà! You have created a model of how Earth rotates on its axis. Now add this detail: Look down on your model from above the North Pole (where the North Pole is oriented up) and rotate it counterclockwise. Your model now correctly represents the direction of rotation of Earth around its axis. The Sun rises in the east because the Earth rotates towards the east. That means the Sun rises first on the east coast of the US and even earlier in the UK.

Earth's Tilt

Next, using a marker, draw an equator at the halfway point between the top and bottom of the orange (i.e., midway between the North and South Poles). Tilt the pencil to a vertical position (straight up and down). The equator you just drew should be horizontal. Now—and this is the most critical part of your demonstration—try a 45-degree tilt (symbolized as 45°), halfway between vertical and horizontal. (Review degrees and angles on the internet if this terminology is unfamiliar to you.) Then try a 22.5° angle, halfway between vertical and 45°. This is close to the angle of Earth's **axial tilt**, the angle between vertical and the axis of rotation of a planet. (Astronomers officially call this obliquity, but that word is harder to remember, so we're sticking with tilt.) Earth's axial tilt is roughly 23.5° in modern times. (To be precise, it's 23.43681°, but most textbooks and websites round it off to 23.5, apparently because it's easier to remember, but what could be easier to remember than 2-3-4?)

Earth's Orbit

Now we need to see what happens when Earth orbits the Sun, what's called Earth's orbital revolution or **Earth's orbit**. For this, you will need a model of the Sun—a lamp, a grapefruit, a chair in the middle of the room, anything that your body can orbit. Start with Earth held so that its axis of rotation is at a 23.5° angle with the North Pole pointed away from your sun. Hold it firm in that position while you walk in a circle around your imaginary sun. When you have returned to your starting position, note the position of your Earth. It should be the same: at a 23.5° angle pointed away from your sun. As you orbited your sun holding your tilted Earth, you traced an **orbital plane**, the horizontal plane in which Earth's orbit occurs. The equator also can be considered as a plane, called the **equatorial plane**. Viewed in this way, the equatorial plane makes a 23.5° angle with the orbital plane. Alternatively (just looking at it a different way), Earth's tilt represents the angle between Earth's axis of rotation and a vertical line drawn perpendicular to the orbital plane. Earth's tilt is maintained throughout its orbit around the Sun, 365.25 days a year.

Now, if you want to be really accurate, your simulation of Earth's orbit would take a slightly elliptical shape rather than a perfect circle. As it turns out, the distance between Earth and the Sun varies during Earth's annual orbit around the Sun. You may recall this distance as the astronomical unit, or AU. By definition, the Earth–Sun distance is 1 AU, about 93 million miles. Although the AU is considered a constant, we know the Earth is slightly closer to the Sun in January. At this location, known as **perihelion**—when a planet is closest to its star—Earth is positioned about 91.4 million miles away from the Sun. In July, at **aphelion**—when a planet is

farthest from its star—Earth is slightly farther away, about 94.5 million miles (e.g., NASA 2001). This should put to rest any notion that the Earth–Sun distance causes the seasons. The Sun is closer to the Earth in January—when the Northern Hemisphere experiences winter—and farther from the Earth in July during Northern Hemisphere summer.

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11.3: How Does Earth's Tilt Affect Surface Warming?

What does all this mean? As Earth orbits the Sun with its equatorial plane tilted at an angle, the Sun's rays—which you can imagine as arrows—strike it at an angle. Some parts of Earth heat more at certain times of the year—those that receive more direct sunlight—and some parts heat less—where the Sun's rays arrive at an angle. When the Northern Hemisphere is tilted toward the Sun and the intensity of sunlight is high, we experience summer. When the Northern Hemisphere is tilted away from the Sun and the intensity of sunlight is low, we experience winter. It's this phenomenon—the tilt of Earth as it orbits the Sun—that creates the differences in heating that we notice as the seasons.

You can model this with a flashlight and a piece of paper. First, turn the flashlight on and hold it directly above the piece of paper. Draw a circle around the lighted region of the paper. Now tilt the flashlight so that the light strikes the paper at an angle. Look at the illuminated part of the paper. Has the circle changed shape? (Yes!) It should now look more elliptical. Draw an ellipse around the lighted portion of the paper. Now compare the circle and the ellipse. Which one covers a greater area of the paper? Hopefully, you can see that the ellipse covers a greater area. If you were as tiny as an insect and stood inside the circle, the light would appear brighter than when you stood inside the ellipse. Although the same total amount of light falls on the circle and the ellipse, the light in the ellipse is spread over a greater area. The light per unit area is greater in the circle than in the ellipse. Sunlight striking Earth's surface at an angle will be less intense than sunlight striking Earth's surface directly. It's like splitting a pizza with more people. With more people, each person gets less pizza.

Earth's tilt explains the change in daylength and the change in the sunrise and sunset points on the eastern and western horizons, respectively. An observer in the Northern Hemisphere sees the Sun low in the sky when the Northern Hemisphere is pointed away from the Sun. When the Northern Hemisphere is pointed toward the Sun, an observer sees the Sun high in the sky. The Northern Hemisphere observer also sees that the sunrise and sunset points are farther south in the winter and more northerly in the summer. The solar path across the sky in winter is lower than the path across the sky in summer. Put another way, the solar altitude angle, or simply, the **noon sun angle**—the position of the Sun above the equatorward (southern in Northern Hemisphere) horizon at noon—is lowest in winter and highest in summer. Stick a toothpick in your orange at the latitude of Southern California—about 30°N—to visualize how the sun angle changes as you orbit the Sun. With the sun higher in the sky from winter to summer, daylength is longer. The opposite is true from summer to winter. The seasonal changes in daylength, the sunrise and sunset points, the solar path, and the pattern of warming and cooling are explained simply as a result of Earth's tilt relative to its plane of orbit around the Sun.

Now, before we proceed, it's important that you recognize that the seasons of the Northern Hemisphere are not the same seasons for the Southern Hemisphere. In fact, they are exact opposites. When it's summer in the Northern Hemisphere, it's winter in the Southern Hemisphere. When it's spring here, it's fall there. Most of South America and all of Australia experience winter during our summer. Their beach days come in January instead of July. When the Southern Hemisphere is pointed toward the Sun, the Northern Hemisphere is pointed away. This causes the seasons of the two hemispheres of Earth to occur in different months of the year. That's why some folks travel south (or north) during their winter. They can enjoy summer almost year round!

Solstices and Equinoxes

The times of year when the Sun is absolutely at its lowest or highest points in the sky are known as the **solstices**, meaning "when the sun is still." These are the days when ancient people perceived that the Sun no longer moved lower or higher. We know these days as the **winter solstice**, the first day of winter and the shortest day (i.e., daylength is at its minimum) of the year, and the **summer solstice**, the first day of summer and the longest day (i.e., daylength is at its maximum) of the year.

What happens to daylength on the day following a solstice? Daylength on the day after the winter solstice is slightly longer, and the day after the summer solstice, it's slightly shorter. In fact, daylength increases from the date of the winter solstice to the date of the summer solstice. On the other hand, daylength decreases from the date of the summer solstice to the date of the winter solstice. If you can remember the shortest day of the year (first day of winter, the winter solstice) and the longest day of the year (first day of summer, the summer solstice), then you can easily figure out what is happening to daylength at any time of the year.

We also mark the days when the Sun crosses directly overhead at the equator. These are known as the **equinoxes** (equi = "equal"; nox = "night"), the times of the year when day and night are of equal length. The moment when the Sun is directly over the equator on its way into the Northern Hemisphere is called the Northern Hemisphere **spring equinox** or vernal equinox. Half a year later, as

the Sun passes southward on its way into the Southern Hemisphere, the moment when it's directly over the equator is called the Northern Hemisphere **fall equinox** or autumnal equinox. Of course, the seasons are reversed for the Southern Hemisphere. On the spring and fall equinoxes, you'll find the Sun directly over the equator. That means if you stood on the equator at local noon on this day (when the Sun is directly overhead), you would barely see a shadow at your feet. "Look, Mom, no shadow!"

The Midnight Sun

Earth's axial tilt dramatically affects daylength at the North and South Poles. When the Northern Hemisphere is tilted away from the Sun—during the Northern Hemisphere fall and winter—sunlight can't reach the North Pole. This region experiences 24 hours of darkness or twilight for six months out of the year. Alternatively, when the Northern Hemisphere is pointed toward the Sun—during the Northern Hemisphere spring and summer—the northern polar region experiences 24 hours of sunlight. People refer to regions poleward of the Arctic and Antarctic Circles as the **land of the midnight sun**, places where the Sun appears 24 hours a day. The period when this occurs is referred to as the **polar day**, the six-month-long period of continual (or near-continual) sunlight in these regions. The six-month-long period of darkness in these regions is called the **polar night**. More than a novelty, polar day and polar night have profound effects on polar environments.

Lines of Latitude Mark the Seasonal Cycle

Astronomers and geographers have long noted the changing positions of the Sun in the sky over the course of a year. These positions have been given special importance by the establishment of names for latitudes of astronomical significance. The place where the Sun is directly overhead on the first day of summer in the Northern Hemisphere, 23.5°N, is called the **Tropic of Cancer**. Where the Sun is directly overhead on the first day of Northern Hemisphere winter, 23.5°S, we find the **Tropic of Capricorn**. The latitude above which no sunlight can reach following the fall equinox is known as the **Arctic Circle**, 66.5°N. At the other end of Earth, the latitude below which no sunlight falls following the Southern Hemisphere fall equinox, we find the **Antarctic Circle**, 66.5°S.

We should also note that regions of Earth that receive direct sunlight most times of the year stay warm, and those that receive less sunlight or variable sunlight experience colder temperatures. Because of these differences, we can divide Earth into three simplified **climate zones**, the average weather for a region of Earth based on the amount of sunlight they receive. The region of Earth bounded by the Tropic of Cancer and the Tropic of Capricorn is known as the **tropical zone**, or the tropics. This zone experiences the warmest weather on the planet because the Sun is mostly overhead most days of the year. The **polar zones**—regions north of the Arctic Circle and south of the Antarctic Circle—encompass the coldest regions of the planet. The region between the tropical and polar zones—the middle latitudes of Earth—are known as the **temperate zones**. Here, where most of the continental United States lives, the climate is moderate—not too hot and not too cold, on average.

The tropical, temperate, and polar climate zones have precise astronomical meaning. Their boundaries refer to extremes in the positions of the Sun (i.e., Tropic of Cancer and Tropic of Capricorn) or its rays (Arctic Circle and Antarctic Circle). The three climate zones also provide a general guide to the kind of climate one might experience. The tropical zone at low latitudes is generally warm, humid, and rather seasonless. The temperate zones at middle latitudes are mild, with the four classic seasons (winter, spring, summer, and fall). The polar zones at high latitudes are cold and dry, with two seasons: the cold season—polar summer and fall—and the colder season—polar winter and spring. Though other configurations of climate regions based on temperature and precipitation patterns (e.g., the Köppen classification) provide more detail and remain the ones preferred by meteorologists and climatologists, the three-climate-zone model serves well for understanding most ocean-related phenomena. The interested reader may consult a good introductory meteorology textbook for fancier models (e.g., Ahrens and Henson 2018).

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11.4: The Ocean Layer Cake

Now, to get the most out of this next section, you'll want to place a multilayered cake in front of you. The concepts here will make more sense if you place a slice of your favorite, delicious, hard-to-resist layer cake in front of you. Even if you don't like to eat cake, the presence of a slice will help. Avoid eating it for now. We'll refer to cake throughout the rest of this chapter. And when you finish the chapter, you'll have a nice reward!

The three climate zones mentioned above—the tropical, temperate, and polar zones—receive varying amounts of sunlight due to Earth's orbit around the Sun. This means that the parts of the ocean within these zones receive seasonally varying amounts of sunlight. Tropical oceans heat the most; polar oceans heat the least. This differential heating of the planet drives a number of important processes. Here we take a look at how seasonal changes in heating affect the physical structure of the ocean; that is, how heating and cooling cause changes in the temperature structure of the water column. Fear not, if you like swimming in lakes in the summer, this section will be a piece of cake.

Seawater Density (Revisited)

In earlier chapters, you learned that changes in seawater temperature and salinity can cause changes in seawater **density**, the mass of molecules occupying a given volume of seawater (i.e., mass per unit volume). Here we examine those changes in greater detail.

The exchange of heat across the air–sea interface may bring heating or cooling of the surface of the ocean. The amount of heating or cooling depends on the solar intensity and the temperature of the atmosphere. When sunlight is intense—or the atmosphere is warmer—the surface waters will warm. When sunlight is less intense—or the atmosphere is cooler—the surface waters will cool. Of course, a number of additional factors can affect heating and cooling of the ocean's surface. Clouds, airborne or waterborne particles, winds, waves, and even the color of the water may affect temperature changes. But in general, sunlight and atmospheric heat are considered the major factors governing ocean heat content (e.g., Lindsey and Dahlman 2020).

Temperature affects seawater density because it affects the spacing between the molecules of water and its dissolved salts. As we heat seawater, its molecules move faster, and the space between the molecules gets larger. As we cool seawater, the molecules move slower, and the molecules get closer together. In the first case—heating—a rise in temperature causes the density of seawater to decrease. We say the seawater becomes less dense. In the second case—cooling—the lowering of temperature causes the seawater to become more dense. Temperature and density have an inverse relationship: As one quantity goes up, the other goes down, and vice versa.

The concentration of salts in seawater—its salinity—also affects its density. As the salinity—the concentration of salts—increases, the density increases. That's because there are now more molecules packed into the same volume of seawater. If we add freshwater and lower the salinity, we decrease the density. Salinity and density have a positive relationship (or correlation). As one increases or decreases, so does the other.

And we shouldn't forget that the solid form of water—ice—is less dense than the liquid form of water. That's because water molecules repel each other and the structure of water changes at temperatures below 39.2°F (4°C). Because ice is less dense than liquid water, it floats.

Finally, as noted in Chapter 11, freezing of seawater and formation of sea ice cause brine rejection, extrusion of a syrup of salts into the surrounding ocean. The sea ice is fresh, but the brine increases local seawater salinity as it dissolves.

The Concept of Buoyancy

Heating and cooling and increases and decreases in salinity change the density of seawater. As a result of changes in density, a **seawater parcel**—an oceanographer's informal term for an unspecified volume of seawater—may sink or rise. The position of a water parcel in the ocean depends on the **buoyant force**, the upward force exerted on a fluid or object immersed within it. The buoyant force counteracts the **gravitational force**—the pull of gravity on the water parcel or objects within it. It's these two forces that determine **buoyancy**—the tendency of a fluid or object to rise or sink in a fluid. Buoyancy underlies the different density layers in the ocean—that is, the ocean layer cake.

A brief explanation provides some context for the physics. The buoyant force arises because water pressure—exerted in all directions—increases with depth (as the weight of water above an object increases). The deeper the depth, the greater the buoyant

force. The buoyant force also depends on the volume of the parcel or object. The larger the volume, the greater the buoyant force on that object. Objects of equal volumes at the same depth will experience the same buoyant force. However, if their masses differ, the gravitational force on them will differ. That's because the gravitational force depends on the mass of the object (i.e., the gravitational force equals the mass of the object times the gravitational constant). The mass of a given volume depends on its density: the higher the density, the greater its mass. In short, water parcels with a higher density will experience a greater gravitational force. And this will influence where the water parcel comes to rest in the water column.

Here are the key concepts related to the importance of buoyancy for understanding ocean layering. If the buoyant force is less than the gravitational force, then the fluid or object sinks, which is known as **negative buoyancy**. If the buoyant force exceeds the gravitational force, then the fluid or object rises, a condition known as **positive buoyancy**. If the buoyant force and the gravitational force are equal, then the fluid or object remains stationary—it has achieved **neutral buoyancy**. If you are on a sinking ship, you will want to grab something that will help you stay afloat, something that has positive buoyancy in water. If you want to hide a dead body, then you will want to attach it to something that will sink, something with negative buoyancy. All kidding aside, the principles of buoyancy have important practical applications, such as scuba diving, shipbuilding, and operating a submarine, among others.

The principles of buoyancy are more obvious with a familiar example, such as a hot air balloon—invented in 1783, making it the oldest form of human flight (Kotar and Gessler 2011). By heating air inside a flexible container—the balloon—it becomes positively buoyant. The air becomes less dense, the balloon gains buoyancy, and it rises. When the hot air cools, either by conduction through the fabric of the balloon or by letting cool air into the balloon, the balloon loses buoyancy and it sinks. But how does a balloon remain stationary at an ideal altitude above the ground? There comes a point in its upward transit where the density (and pressure) of the surrounding air matches the density (and pressure) of the air inside the balloon. At that point, the hot air balloon stops its ascent. The air inside and outside the balloon has the same density, and the balloon achieves neutral buoyancy.

Scuba divers maintain their buoyancy using a combination of weights (negative buoyancy) and a special air-holding vest called a **buoyancy compensator**, or BC, for short (positive buoyancy). When the diver wishes to descend, they need negative buoyancy, so they release air from their BC. When they wish to maintain a particular depth—to hover over a shipwreck or beautiful reef, for example—they inflate their BC just enough to balance the gravitational force of their weights and so achieve neutral buoyancy. When they want to ascend and return to the surface, they add a little more air to their BC, which causes them to acheive positive buoyancy and rise slowly.

Water parcels also sink and rise in the water column, albeit without weights and BCs. If the water parcel loses heat or gains salts, it may become negatively buoyant and sink. Gaining heat or freshwater, the parcel may become positively buoyant. It rises—unless it's already at the surface. If the water parcel is neutrally buoyant, it remains in place. Just as they do with hot air balloons and scuba divers, the principles of buoyancy govern the movements of water masses and play a role in the productivity of the ocean.

A Stable or Unstable Water Column

In a given region of the ocean or a lake, the water parcels will naturally arrange themselves according to their density and buoyancy. The least dense and most buoyant water parcels will be at the surface. The most dense and least buoyant water parcels will be at the bottom. We can view these water parcels as density layers—like a layer cake—where the water parcels are arranged according to their density. When the layers are arranged in order of increasing density—least dense on the top and most dense on the bottom—we have a **stable water column**. If one or more of the layers are out of order—if they are not arranged in order of increasing density from the surface to the bottom—then you have an **unstable water column**.

Looking at the water column as a stack of water parcels with different densities helps explain many of the phenomena we observe in the ocean or even a lake. Ever swim in a lake during summer and noticed that it's very cold when you dive deeper? That's because the lake consists of different layers of water, each with its own density. The top layer is warm, relatively light (i.e., less dense), and positively buoyant. The bottom layer is cold, relatively heavy (i.e., more dense), and negatively buoyant. What seems like a nice, warm summer swim turns into a shockingly cold experience when you take a dive. In a nutshell, the same thing happens in the ocean.

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11.5: Measuring the Ocean's Layers

Since the time of the Challenger expedition, oceanographers used various types of water sampling bottles for obtaining seawater samples at depth. The **Pettersson–Nansen bottle**, co-invented by Norwegian oceanographers Otto Pettersson (1848–1941) and Fridtjof Nansen (1861–1930), became commonplace on oceanographic vessels by the early 20th century (e.g., Mill 1900). Typically, a single bottle or a string of bottles is lowered in the open position until the bottles reach the desired depth, whereupon they're closed, trapping a volume of seawater inside. When the bottles are brought back on board, samples of water are taken for immediate analysis or preserved for future analysis.

While perfectly fine for many types of chemical analyses, this method introduces problems for measurements of temperature. As the sample is raised, its temperature may change as it exchanges heat with the surrounding seawater. This gives an inaccurate reading of the sample's actual temperature at depth. The invention of **reversing thermometers** solved the problem of temperature measurements at depth. These thermometers could be attached to sampling bottles and turned upside down at depth using a weighted messsenger sent down the line. This to cut off the supply of mercury and prevented any further changes in the reading (e.g., Deacon 1971).

So, too, oceanographers desired a faster means for determining salinity. The **salinometer**—an electronic instrument for measuring salinity—reduced the need for laborious chemical measurements. Combined, reversing thermometers and salinometers permitted oceanographers to take more samples in more places in the world ocean (e.g., Salinometry 2023).

Improvements in computing technology and reductions in the size of computers by the early 1970s paved the way for development of a new kind of instrument, the **CTD**—the **conductivity–temperature–depth instrument**. Based on an instrument developed by American engineer Neil Brown and colleagues in the early 1960s, the CTD is considered the workhorse of oceanographic research (e.g., Salinometry 2023). There is perhaps no better instrument for obtaining a near-instantaneous measurement of the properties of the water column. If CTDs had public appeal, you can imagine an ad campaign similar to one for a popular credit card: "The CTD —Don't leave your home port without it." (See The Drum Team 2016 for the history of the ad from which this popular phrase is borrowed.)

It didn't take long for oceanographers to trick out their CTDs. One of the first things they did was attach the instrument package (the CTD) to a frame on which water sampling bottles could be placed. Modern CTDs come equipped with a **rosette**, a series of water sampling bottles. Most often these are **Niskin bottles**, invented by American businessman Shale Niskin (1926–1988; Niskin 1962). Arranged in a circle of 12 to 24 bottles and triggered electronically, the Niskin bottles provide a means of taking water samples on the fly. An oceanographer can look at the vertical profile of temperature and salinity and choose a depth to take a water sample simply by raising or lowering the CTD rosette to that depth. Other kinds of electronic sensors can be attached for measurements of submarine light intensity (i.e., radiometers), chlorophyll concentration (i.e., fluorometers), pH (pH probes), dissolved oxygen (oxygen probes), and more. When an oceanographer raises a CTD to go over the side and watches it swinging back and forth as the ship rocks in the waves, they pray that it will come back safely. One cable snap can send a $250,000 fully outfitted CTD rosette to the bottom of the sea—and an oceanographer crying all the way home.

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11.6: Visualizing Layers- The XZ Graph

To represent the properties of the water column—such as those measured during a CTD cast—oceanographers have created a special kind of graph. The **XZ graph** resembles an upside-down XY graph, except that the vertical axis, the z-axis, extends downward from the origin. In an XY graph, the y-axis extends upward from the origin. The vertical z-axis represents water depth, usually in meters. In the top left corner of the graph—the origin, where the x-axis and the z-axis intersect—the depth is set to zero. Thus, the x-axis at zero depth represents some property, X, at the surface of the ocean. Properties such as temperature, salinity, and light often change with depth. An XZ graph illustrates the changes in ocean properties you might experience as you descend into the deep. Multiple x-axes are allowed too. By adding x-axes above the first one to represent other properties (such as salinity, chlorophyll, and others), oceanographers can see how properties vary simultaneously with depth in the water column. (See Hautala for additional details.)

A useful way to envision the water column and how its properties change with depth is to stare at a ceiling, the higher the better. Imagine that you are looking up at the ocean surface—the ceiling—from the sea bottom—the floor. Then consider how some property, like temperature, might vary from the ceiling (i.e., ocean surface) to the floor (i.e., sea bottom). In your home, hot air rises, so the warmest air accumulates near the ceiling. As you descend from the ceiling, the air becomes cooler. The coldest air can be found at floor level. And so it is with the ocean. Warm surface waters lie atop deeper, cold waters.

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11.7: The Seasons and the Thermoclines

We now come to my honest-to-goodness favorite topic in oceanography: the layering of the ocean due to seasonal heating by the Sun. For me, it's one of the best examples of how the ocean works as a system. The physics affects the biology, which in turn affects the chemistry of the ocean. Physics drives ocean life, which alters the ocean's chemistry. But that's getting ahead of our story. In this chapter, we'll focus mostly on the physics. And we'll look just at temperate oceans for the time being. But be prepared. We'll return to these topics later in the book and explore the marvelous symphony of processes conducted by the Sun.

Winter and the Permanent Thermocline

The different layers that we observe in the ocean result largely from seasonal differences in heat exchange. Salinity plays an important role too—especially in the polar oceans—but we'll concentrate on heating first. The temperate zone ocean provides the best example of how changes in heat exchange at the surface affect the layering. And the best place to start is winter.

In the winter, the ocean generally loses heat to the atmosphere because the overlying atmosphere is colder. Surface heating is low because daylengths are short and sun angles are low. The loss of heat from the ocean to the atmosphere cools the ocean's surface. A cold, dense, negatively buoyant layer of surface water forms. Because this cold surface layer rests on top of a warmer, less dense, and more positively buoyant layer, the water column becomes unstable. The surface layer begins to sink.

Sinking of surface waters continues throughout the winter, as long as the top layer gets colder than the layer beneath it. At some point—when the coldest seasonal air temperatures have been reached—the coldest surface layer forms. This layer represents the most negatively buoyant layer formed during the season. As a result, this layer will sink the deepest.

The sinking of surface waters in winter represents an important process by which the upper ocean is mixed. **Mixing** is just what it sounds like (minus the DJ): the ocean is blended, combined, homogenized, and stirred. Any water parcels with slightly different temperatures (or salinities) may be mixed by the sinking action of denser and thus less buoyant water parcels. This is called **buoyancy-driven mixing**. It's important for distributing heat, gases, salts, biologically important nutrients, particles, plankton, larvae, and all sorts of other things in the upper ocean. This wintertime mixing often results in an **isothermal** water column (iso = "same"; thermal = "temperature"), one in which temperature does not change with depth. This layer of mixed waters in the upper ocean is called—wait for it—the **surface mixed layer.** The distance from the surface to the bottom of the mixed layer is called the **mixed layer depth**. The mixed layer depth gives an estimate of the depth of mixing of the water column.

How deep is the mixed layer? Negatively buoyant surface waters sink until they reach a depth where the surrounding water has the same density—they sink until they become neutrally buoyant. In tropical oceans, the surface layer may sink a few tens of meters in winter (e.g., Longhurst 1993). In temperate oceans, the surface layer may sink from 15 to 75 meters on average (e.g., Bathen 1972). In polar environments, where the coldest air temperatures occur, the surface layer may sink thousands of meters, even all the way to the seafloor (e.g., Johnson 2008). The densest waters in the world ocean are formed in polar oceans. These **abyssal waters**—as they are collectively called—spread along the seafloor from the poles to the equator and beyond. Abyssal waters make up the deepest layers in the world ocean, even in temperate and tropical zones.

Now, if you were to descend in a submarine to the depth where the mixed layer meets the abyssal waters and hold a thermometer out an open porthole, the submarine would fill with water, sink, and kill everyone aboard. (Words to live by: never open a porthole on a submerged submarine.) But if you attached a thermometer to the hull and connected it to a computer so that you could read the external water temperature as you descended, you would notice no change in temperature in the isothermal water column. But in a temperate ocean, you would reach a boundary between the winter-formed deep mixed layer and the polar-formed abyssal waters. At this boundary, you would notice a rapid change in temperature as you crossed from the bottom of the mixed layer to the top of the abyssal waters. This boundary—the region where temperature changes rapidly—is called a **thermocline**. The suffix -cline means "slope," just like "incline" means up slope and "decline" means down slope. Where upper ocean waters—mixed ones—meet abyssal waters—ones formed in polar oceans—a **permanent thermocline** may be formed. Temporary thermoclines—seasonal ones—may be formed, too, as we'll see in the next section.

The thermocline is a classic structure in descriptions of the physical properties of the ocean. It represents a boundary between different water parcels. The presence of a thermocline indicates that these water parcels are distinct and separate from each other. In graphs of the water column—XZ graphs with the z-axis representing depth and an x-axis representing temperature—the thermocline appears as a slope in the temperature profile. Thus, you may think of the thermocline as a temperature slope.

Spring and the Seasonal Thermocline

As the days get longer and the sun gets higher in the sky in late winter or early spring (depending on the latitude), solar heating is more direct. The sea surface begins to warm. Air temperatures and water temperatures may be highly variable, subject to changing weather conditions. But at some point, the atmosphere in contact with the ocean becomes warmer than its surface. The net exchange of heat now is from the atmosphere to the ocean. When the sea surface warms, the seawater becomes less dense and more positively buoyant. But it doesn't rise into the sky. Ocean water is about 800 times denser than even the most dense air, so the surface water remains at the surface.

The warming of the surface waters creates a temperature difference between the uppermost layer and the layer beneath it. The boundary between the now-warmer surface layer and the still-cold layer beneath it represents a different kind of thermocline, the **seasonal thermocline**. It forms as a result of surface warming and will disappear the following fall when the water cools again. It occurs seasonally—hence the name.

Previous to the formation of the seasonal thermocline, the entire mixed layer is isothermal. Now the top of what used to be the mixed layer is warmer. The mixed layer has been split in two, so to speak. As a result, the mixed layer depth becomes shallower. The surface mixed layer is now confined to the region from the surface to the top of the seasonal thermocline. As the surface of the ocean continues to warm, multiple thermoclines may be present. It can get pretty complex, and we're not going to dwell on all of the possibilities, but just be aware that the seasonal thermocline represents a temporary boundary between water parcels with different densities. The thermocline originates as the surface of the ocean warms. In a graph of the entire water column, from the surface to the seafloor, both the shallower seasonal thermocline and deeper permanent thermocline may be present.

The layering of the ocean that occurs as a result of warming of surface waters and formation of a seasonal thermocline is called **stratification**. The word stratum means "layer," and it's used to describe clouds (e.g., stratus clouds), rocks (e.g., strata of sedimentary rock), or an archaeological dig (e.g., strata of ruins or refuse piles). Stratification of the water column signals a major event in the physics, chemistry, and biology of the upper ocean. It means, in effect, that the upper layers of the ocean are practically cut off from the lower layers. The upper and lower layers can't mix, or mixing is severely restricted. Exchanges of heat, gases, salts, and biologically important nutrients between the surface mixed layer and lower layers can no longer occur or occur much more slowly. It won't be until fall or even winter before these waters mix again. Keep this process in the back of your mind. When we get to chapters on productivity and food webs, the isolation of the upper ocean will help you appreciate how physical processes drive the chemistry and biology of the ocean.

Summer and the Multiple Thermoclines

The surface layer continues to warm well into summer as high sun angles permit solar radiation to penetrate deeper into the ocean. The upper ocean warms to its highest temperatures of the year. Double or even **multiple thermoclines**—more than a single thermocline visible in vertical profiles of the water column—may be observed (e.g., Fan et al. 2014). With layers of positively buoyant water parcels stacked on top of one another, the summer water column represents one of the most stable water columns of the year. The stability of the water column may lead to the formation of **phytoplankton thin layers**, bands of highly concentrated phytoplankton confined to a narrow depth interval. Having a vertical thickness of less than a few feet, they may extend horizontally for miles. Formation of thin layers requires a very stable water column, and in some places and under the right conditions, they may persist for weeks or longer (e.g., Durham and Stocker 2012).

Though plant life on land tends to be highly productive in summer, phytoplankton concentrations in temperate oceans tend to be low. That's because stratification of surface waters limits mixing of biologically important nutrients. Starved of nutrients, phytoplankton grow more slowly. Species able to subsist under low nutrient concentrations replace those with high nutrient requirements. That's just a snippet of the interaction of the ocean's biology during the seasons of the sea.

Fall and the Disappearing Thermocline

In the temperate zone, all stable water columns must come to an end. The shortening of the days and the lower sun angles in fall reduce solar heating. The atmosphere cools quickly, much quicker than the ocean. At some point during fall, the air becomes cooler than the ocean, and the trend of heat exchange is reversed. The ocean begins to lose heat to the atmosphere. As the surface waters cool, they lose buoyancy and sink. Initially, they sink only a little. They remain plenty warm compared to the temperature minimum of winter, but it just takes a little cooling at the very surface of the ocean to make the water column unstable. As the

cooling continues, the surface waters sink deeper. As the surface waters sink, they mix the upper ocean. Deeper waters begin to mix upward. Differences in heat, gases, salts, chemicals, biologically important nutrients, particles, plankton, and larvae disappear as the surface layer becomes colder and mixes deeper. The seasonal thermocline disappears too. The multiple layers of different density that were stacked up in the stable water column of summer become unstable and begin to blend and mix. The disappearance of the seasonal thermocline and the blending of the different layers characterize a process called **destratification**, the unmaking of the layers of the ocean. Of course, this process will continue throughout winter until the coldest days once again set the minimum temperature for the upper ocean.

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11.8: The Importance of the Ocean's Seasonal Cycle

The seasonal cycle of stratification and destratification drives some of the most important processes in the ocean. Seasonal production of cold water at the surface in polar oceans plays a key role in the formation of deep and abyssal waters, critical to the deep ocean circulation. The seasonal cycle of primary production in temperate and polar oceans nourishes marine food webs and supports fisheries. And the seasonal growth and decay of the polar ice caps has profound implications for a number of physical, chemical, and biological processes as well.

Formation of the seasonal thermocline in spring and summer and its disappearance in fall and winter represent one of the best examples of the connection between physical, chemical, and biological processes in the ocean. The seasonal dynamics of food webs—from tropical to polar ocean—emerge from the seasonal cycle of heating and cooling. In turn, these dynamics drive changes in the chemistry of the upper ocean, which have important implications for the carbon cycle and Earth's climate. More will be revealed in the chapters ahead.

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11.9: Chapter References

Ahrens, C. Donald, and Robert Henson. 2018. *Essentials of Meteorology: An Invitation to the Atmosphere*. 8th ed. Boston: Cengage. https://www.cengage.com/c/essentials-of-meteorology-8e-ahrens/9781305628458/

Bathen, Karl H. 1972. "On the Seasonal Changes in the Depth of the Mixed Layer in the North Pacific Ocean." *Journal of Geophysical Research* 77(36): 7138–7150. https://doi.org/10.1029/JC077i036p07138

Deacon, Margaret. 1971. *Scientists and the Sea, 1650–1900*. New York: Academic Press. https://www.google.com/books/edition/Scientists_and_the_Sea_1650_1900/V5ITAAAAYAAJ

Drum Team. 2016. "1975: American Express 'Don't Leave Home Without It.'" The Drum. March 31, 2016. https://www.thedrum.com/news/2016/07/03/marketing-moments-11-american-express-dont-leave-home-without-it

Durham, William M., and Roman Stocker. 2012. "Thin Phytoplankton Layers: Characteristics, Mechanisms, and Consequences." *Annual Review of Marine Science* 4: 177–207. https://doi.org/10.1146/annurev-marine-120710-100957

Fan, Wei, Jinbao Song, and Shuang Li. 2014. "A Numerical Study on Seasonal Variations of the Thermocline in the South China Sea Based on the ROMS." *Acta Oceanologica Sinica* 36: 56–64. https://doi.org/10.1007/s13131-014-0504-8

Gilmour, Morgan E., E. A. Schreiber, and Donald C. Dearborn. 2012. "Satellite Telemetry of Great Frigatebirds *Fregata minor* Rearing Chicks on Tern Island, North Central Pacific Ocean." *Marine Ornithology* 40: 17–23. http://www.marineornithology.org/content/get.cgi?rn=956

Hautala, Susan. 2023. "Coordinates." In *Physics Across Oceanography: Fluid Mechanics and Waves*. UW Pressbooks. Accessed January 25, 2023. https://uw.pressbooks.pub/ocean285/chapter/chapter-1/

Johnson, Gregory C. 2008. "Quantifying Antarctic Bottom Water and North Atlantic Deep Water Volumes." *Journal of Geophysical Research: Oceans* 113(C5): C05027. https://doi.org/10.1029/2007JC004477

Kotar, S. L., and J. E. Gessler. 2011. *Ballooning, A History: 1782–1900*. Jefferson: McFarland Books. https://mcfarlandbooks.com/product/ballooning/

Lindsey, Rebecca, and Luann Dahlman. 2020. "Climate Change: Ocean Heat Content." NOAA Climate. August 17, 2020. https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

Longhurst, Alan. 1993. "Seasonal Cooling and Blooming in Tropical Cceans." *Deep Sea Research Part I: Oceanographic Research Papers* 40(11–12): 2145–2165. https://doi.org/10.1016/0967-0637(93)90095-K

Mill, Hugh Robert. 1900. "The Pettersson-Nansen Insulating Water-Bottle." *Geographical Journal* 16(4): 469–471. https://doi.org/10.2307/1774328

NASA. 2001. "Earth at Perihelion." NASA Solar System Exploration. January 3, 2001. https://science.nasa.gov/science-news/science-at-nasa/2001/ast04jan_1

Niskin, Shale J. 1962. "A Water Sampler for Microbiological Studies." *Deep Sea Research and Oceanographic Abstracts* 9(11–12): 501–502. https://doi.org/10.1016/0011-7471(62)90101-8

Salinometry. 2023. "Development of Salinometers." Salinometry. Accessed January 25, 2023. https://salinometry.com/development-of-salinometers/

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CHAPTER OVERVIEW

12: Atmospheric Circulation

With a wingspan reaching 11 feet, the albatross can glide across thousands of miles of ocean without ever flapping. In flight they reach speeds of over 70 miles per hour and remain in the air for 20 hours or more. The distances they cover are epic. One tagged albatross completed a circumnavigation of Antarctica—a journey of more than 16,000 miles—in just 46 days. The albatross achieves these long flights because its slender, glider-like wings lock in place like snap-together tent poles and enable it to fly without moving a muscle. The albatross's heart rate while flying barely exceeds its resting heart rate. This bird is a marvel of evolutionary engineering and a paragon of energy-efficient flight.

The albatross can teach us a good deal, and so we take to the air on the wings of an albatross in our exploration of winds, those great currents of air that sweep our globe. Modern technology permits us to tag along and experience the flight of these great birds. Albatross cams have captured these birds gliding across the ocean, soaring next to icebergs, and following killer whales—presumably while they're hunting, an activity at which the killer whale excels. But we are going to follow an imaginary albatross, a robotic one we'll call a robotross. Though an actual robotross doesn't yet exist, engineers are very keen to build one to carry out long-lasting, energy-efficient flights. Because ours is imaginary, it may disobey a few engineering limitations and laws of physics. Our robotross does whatever we ask it to do.

In our robotross trek around the globe, we will explore **meteorology**, the study of the atmosphere. We'll soar to the very top of the atmosphere and from the equator to the poles. This global flight will introduce us to the structure of Earth's atmosphere and the global wind patterns. With these basic concepts, we can better understand the nature of global shifts in Earth's winds, such as those that occur during cycles of El Niño and La Niña, and one of the most powerful forces of nature on the planet—hurricanes. We'll use this knowledge in future chapters to understand currents and waves.

12.1: Earth's Atmosphere
12.2: What Causes Winds?
12.3: Local and Regional Winds
12.4: Global Atmospheric Circulation
12.5: Final Thoughts
12.6: Chapter References

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12.1: Earth's Atmosphere

Our **atmosphere** exists as a shell of gases held close to Earth's surface by the force of gravity. If our robotross could turn back time and visit Earth soon after it formed some 4.56 billion years ago, we would find an atmosphere much different than the one we experience today. Though the thickness and composition of Earth's early atmosphere remains controversial (e.g., Emspak 2016), scientists are fairly certain that it lacked oxygen (O_2). However, owing to the evolution of oxygenic photosynthesis some 2.5 billion years ago, atmospheric concentrations of O_2 began to rise. This momentous occasion in Earth's history has been named the **Great Oxidation Event**. Fortunately for us (and every other aerobic organism), the modern-day concentration of atmospheric O_2 hovers around 21 percent (by volume).

The most abundant gas in Earth's modern atmosphere is nitrogen (N_2), at a concentration of about 78 percent. This is an important element for agriculture and oceanic phytoplankton—but one that is not easily obtained. Turning nitrogen gas into industrial fertilizer takes tremendous amounts of energy. Natural conversion of N_2 into biologically available forms (e.g., ammonium, nitrate, nitrite) is carried out by a special group of organisms: the **nitrogen-fixing bacteria**. So though N_2 is quite abundant in the atmosphere, it tends to be a limiting factor for biological processes, especially in the ocean.

Argon (Ar), a noble gas left over from Earth's formation that is resupplied through the radioactive decay of potassium (K), ranks third among the gases present in Earth's atmosphere. Because it is non-reactive, welders use Ar to prevent oxygen from reacting with the metals being welded. Otherwise, most people give it no thought.

The other gases in our atmosphere (possibly hundreds) exist only in trace amounts, but a few of them exert a profound effect on our planet. From Chapter 10, you may recall ozone, naturally abundant in the stratosphere and produced via photochemical reactions with car exhaust at Earth's surface. Stratospheric ozone acts as a shield to protect organisms from mutation-causing UV radiation. We also learned about manufactured chlorofluorocarbons that eat away at stratospheric ozone and increase the intensity of harmful UV radiation reaching Earth's surface, especially at Earth's poles.

Of course, greenhouse gases (Chapter 12) keep Earth warm by absorbing longwave radiation from Earth's surface. Greenhouse gases, especially water vapor, belong to a category known as **variable gases**, substances whose concentrations vary in the atmosphere. Among the variable gases, water vapor reigns supreme, accounting for up to 4 percent of the atmospheric gases at times. Of course, invisible water vapor and its visible cousins, liquid water and ice, make up the trio of forms responsible for precipitation and other important processes on our planet.

Earth's Geophysical Fluids

As every robotross knows (or soon learns), it's easier to fly through air than water. That's because the atmosphere is 800 times less dense than the ocean. This difference in density explains the difference in the response of the atmosphere and ocean to forces that set them in motion. Atmospheric flows behave like Aesop's speedy hare, whereas the ocean moves more like the slow, but steady, tortoise. Light transmits much farther in the atmosphere too, permitting us to see for miles and miles. By contrast, visibility in even the clearest ocean water rarely exceeds a couple hundred feet. Sound, however, can be transmitted for hundreds of miles in the ocean; in the atmosphere only something like a violent volcanic explosion can be heard that far away.

Despite their differences, the atmosphere and ocean belong to what scientists call **Earth's geophysical fluids**—the air, water, and molten rock found on our planet. The properties and motions of these fluids occupy the attention of numerous disciplines of science, including meteorology, climatology, oceanography, geophysics, volcanology, engineering, and many more. But their study principally falls to a field of science called **geophysical fluid dynamics**—the study of fluid flows in nature. Our understanding of geophysical fluid dynamics extends well beyond academics—these fluids determine the habitability of our planet. As Vallis puts it (2016): "Geophysical fluid dynamics plays an enormous role in the development of our understanding of the natural world."

Weather vs. Climate

A simple explanation for the difference between weather and climate comes from a 19th-century school child (whose name, unfortunately, was never recorded): "Climate lasts all the time and weather only a few times" (Le Row 1887). That's a pretty good way to think about it. In Chapter 1, you learned **weather** represents what is happening in the atmosphere right now at a given location. Air temperature, precipitation, humidity, cloud cover, barometric pressure, wind speed and direction, and visibility are a few of the weather conditions that might be observed. **Climate**, on the other hand, is the long-term average of weather conditions at

a given location or globally. Climate scientists typically use a 30-year period to compute the average climate for a location. When you hear the TV weatherperson talk about today's temperatures being so many degrees above or below normal, the benchmark they are referring to is the 30-year average.

The terms weather and climate apply to the ocean as well (e.g., Carlowicz 2006; Pope 2021). Ocean weather may be expressed as a day when the water is cold or warm, with big waves or none, clear or murky water. **Ocean weather**, like atmospheric weather, changes day to day. **Ocean climate** refers to longer timescale changes in the ocean, such as El Niño/La Niña or the Pacific Decadal Oscillation.

The atmosphere and ocean work in concert to orchestrate Earth's weather and climate. The air–sea boundary exchanges heat, water, gases, and chemicals between the atmosphere and the ocean. The atmosphere connects to the ocean; the ocean connects to the atmosphere. Together they drive much of what we experience on the surface of our planet.

Layers of the Atmosphere

If we send our robotross straight up from Earth's surface into the sky, it would encounter different layers of the atmosphere. Generally speaking, the layers of the Earth's atmosphere correspond to changes in temperature that occur with altitude. Meteorologists divide the atmosphere into five layers based on temperature or the presence of certain gases or other kinds of matter. The five layers of the atmosphere include (following NOAA/NESDIS 2016):

- The **troposphere**—the layer closest to Earth's surface and the one in which we live. This is where we experience weather directly. Temperature here typically decreases with increasing altitude.
- The **stratosphere**—the layer above the troposphere and the one that produces the highest weather-related clouds, such as cirrus, cirrostratus, and cirrocumulus. Temperature increases with altitude in the stratosphere.
- The **mesosphere**—the layer above the stratosphere in the middle of Earth's atmospheric layers, where meteors become visible as they are heated through friction with the gases present in this layer. The mesosphere produces noctilucent clouds, which are made of ice crystals that mysteriously glow at night. These are the highest clouds. In this layer temperature decreases with altitude.
- The **thermosphere**—the layer above the mesosphere named for its high temperature. That's a bit misleading because despite the presence of gas molecules with high kinetic energy—the technical definition of high temperature—the molecules are so thin that you wouldn't feel warmth were you to step out of an aircraft at this height. Temperature increases with altitude in the thermosphere.
- The **exosphere**—the layer above the thermosphere, so named because "exo" means outer, and this is the atmosphere's outermost layer. The exosphere is really, really thin and really, really big. A recent analysis of decades-old data revealed that it extends beyond the Moon (Baliukin et al. 2019).

You may also notice at left a dashed line called the **Karman Line**. This line represents the official-but-not-quite-scientific boundary between our atmosphere and outer space. (Learn more at astronomy.com.)

Atmospheric Pressure

Like we did for the ocean, we can think of the atmosphere as a column—this time it's a column of air. Meteorologists define an **air column** as an undefined cylindrical (or rectangular) volume of the atmosphere that extends from Earth's surface to a given height. Similar to the concept of a water column, visualizing a column of air provides a convenient way to understand the nature of the forces that act upon the atmosphere.

Like the ocean, the atmosphere exerts **pressure**, the force exerted by a fluid on an object immersed within it. The weight of the atmosphere acting on a unit area of Earth's surface (or us) represents atmospheric, or air, pressure. Air pressure at sea level exerts about 14.7 pounds per square inch (psi). Equivalent units in common use include millibars (1,013.25 mb) and inches of mercury (29.92 in. Hg; Ahrens and Henson 2018). Fortunately, gases in our bodies push back with an equal force so we don't experience this crushing weight.

Unlike the ocean, however, air is compressible. Gravity pulls down on our atmosphere, causing air molecules to be packed more closely (compressed) at the Earth's surface. Meteorologists refer to the packing of air molecules as **air density**—the number of molecules in a given volume. Fewer air molecules means less air pressure: the less air above you, the lower the pressure. So, in

effect, as we climb higher into the atmosphere, both air density and air pressure diminish—rapidly at first, then slower as altitude increases. In mathematical terms they decrease exponentially.

The rapid decrease in air pressure with altitude explains why your ears pop when you travel into the mountains. Air pressure at higher elevations is less than air pressure at lower elevations, so your ears have to adjust. Your eustachian tube opens to equalize the air pressure inside your middle ear and the surrounding air, which occasionally leads to a pop, like a champagne cork releasing gases.

Changes in temperature also cause changes in pressure and density. Anyone familiar with a hot air balloon (or heating in a home) knows that hot air rises. As air warms, its molecules get farther apart. Fewer molecules in a space results in lower air density and pressure for that volume of warmed air. Because the warmed air has a lower pressure than the surrounding air, it rises. The surrounding air pushes the volume of warmed air upward until it reaches an altitude where the pressure of surrounding air and the pressure inside the balloon are equal. Similarly, cooling a body of air results in an increase in its density and pressure. As we know, cold air sinks. The changes in air pressure with temperature are key to understanding motions in the atmosphere.

Highs and Lows

Differences in the heating of Earth's surface result from differences in latitude and seasonal variations in solar radiation. This and a number of other factors generate regions in our atmosphere with different air pressures. Meteorologists designate regions of high and low pressure. Places where the pressure in a particular area is higher than that of the surrounding region are called **high-pressure regions**, or highs. Places where the pressure is lower than the surrounding region are called **low-pressure regions**, or lows. On weather maps or the local news on TV, you'll often see these regions symbolized with a red letter L for a low and a blue letter H for a high. Designating highs and lows is a kind of shorthand for illustrating regions with mild and stable weather, which typically occurs in high-pressure regions. Regions with unsettled and unpleasant weather generally occur in low-pressure regions.

Observations of air pressure at different locations (or altitudes) provide the basis for designating high- and low-pressure areas. A surface map of air pressure typically illustrates lines of equal pressure, or **isobars**. Looking at the center of a high-pressure system on an isobaric map, you can see that the pressure here is higher than the surrounding areas. Similarly, the center of a low-pressure system will have a lower pressure than the surrounding areas. While a complete understanding of isobaric maps is beyond the scope of this text, a general familiarity with them proves useful for understanding wind and ocean currents.

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12.2: What Causes Winds?

Winds—movements of air—arise from an imbalance of pressure. They are nature's way of bringing balance to an unbalanced atmosphere. To achieve that balance, winds blow from regions of high pressure to regions of low pressure. To understand winds, we need to understand something about the forces generated by differences in air pressure between different locations (following Ahrens and Henson 2018).

Hydrostatic Equilibrium, a Balance of Forces

As we learned above, air pressure decreases with altitude. It's highest at Earth's surface and lowest at the top of the atmosphere. So if winds blow from high to low pressure, why aren't winds blowing upward from Earth's surface? The answer is gravity. The force of gravity counteracts the force generated by the upward difference in pressure. When these two forces are equal, and no net vertical motion of the atmosphere occurs, a **hydrostatic equilibrium** is maintained. The upward forces are balanced by the downward forces, and the fluid is at rest. The hydrostatic equilibrium concept (i.e., a balance of forces) applies to vertical motions in the ocean as well (as we learned in Chapter 13). We'll visit this topic again in our chapter on ocean circulation.

Of course, some vertical motions in the atmosphere (and ocean) do occur. Sinking air generally accompanies high-pressure systems, while rising air characterizes low-pressure systems. **Thermals**—rising columns of warmed air (sought out by birds, hang glider enthusiasts, and presumably robotrosses)—also represent vertical motions of air. Violent vertical air motions occur during thunderstorms and tornadoes. Nevertheless, the strongest motions of air lie with pressure differences across horizontal scales—that is, the force that causes winds.

The Pressure Gradient Force

To express the strength of the pressure differences that cause winds, meteorologists and oceanographers define the **pressure gradient force** (PGF), which is generated by differences in air pressure between two locations. Mathematically, we represent the PGF between two locations as:

$$PGF = \text{Pressure difference} / \text{Distance}$$

$$\textit{(Eq. 15.1)}$$

The strength of the PGF determines the strength of the winds. This equation predicts that when the pressure difference between two locations is high, the PGF will be strong. When the pressure difference between those two locations is low, it will be weak. What really matters is how pressure changes over distance—the gradient of pressure changes. In an isobaric map, steep changes appear as closely spaced isobars, while gradual changes in pressure are represented by isobars that are farther apart. Steep changes in pressure over short distances bring about very high winds; weak winds will be present where isobars are widely spaced.

A Description of the Coriolis Force

One other force plays a role in the motions of air (and water) on our planet. Formulated by French mathematician Gaspard Gustave de Coriolis (1792–1843), the **Coriolis force** refers to the apparent deflection of moving objects across Earth's surface from the standpoint of an observer on Earth. This deflection occurs because the object is in motion on a rotating frame of reference—the spinning Earth. Though not correct in physical terms, the Coriolis force has been compared to what happens to a ball thrown to the other side of a playground merry-go-round. By the time the ball reaches the other side, the target has moved. From the standpoint of a person on the merry-go-round, it appears as if the path of the ball curves, though, of course, it doesn't.

If this sounds complicated, it is, and a proper understanding would take many pages and some advanced mathematics. Many valiant attempts have been made in textbooks to explain the Coriolis effect, but they generally confuse and muddy the topic more than they help students understand it (e.g., Kearns 1998; Perrson 1998; Shakur 2014). Simply knowing what happens as a result of the Coriolis force suffices for our purposes here. The Coriolis force underlies the clockwise and counterclockwise motions of winds and currents around centers of high and low pressure, helps to explain the formation and circulation of hurricanes, and a lot more.

As a result of the Coriolis force, winds and currents appear to be pulled sideways, or perpendicular to the direction of their motion. In the Northern Hemisphere, the Coriolis force causes moving objects to deflect toward the right (clockwise). In the Southern Hemisphere, the Coriolis force causes moving objects to deflect toward the left (counterclockwise). In other words, the Coriolis force influences the direction of winds and currents. If that's all you remember about the Coriolis force, you'll be fine.

For the sake of completeness, you should be aware that the strength of the Coriolis force—the degree to which it influences direction—increases with latitude and the speed of the object. Horizontal motions along the equator experience no Coriolis force. As well, the Coriolis force acts largely over long distances, on the order of tens of kilometers—scales that are important for the circulation of the atmosphere and the ocean. Despite popular notions, the Coriolis force does not cause water in sinks and bathtubs to swirl clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Compared to the forces within the sink or bathtub (such as the shape of the basin and whether it's level), the Coriolis force is too small to alter the rotation of water down the drain.

To visualize the effect of the Coriolis force on the direction of winds and currents, I recommend that you employ the three-legged handperson model. You'll need a right hand (or a reasonable facsimile) and a map or piece of paper representing a map. Let your three middle fingers be the legs of your handperson (yes, this handperson has three legs). Let your thumb represent the left hand of your handperson and your pinky finger represent the right hand. Now walk (using your three legs) across a map to the north of the equator. As the handperson moves toward the North Pole, move it in the direction of your pinky, or toward the right. Turning your handperson to the right in the Northern Hemisphere represents the change in motion that occurs as a mass of air or water moves in the Northern Hemisphere. The direction you travel makes no difference; when you are in the Northern Hemisphere, a moving object will be deflected toward the right. Alternatively, when you walk your handperson into the Southern Hemisphere, you will turn in the direction of your thumb—toward the left. Remember that your knuckles are the eyes of the handperson so you're always facing in the correct direction as you walk across the map. In this way you can visualize and better understand the consequences of the Coriolis force as it acts on winds or currents.

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12.3: Local and Regional Winds

In the sections that follow, we'll use the concepts of pressure, the PGF, and the Coriolis force to understand local, regional, and global winds. Local winds, such as sea and land breezes, operate over the **mesoscale**—a few to a hundred kilometers. These winds affect coastal air temperatures and local wave conditions. Regional winds, such as Santa Ana winds and monsoonal circulation, operate over **synoptic scales**, on the order of hundreds to a thousand kilometers. These winds directly impact weather and coastal ocean processes. Global winds, including trade winds, westerlies, and jet streams, operate over **global scales** greater than a thousand kilometers. These winds drive the ocean currents.

Sea and Land Breezes

A wind coming onto the shore of a coastline, known as an **onshore wind**, provides a perfect opportunity for a robotross to take flight. Unlike most birds, albatrosses (and our robotross) cannot just flap their wings and take flight. They require some wind or, at the very least, a good runway so they can trot into the wind. The **sea breeze**, a thermally driven onshore wind, provides an ideal launching pad.

The sea breeze forms as a result of uneven heating of land and water along a coastline. Land, compared to water, heats quickly, so a temperature gradient forms across the land–water boundary. Heating land surfaces causes the air over the land to rise, creating lower pressure at the surface. A pressure gradient forms, causing higher-pressure air over the ocean to move onto the shore. Aloft, the rising air over land creates a higher pressure than that of the corresponding altitude over water. So air at altitude begins to move offshore, from the land to the ocean. A circulation cell thus develops, with ocean-cooled air coming onto the shore at the surface and land-warmed air moving offshore aloft. Because heating of land generally becomes most intense in the afternoon, the sea breeze generally peaks at that time. At night the opposite situation occurs. Land cools more quickly than water, so an area of lower pressure develops over the water. A pressure gradient forms, directed from land to ocean, and an **offshore wind** develops—a wind that blows from land to ocean. We call this wind a **land breeze**, a thermally driven wind that blows from land toward the ocean.

Sea breezes and land breezes can moderate coastal temperatures. Sea breezes cool coastlines during the day, and land breezes warm them at night. Sea and land breezes can also generate local waves. An afternoon wind swell is a familiar feature to Southern California surfers, especially during the summer, when the difference between land and ocean temperatures is greatest. Thermal circulations, such as sea and land breezes, require relatively stable atmospheric conditions to form. They also require a strong temperature gradient between the land and the ocean. A stable atmosphere and strong temperature gradient typically occur during the summer months, so sea and land breezes are most common in the summer.

On- and Offshore Winds

Winds that blow from the ocean to land—onshore winds—and winds that blow from the land to the ocean—offshore winds—can also be caused by pressure gradients over synoptic scales. Pressure gradients develop when air mass movements and other factors cause pressure differences between inland and coastal or offshore locations. These pressure gradients may enhance or overpower thermally driven, local wind patterns. On- and offshore flows exert a strong influence over weather along coastlines and can modify conditions within coastal waters.

Television weather forecasts in coastal California cities such as San Diego, Los Angeles, and San Francisco include a reference to on- or offshore winds. Onshore winds typically bring with them the **marine layer**, a low-altitude cover of stratus clouds that forms over a cool ocean. In places like San Francisco, onshore winds in summer can bring **fog**, simply defined as a cloud formed near the ground. Because nighttime ocean temperatures are generally warmer than nighttime land temperatures, an onshore flow brings warm, moist air in contact with the cooler land surface, and fog forms. Like a cat, the fog sweeps quietly inland until warmer daytime temperatures cause it to dissipate. Meteorologists often refer to onshore winds as "nature's air-conditioner," especially in summer, when the deck of clouds or fog they bring keeps land temperatures cooler than they otherwise would be.

An offshore flow brings higher temperatures to coastal cities. Without a reflective layer of near-surface clouds and cool air from the ocean, offshore winds allow the land to heat faster. Offshore winds also carry airborne particles and air pollution across the ocean. The particles these winds carry can have impacts on marine life. Nitrogen compounds in the air may stimulate phytoplankton growth. On the other hand, toxic metals may inhibit the growth of some organisms (Mahowald et al. 2018).

Santa Ana Winds

Locally infamous offshore winds, the **Santa Ana winds**, deserve special attention. Named in 1880 for their occurrence through Santa Ana Canyon (along I-91 between Chino Hills and the Santa Ana Mountains), the Santa Ana winds have become the stuff of Southern California legend. They've appeared in books and movies, grabbed the attention of songwriters and artists, and struck fear into anyone living at the edge of the chaparral. Santa Ana winds can bring hot, dry, dust- and smoke-filled, hurricane-strength wind gusts across the Southland. They've been responsible for some of the worst wildfires in Southern California history. Perhaps that's why some locals call them "devil winds" (e.g., Masters 2012).

Scientists define Santa Ana winds as "episodic pulses of easterly, downslope, offshore flows over the coastal topography of Southern California and Northern Baja California" (e.g., Guzman-Morales et al. 2016). Let's dissect this definition.

First, Santa Ana winds are episodic, meaning they occur at irregular intervals. On average Southern California experiences 32 Santa Ana wind events per year, typically from October to April. However, September and May events are not uncommon.

Second, Santa Ana winds blow from the east or northeast at speeds (generally 10 to 30 mph; 4.5 to 13.5 m s^{-1}) that exceed the local wind field for more than 12 hours. Most Santa Ana wind events last from a few to 6 days; about 10 percent last up to 12 days (e.g., Guzman-Morales et al. 2016). Extreme events can generate gusts up to 80 miles per hour (35 m s^{-1}; Fovell and Gallagher 2018).

Third, and perhaps most important, Santa Ana winds are **downslope winds**, meaning they blow from higher to lower elevations. The movement of air from a higher to a lower elevation causes it to undergo an increase in pressure (because, as we learned above, air pressure is greatest at sea level). This increase in air pressure results in a process called **compressional heating** (also known as adiabatic heating). It's the same as what happens when you add air to a bicycle or car tire. Ever feel the valve stem when adding air? It gets hot because you are compressing a given volume of air and the energy it contains into a smaller volume. Compressional heating (and its opposite, expansional cooling) also happens in the ocean, but because air is more compressible than water, the effect is not as dramatic. Compressional heating causes Santa Ana winds to heat up as they travel from east-northeast toward the coast. In fact, during Santa Ana wind events, coastal cities are hotter than areas a few or even several miles inland by a few degrees or more. A few hundred miles or more inland, air temperatures may be quite chilly. The heat of Santa Ana winds comes from compression, not from blowing across a desert. Compressional heating also results in very low humidity values—a measure of the water vapor in a parcel of air. High temperatures and low humidity values increase fire danger.

Finally, like land breezes, Santa Ana winds blow offshore due to the PGF that develops when inland areas have higher air pressure than along the coast. Specifically, Santa Ana winds form when a ridge of high pressure occupies the Great Basin region, an expanse of basins and mountain ranges that cover parts of California, Idaho, Nevada, Oregon, Utah, and Wyoming. The resultant pressure gradient generates winds that blow from the Great Basin toward Southern California and Baja California Norte (i.e., Northern Baja). Because they encounter a barrier of mountains surrounding Southern California (the San Gabriel and San Bernardino ranges), they accelerate as they funnel through the narrow mountain passes and canyons that open onto the coastal plain.

The elevated heat, single-digit humidity, and near-hurricane-strength winds bring a host of discomforts. The heat and low humidity dry out your skin, irritate your eyes, and, according to one author, "curl your hair and make your nerves jump" (Chandler 1946). The high winds send plumes of dust and debris into the air, making it difficult to drive and even breathe. And, of course, their peak season occurs at the end of summer, when vegetation is driest, and the danger of wildfire is greatest. Some of Southern California's worst wildfires have been stoked or even caused by Santa Anas and similar downslope winds. High winds can knock down power lines or cause them to spark. Once the vegetation ignites, a wildfire in the presence of Santa Ana winds can be very difficult to stop. As one firefighter puts it, "About the only firebreak that works is the Pacific Ocean" (Wolansky 2016).

Their numerous negative qualities aside, Santa Ana winds do bring some benefits, especially to Southern California's coastal waters, where trace metals such as iron (Fe) may limit phytoplankton productivity. Offshore winds, and especially Santa Ana winds, deliver dust and biologically important micronutrients (namely metals, such as manganese and iron) in quantities sufficient to enhance the growth of phytoplankton. A study in 2017 suggested that as much as 15 percent of phytoplankton growth during winter and spring could be attributed to additional micronutrients supplied by Santa Ana winds (Felix-Bermudez et al. 2017). A number of studies also suggest that atmospheric dust particles delivered to the ocean can act as "ballast" for particulate organic carbon and enhance the sinking rates of these carbon-rich particles (Bressac et al. 2014; Pabortsava et al. 2017; van der Jagt et al. 2018). Such effects—phytoplankton fertilization and ballasting of carbon to the deep sea—have implications for the ocean carbon

cycle and climate change. Next time you're complaining about the Santa Ana winds, just remember that they are fertilizing phytoplankton that feed fishes and removing carbon dioxide from the atmosphere, a benefit to us, the ocean, and the planet.

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12.4: Global Atmospheric Circulation

We now turn our attention to **global atmospheric circulation**, the three-dimensional motions of air within the troposphere. Global atmospheric circulation transports momentum (i.e., mass in motion), heat, gases, water (as water vapor and as a liquid or solid in clouds), suspended particles, and even microscopic organisms on a journey around the globe. Most important for ocean dwellers, global atmospheric circulation gives rise to the surface winds that "stir" the ocean; accelerate air–sea transfer of energy, materials, and gases; generate ocean currents and up- and downwellings; and create waves. We'll explore some of these topics in the chapters ahead. But for now, let's get a general sense of the patterns of atmospheric motions and the forces that cause them.

A One-Cell Model

The simplest model of atmospheric circulation assumes a nonrotating Earth. As you know from our discussion above, the Coriolis force (caused by Earth's rotation on its axis) plays a role in the direction of fluids, winds, and currents moving across Earth's surface. Absent Earth's rotation and the Coriolis force, the circulation of the atmosphere works much like the circulation of a room with a space heater on the floor of one side. The air above the heater warms and rises vertically. Reaching the ceiling, the warmed air flows horizontally toward the opposite wall. As it moves along the ceiling, the air loses heat and cools, causing it to sink. Once it reaches the floor, the cooled air is drawn toward the heater as the rising air above creates an area of low pressure. The circulation of the air from heater to ceiling to floor back to heater describes the journey of air in a **convection current**—the heat-driven, circular motion of fluids (air and water) from one place to another.

On a global scale, the movement of air in the atmosphere traces a similar three-dimensional path. Just as a space heater supplies the energy that causes the air in a room to move, the Sun's rays supply the energy that causes the atmosphere (and, indirectly, the ocean) to move. You may recall that the Sun's rays strike Earth's surface most directly in the tropics, the region between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S). This radiant energy raises the temperature of the ocean and land. The warmed ocean and land surfaces in turn heat the atmosphere. The heated tropical air rises. In this sense the tropics serve as the "firebox" of the atmosphere, acting as the main source of heat that drives its motions (Garstang and Fitzjarrald 1999, after Malkus 1962).

We can also see how this works in a simple model of the radiation balance from the equator to the poles. Using our simple reservoir model, we know that the total energy at any location on Earth depends on how much energy that location receives (from the Sun) versus how much it loses (ultimately, to outer space). Mathematically, we can state Earth's radiation balance as:

$$E_{total} = E_{in} - E_{out}$$

(Eq. 15.2)

It should make sense to you that if $E_{in} > E_{out}$, then the location gains energy. If, on the other hand, $E_{in} < E_{out}$, then that location will lose energy. Viewed in this way, we can see that between 40°N/S—a region that includes the tropics—there is a net gain of energy: $E_{in} > E_{out}$. But from 40°N/S to the poles, there is a net loss of energy: $E_{in} < E_{out}$ (see Garstang and Fitzjarrald 1999, p. 4).

Heating of Earth's surface by the Sun at equatorial regions causes the air in this region to rise. The entire column of air above the equator expands upward (because, as you know, heating causes expansion of air). Aloft, at the top of the warmed and expanded column of air, the air pressure of the heated column is greater than that of the unheated air on either side of it. Because winds blow from regions of high pressure to regions of low pressure, the air at the top of the warmed column begins to flow outward. Visualizing this process in three dimensions, the air at the top of the warmed column flows to higher latitudes, or toward the poles. The flow of air aloft causes a reduction in air pressure at the surface because there is now less air above the surface. The low air pressure at the surface around the equator draws in air from surrounding regions—that is, from nearby latitudes. Winds flow toward the equator, drawn there by the low pressure caused by the rising air at the equator.

The vertical and horizontal flows of air in the atmosphere constitute an **atmospheric cell**, the large-scale convection of a part of the atmosphere. Air rises at the equator and moves poleward aloft. Surface air from the poles rushes toward the equator to replace the rising air. The poleward-moving air cools, sinks to the surface, and replaces the air that moved toward the equator. It's a giant cell of moving air, and this pattern describes the three-dimensional circulation of air in Earth's atmosphere. In our simple model of an Earth that is not turning, we observe one atmospheric cell in each hemisphere.

The temperature imbalance between the tropics and subtropics and the polar and subpolar regions drives atmospheric circulation. Differences in temperature create differences in pressure, and when that happens, winds occur. Global winds act to compensate for the imbalances in pressure that result from temperature differences across the globe. They try their best to bring Earth's atmosphere into balance, but because temperature and pressure differences always exist somewhere on Earth, the winds are constantly blowing. Such is the dynamic nature of our atmosphere. But what happens when we allow Earth to rotate as it normally does? Enter the Coriolis force.

A Three-Cell Model

The Coriolis force causes winds to deflect to the right in the Northern Hemisphere and left in the Southern Hemisphere. As a result, the warm equatorial air moving poleward and the cool, higher-latitude air moving equatorward in our one-cell model never make it to their destination. Our one-cell model transforms into a **three-cell model**—three cells in each hemisphere—when we add the effects of the Coriolis force. Because they were discovered independently, each of the three cells has a different name. The atmospheric cell positioned in the tropics is called the **Hadley cell**, named after English lawyer and amateur meteorologist George Hadley (1685–1768), the man who first developed a mathematical description of tropical circulation. The middle-latitude atmospheric cell is called the **Ferrel cell**, named after American meteorologist and Tennessee school teacher William Ferrel (1817–1891; Persson 2006). The polar-region atmospheric cell is simply called the **polar cell**; apparently, no single discoverer can claim credit for it.

In the three-cell model, poleward air aloft (the air that rose over the heated tropics in the one-cell model) sinks, descending to the surface at about 30°N/S. This motion of air from the equator to 30°N/S aloft and back again at the surface belongs to the Hadley cell. But this equatorward surface wind also bends due to the Coriolis force. This gives rise to surface winds that move northeast to southwest in the Northern Hemisphere and southeast to northwest in the Southern Hemisphere. Because these winds are constant, they became known as the **trade winds** (from the Middle Dutch/German meaning "course," "track," or "habitual," according to etymonline.com 2023). Note that in the Northern Hemisphere, these trade winds are referred to as the **northeast trade winds**. In the Southern Hemisphere, they are called the **southeast trade winds**.

In the absence of a connected single cell, as would occur on a nonrotating Earth, the poles develop their own cells—the polar cells. Here cold air descends to the surface and moves toward the equator. As it moves poleward, the Coriolis force deflects it right (Northern Hemisphere) or left (Southern Hemisphere). The net effect is a surface flow that moves from the east in either hemisphere. This gives rise to a wind pattern at high latitudes called the **polar easterlies**.

As polar air moves toward the equator, it warms, and as it warms, it rises. As a result, there is another limb of ascending air at about 60°N/S similar to, but not as strong as, the rising limb of air at the equator. The rising limb of air at 60°N/S and the descending limb of air at 30°N/S act like gears to create a third atmospheric cell between the Hadley cell and the polar cell. This circulation cell is the Ferrel cell, which operates intermittently and, at times, doesn't even exist. Nevertheless, it provides a useful part of the global atmospheric circulation model because it links the Hadley and polar cells.

The Ferrel cell features its own set of winds—the **westerlies**—which flow west to east at latitudes between 30° and 60°N/S, that is, at mid-latitudes. Though not as dependable as the trade winds, the westerlies provide a convenient return route for sailing ships. Of course, their higher latitude often brings more severe weather. Winds here go by names like the Roaring Forties, the Furious Fifties, and the Screaming Sixties, a reference to the latitudes where they occur. No doubt these names helped sailors weave more dramatic stories when (if) they returned home.

One other consequence of the rising and descending limbs of the atmospheric cells is that at latitudes where air is rising or descending, the surface winds are very light, if not downright calm. The best known are the **equatorial doldrums**, a region of calm rising air near the equator. A similar region—the **horse latitudes**—occurs as a region of sinking calm air at about 30°N/S. Sailors on sailing craft dreaded these regions—the calm winds and stifling heat drove men mad. The days and weeks of additional time at sea often proved deadly.

A popular mythology of the horse latitudes is that they derive their name from the practice of Spanish sailors casting dead horses overboard in these regions. The animals died due to lack of water or food or both while the ship drifted. In some cases the horses may not have been dead yet, and with no Monty Python crew to check the status of their deceasedness, it may well be true. Lest this upset you, let me assure you that every horse—dead or alive—once entering the ocean turned into a seahorse and may swim the ocean to this very day.

Though both calm regions feature light and variable winds, the equatorial doldrums and the horse latitudes differ markedly in their precipitation patterns. Air rising from the equator carries with it a lot of moisture in the form of water vapor. When that air cools, the water vapor condenses and forms clouds. Towering thunderheads develop and generate copious amounts of rainfall. We can see this in satellite images of equatorial regions. The dense band of clouds that develops over the equator is known as the **Intertropical Convergence Zone**, or ITCZ. This is the region where northeast trade winds meet southeast trade winds—they converge. The high amounts of rainfall in the ITCZ actually lower the salinity of surface waters along the equator. The ITCZ is also responsible for producing the world's most diverse ecosystems, the tropical rainforests, which contain at least half of all of the plant and animal species in the world. I like to call them the "coral reefs of the land."

At the other end of the Hadley cell, at the horse latitudes, the opposite process happens. Sinking air warms as it moves to lower altitudes. The increase in pressure that accompanies a decrease in altitude causes compressional heating, the same phenomenon created by the Santa Ana winds. The increase in temperature lowers the relative humidity of the air and makes it much more difficult for clouds and precipitation to form. Take a look at any world map, and you will see that the great deserts—the Sahara, the Kalahari, the Arabian, the Gobi, the Great Victoria, the Patagonian, the Mojave, and the Sonoran, among others—generally occur in the subtropics at the latitude of the descending limb of the Hadley cell. The global pattern of atmospheric circulation does not favor these regions with precipitation like it does the equatorial regions. Less than 10 inches of rain falls on these places annually—the very definition of a desert. Sinking air also creates polar deserts. And while we don't usually think of polar regions as deserts, Antarctica qualifies as the biggest desert in the world, receiving less than 10 inches of precipitation annually. The snow covering Antarctica has accumulated very slowly over time because it doesn't melt. Someday I hope to ride a camel across the Antarctic desert.

At times the winds over the subtropical deserts blow so hard that they lift sand and small grains of sediments into the air. These sandstorms can be quite intense and bring blackout conditions. While sand is rarely transported very high, dust particles 1 to 100 micrometers in size may be carried 20,000 feet into the air. At this height these particles get picked up by upper-level winds and may be distributed around the globe. Saharan dust storms are the most famous. Dust from the Sahara actually settles over Florida and Texas in the days and weeks after a large sandstorm. Other desert locations generate similar dust storms.

A More Realistic Model

While the three-cell model of global atmospheric circulation does a decent job of explaining surface wind and pressure observations, it is inadequate to describe the wind patterns that meteorologists observe in the upper levels of the atmosphere. Observations from weather balloons reveal a more complex wind environment in the upper troposphere. While the Hadley cell model closely approximates observations, the Ferrel and polar cell models do not match what is observed. Instead, swift currents of air known as **jet streams** interrupt the idealized flow of the atmosphere. At subpolar latitudes at an altitude of 5–9 miles (8–14 km), we find the **polar jet streams**, high-altitude flows of cold air that meander like rivers around the North and South Poles (e.g., Lindsey 2021). Farther south (between 20° and 30° latitude) and at higher altitudes (6–10 miles high), the **subtropical jet stream** can be found. Both jet streams occur at the boundaries between air masses with different temperatures and reach their highest speeds—at times greater than 200 miles per hour—during winter when the temperature difference between their air masses is greatest.

The strongest and most pronounced atmospheric jet stream is the polar jet stream, which is the major weather maker across most of the United States, especially the Midwest. The polar jet stream often bends and dips across the middle part of the United States due to a phenomenon known as a **Rossby wave**, a large-scale, wave-like motion of the upper troposphere. Rossby waves are one of the reasons the weather in the Midwest can be so unpredictable and deadly. As the westward-traveling wave meanders and dips toward the south, cold polar air behind it rushes in. Westward-propagating Rossby waves in the polar jet stream cause changes in the position of cold and warm air masses, or fronts, that generate weather. Tornado Alley in the Midwest is a good example of what happens when cold and warm air masses collide. Some studies suggest that the propagation of Rossby waves in the polar jet stream has slowed down so that weather patterns associated with the movements of Rossby waves persist for longer than normal (e.g., Francis and Vavrus 2012). Other studies find no evidence for this (e.g., Blackport and Screen 2020). The now-popular "polar vortex" and its odd behavior suggest some relationship to global warming, but meteorologists have yet to identify the underlying processes. In any case, we can expect Earth's weather to continue to change in unexpected ways as we add heat to the system.

The subtropical jet stream can spawn the **Pineapple Express**, a stream of warm, humid subtropical air that can bring heavy rains to the West Coast of the US. The Pineapple Express is now included in a category of extremely wet upper-air currents dubbed **atmospheric rivers**. Extending across thousands of miles, they may contain more water than a dozen Mississippi Rivers!

Winds also distribute heat, but they are not sufficient in and of themselves to balance the temperature inequality that exists from the equator to the poles. To more adequately distribute heat across the globe, Mother Nature uses a stronger force—storms. The most powerful storms on Earth, hurricanes, are one way to transfer heat from the tropics to higher latitudes. But those are topics beyond the scope of our discussion here. Consult a meteorology text to learn more.

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12.5: Final Thoughts

Our whirlwind “robotross” tour in this chapter has connected us with those properties and behaviors of the atmosphere that most affect the ocean. As with all such tours, the story is incomplete. A fuller reckoning of the atmosphere can be found in a semester-long course in meteorology, which I encourage you to pursue. Weather and climate play enormous roles in our daily and future lives. A better understanding of your local weather can help you avoid unpleasant drenchings or bone-chilling cold. An appreciation for Earth’s climate and how it is changing can help you chart a course toward a career and a place to live less affected by the extremes of weather and natural disasters climate change will bring. Perhaps you may even choose to take action to help humanity find a more sustainable and less environmentally destructive way of life. Whatever thoughts this chapter inspires, I hope you’ll maintain a greater appreciation for our atmosphere and the ways it affects our lives. As Sting might say, “Every breath you take, every move you make. The atmosphere will be watching you” (Sting 1983).

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12.6: Chapter References

Ahrens, C. Donald, and Robert Henson. 2018. *Essentials of Meteorology: An Invitation to the Atmosphere*. 8th ed. Boston: Cengage. https://www.cengage.com/c/essentials-of-meteorology-8e-ahrens/9781305628458/

Baliukin, I. I., J.-L. Bertaux, E. Quémerais, V. V. Izmodenov, and W. Schmidt. 2019. "SWAN/SOHO Lyman-α Mapping: The Hydrogen Geocorona Extends Well Beyond the Moon." *JGR Space Physics* 124: 861–885. https://doi.org/10.1029/2018JA026136

Blackport, Russel, and James A. Screen. 2020. "Insignificant Effect of Arctic Amplification on the Amplitude of Midlatitude Atmospheric Waves." *Science Advances* 6(8): eaay2880. https://doi.org/10.1126/sciadv.aay2880

Bressac, M., C. Guieu, D. Doxaran, F. Bourrin, K. Desboeufs, N. Leblond, and C. Ridame. 2014. "Quantification of the Lithogenic Carbon Pump Following a Simulated Dust-Deposition Event in Large Mesocosms." *Biogeosciences* 11: 1007–1020. https://doi.org/10.5194/bg-11-1007-2014

Carlowicz, Michael. 2006. "The Oceans Have Their Own Weather Systems." *Oceanus*. April 13, 2006. https://www.whoi.edu/oceanus/feature/the-oceans-have-their-own-weather-systems/

Chandler, Raymond. 1946. *Red Wind: A Collection of Short Stories*. Cleveland: World Publishing Company. https://www.google.com/books/edition/Red_Wind/rxIfAAAAIAAJ See also https://delong.typepad.com/files/red-wind.pdf

Emspak, Jesse. 2016. "Early Earth's Atmosphere Was Surprisingly Thin." *Scientific American*. May 14, 2016. https://www.scientificamerican.com/article/early-earth-s-atmosphere-was-surprisingly-thin/

Etymonline. 2023. "Trade Winds." Accessed March 14, 2023. https://www.etymonline.com/search?q=TRADE+WINDS

Félix-Bermúdez, A., F. Delgadillo-Hinojosa, M. A. Huerta-Diaz, V. Camacho-Ibar, and E. V. Torres-Delgado. 2017. "Atmospheric Inputs of Iron and Manganese to Coastal Waters of the Southern California Current System: Seasonality, Santa Ana Winds, and Biogeochemical Implications." *JGR Oceans* 122(11): 9230–9254. https://doi.org/10.1002/2017JC013224

Fovell, Robert G., and Alex Gallagher. 2018. "Winds and Gusts during the Thomas Fire." *Fire* 1(3): 47. https://doi.org/10.3390/fire1030047

Francis, Jennifer A., and Stephen J. Vavrus. 2012. "Evidence Linking Arctic Amplification to Extreme Weather in Mid-Latitudes." *Geophysical Research Letters* 39(6): L06801. https://doi.org/10.1029/2012GL051000

Garstang, Michael, and David R. Fitzjarrald. 1999. *Observations of Surface to Atmosphere Interactions in the Tropics*. New York: Oxford University Press. https://www.google.com/books/edition/Observations_of_Surface_to_Atmosphere_In/HiaP4yJ8wNMC

Guzman-Morales, Janin, Alexander Gershunov, Jurgen Theiss, Haqin Li, and Daniel Cayan. 2016. "Santa Ana Winds of Southern California: Their Climatology, Extremes, and Behavior Spanning Six and a Half Decades." *Geophysical Research Letters* 43(6): 2827–2834. https://doi.org/10.1002/2016GL067887

Kearns, Graham. 1998. "The Great Coriolis Conspiracy." *Weatherwise* 51: 37–39. https://doi.org/10.1080/00431672.1998.9926132

Le Row, Caroline. 1887. *English As She Is Taught*. London: T. Fisher Unwin. https://www.gutenberg.org/files/61212/61212-h/61212-h.htm

Lindsey, Rebecca. 2021. "Understanding the Arctic Polar Vortex." NOAA Climate. March 5, 2021. https://www.climate.gov/news-features/understanding-climate/understanding-arctic-polar-vortex

Mahowald, Natalie M., Douglas S. Hamilton, Katherine R. M. Mackey, J. Keith Moore, Alex R. Baker, Rachel A. Scanza, and Yan Zhang. 2018. "Aerosol Trace Metal Leaching and Impacts on Marine Microorganisms." *Nature Communications* 9: 2614. https://doi.org/10.1038/s41467-018-04970-7

Malkus, Joanne S. 1962. "Large-Scale Interactions." In *The Sea: Ideas and Observations on Progress in the Study of the Seas, Physical Oceanography*, Vol. 1. Edited by Maurice Neville Hill, 88–294. New York: Interscience Publishers. https://www.google.com/books/edition/The_Sea/zoajxgEACAAJ

Masters, Nathan. 2012. "The Devil Wind: A Brief History of the Santa Anas." KCET. October 25, 2012. https://www.kcet.org/shows/lost-la/the-devil-wnd-a-brief-history-of-the-santa-anas

NOAA NESDIS. 2016. “Peeling Back the Layers of the Atmosphere.” National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite Data and Information Service (NESDIS). February 22, 2016. https://www.nesdis.noaa.gov/news/peeling-back-the-layers-of-the-atmosphere

Pabortsava, Katsiaryna, Richard S. Lampitt, Jeff Benson, Christian Crowe, Robert McLachlan, Frédéric A. C. Le Moigne, C. Mark Moore, Corinne Pebody, Paul Provost, Andrew P. Rees, Gavin H. Tilstone, and E. Malcolm S. Woodward. “Carbon Sequestration in the Deep Atlantic Enhanced by Saharan Dust.” *Nature Geoscience* 10: 189–194. https://doi.org/10.1038/ngeo2899

Persson, Anders. 1998. “How Do We Understand the Coriolis Force?” *Bulletin of the American Meteorological Society* 79(7): 1373–1386. https://doi.org/10.1175/1520-0477(1998)079%3C1373:HDWUTC%3E2.0.CO;2

———. 2006. “Hadley’s Principle: Understanding and Misunderstanding the Trade Winds.” *History of Meteorology* 3: 17–42. https://journal.meteohistory.org/index.php/hom/article/view/58

Pope, Kristen. 2021. “Scientists Examine Energetic Oceans, Eddies, and Kinetic Energy.” *Yale Climate Connections*, November 23, 2021. https://yaleclimateconnections.org/2021/11/scientists-examine-energetic-oceans-eddies-and-kinetic-energy/

Shakur, Asif. 2014. “Debunking Coriolis Force Myths.” *Physics Teacher* 52(8): 464. https://doi.org/10.1119/1.4897580

Sting. 1983. “Every Breath You Take.” Track 7 on *Synchronicity*. A&M. Vinyl. https://en.Wikipedia.org/wiki/Every_Breath_You_Take

Vallis, Geoffrey. 2016. “Geophysical Fluid Dynamics: Whence, Whither, and Why?” *Proceedings of the Royal Society A: Mathematical, Physical, and Engineering Sciences* 472: 20160140. https://doi.org/10.1098/rspa.2016.0140

van der Jagt, Helga, Carmen Friese, Jan-Berend W. Stuut, Gerhard Fischer, and Morten H. Iversen. 2018. “The Ballasting Effect of Saharan Dust Deposition on Aggregate Dynamics and Carbon Export: Aggregation, Settling, and Scavenging Potential of Marine Snow.” *Limnology and Oceanography* 63(3): 1386–1394. https://doi.pangaea.de/10.1594/PANGAEA.885930

Weimerskirch, Henri, Karine Delord, Audrey Guitteaud, Richard A. Phillips, and Patrick Pinet. 2015. “Extreme Variation in Migration Strategies between and within Wandering Albatross Populations during Their Sabbatical Year and Their Fitness Consequences.” *Scientific Reports* 5: 8853. https://doi.org/10.1038/srep08853

Wolansky, Sara Joe, director. 2016. “The Devil Wind.” *Lost LA*. Los Angeles: KCET. https://www.kcet.org/shows/lost-la/clip/the-devil-wind

Zhu, Yong, and Reginald E. Newell. 1994. “Atmospheric Rivers and Bombs.” *Geophysical Research Letters* 21(18): 1999–2002. https://doi.org/10.1029/94GL01710

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CHAPTER OVERVIEW

13: Ocean Waves

Sit on the shore of the ocean and what do you see? Waves. Surf. Foam. Close your eyes and listen. What do you hear? The crashing of waves. What do you feel? The vibrations of surf pounding against the beach. Draw in a deep breath. What do you taste and smell? The salty air of an ocean alive with waves. Waves stimulate all of our senses simultaneously. Perhaps that's why they have fascinated mankind since the dawn of time.

If any one phenomenon of the sea can define it, it might be waves. They rock ships, wash upon their decks, and crack against their hulls. Where waves come into contact with the seafloor and reach an unstable height, a wave begins to break—this is **surf**. High surf crashes against lighthouses, piers, and buildings, and occasionally destroys them.

But rather than fear the destructive force of waves, humans fashioned planks from trees and paddled them out to meet them head-on. **Surfing**—the use of various types of boards (or your body) to ride waves—certainly ranks as one of the more exhilirating sports. A surfer on a wave experiences a rush of moving energy unlike any other on Earth. And people watching from the beach get to marvel at the speed and agility of a surfer cutting up the waves or whooshing out of a barrel. Though its historical roots date back hundreds of years in Polynesia and Peru (Warshaw 2011), surfing in modern times generates billions of dollars in surfing activities, fashions, vacations, movies, magazines, décor, and a lot more (Statista 2022).

To explore these topics, we follow the timeless words of oceanographer Willard Bascom (1916–2000) and his classic book, *Waves and Beaches*, first published in 1964 (updated: Bascom and McCoy 2021). We'll add other references as needed. But now, let's catch some waves. Cowabunga!

13.1: Energy in Motion
13.2: The Source of a Wave's Energy
13.3: The Geometry of Waves
13.4: Types of Waves
13.5: The Timing of Waves
13.6: The Speed of Waves
13.7: Wave Orbitals
13.8: Wind Stress- A Transfer of Energy
13.9: The Wind-Stressed Sea Surface
13.10: Factors Affecting Wave "Size"
13.11: The Beaufort Wind Force Scale
13.12: Dispersion of Waves
13.13: Deep- and Shallow-Water Waves
13.14: The Making of Surf
13.15: Chapter References

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13.1: Energy in Motion

The waves that we perceive moving across the surface of the ocean actually represent energy in motion. The rise and fall of a wave traces the passing of a pulse of energy. The water itself hardly moves, except in a circular orbit that edges ever so slightly in the direction of the wave. It is energy that moves rapidly through the ocean surface, moving the water upward and downward as it passes. Thus, we may define a **surface wave** as the physical expression of energy moving forward at the surface of the ocean.

Waves occur inside the ocean too. Where water layers have different densities, waves can occur along their boundaries. A wave that propagates along the boundary of water layers with different densities beneath the ocean surface is known as an **internal wave**. Though only detected using scientific instruments, internal waves are the largest waves in the ocean. Their heights may reach hundreds of feet—far larger than the largest waves ever measured on the ocean surface, including tsunami. Thus, we must broaden our definition of an **ocean wave** to the physical expression of energy moving forward at the interface between two fluids of different density. After all, the atmosphere is a fluid too, so the waves at the surface of the ocean—the ones that we are most familiar with—fit this definition as well as the internal waves.

Moving waves are known as **progressive waves** because they move, or progress, forward. Where two progressive waves pass through each other in opposite directions, they may create a **standing wave**. These waves appear to stand still. A standing wave results from **wave interference**, the interaction of the energies of two or more waves to create a wave that is higher or lower than the individual waves. Under the right circumstances, a standing wave may persist for quite some time. You are most likely to notice them where a wave approaches a seawall and bounces off it, a phenomenon known as **wave reflection**. The interference of the incoming wave with the reflected wave creates a standing wave. Look for them next time you're at the beach or walking along a seawall.

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13.2: The Source of a Wave's Energy

The energy for most ocean waves that we observe comes from the wind. The wind is known as the **disturbing force** because it acts upon the surface of the ocean to create an imbalance. It disturbs the ocean from its resting state, the **still-water level** or sea level. While the wind is the most common disturbing force in the ocean, underwater earthquakes, landslides (above and below the water), and meteorite impacts can act as disturbing forces and create waves. Even the gravitational forces that cause tides are a disturbing force because tides are a type of progressive wave.

The disturbing force is counteracted by the **restoring force**, which returns the surface to a resting sea state. For the most part, **gravity**—the attraction between masses—acts as the restoring force. The downward pull of gravity on the water's surface restores it to its resting level, and so nearly all waves may be classified as gravity waves because gravity is the restoring force. However, for extremely small waves (less than 1.73 cm), **surface tension**—the "sticky" forces of water molecules at the surface of a liquid—is the restoring force.

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13.3: The Geometry of Waves

If you take a snapshot of the ocean surface, what do you observe? Its shape appears almost random with hills and valleys and ridges and depressions of different shapes and sizes. But take several photos in succession, and animate them by scrolling rapidly through them, and you see that the hills and valleys and ridges and depressions move in a deliberate manner and interact with each other in unexpected ways.

Though it might not seem possible, the shape of the sea surface at any one point in time can be fairly well described by combining all the individual waves and their motions. The combination of different waves and their shapes provides a kind of model of the sea surface, which is useful for investigating the impacts of waves on structures and ships.

In mathematical terms, waves may be described by three geometric shapes. The most well-known shape is a **sine wave**, the shape of a smooth, up-and-down motion. This symmetrical rising and falling shape can be visualized as a time series graph of a point on a slowly spinning wagon wheel. The x-axis represents the progression of time, and the y-axis represents the height of the point at any moment as measured from the center of the wheel. The center of the wheel may be thought of as the resting level of the ocean surface, and the height of the point above or below the center—the resting level—determines the height of the point at any given moment.

At the top of the wheel, the point reaches its greatest height, and so the sine wave reaches its maximum height. The point of maximum height of a wave is called the **wave crest**. At the bottom of the wheel, the point reaches its lowest height, and so the sine wave reaches its minimum height, the point known as the **wave trough**. The horizontal distance between successive crests is called the **wavelength**. The vertical distance from the crest to the trough—the diameter of the wheel—is called the **wave height**. Waves appear as sine waves when their wave height is small compared to their wavelength. Ocean swell often appears sinusoidal in shape.

The second shape is called a **trochoid**. This too can be visualized by a wagon wheel, only this time, the point is placed on one of the spokes, and the wheel is rolled underneath a flat surface. Trochoids are similar to sine waves, but they're less smooth and have a pointed crest. Most ocean waves resemble a trochoid.

The third shape is called a **cycloid**. To generate this shape, we use the same approach as a trochoid, only the point is placed directly at the perimeter of the wheel. Cycloids resemble trochoids, except that their crests are very pointed. Waves breaking in the ocean resemble this shape.

Three lessons can be drawn from this shape-defining discussion. First, waves progress much like a wagon wheel rolling down a trail. Their motion traces out geometric shapes whose equations are known. Second, the motion of water through which a wave passes is circular. Put another way, as a wave moves through the ocean surface, **water particles**—a term meant to convey something like a dot's worth of water molecules—move in circular orbits. The circular motions of water particles are called **wave orbitals**. (See below.) Third, mathematical descriptions of waves provide great insights into how and where they propagate and allow oceanographers to predict their motions and impacts on shores and structures. Mathematical models of waves also give a heads-up to surfers. **Surf prediction**—predicting the timing, location, and intensity of shore-breaking waves—is big business for commercial and recreational interests alike.

Of course, all of these forms may be present on the sea surface at any time. What happens as these waves encounter each other? Like the people you hang out with, some waves pick you up and some waves let you down. If the crests (or troughs) of two (or more) waves coincide, they add to each other to create a larger wave as they pass through each other, what is called **constructive interference**. This is like when your friends help you out; you're better, stronger, faster. When two waves pass through each other so that their crests and troughs do not coincide, they tend to cancel each other out in what's called **destructive interference**. If you have friends with whom you can get nothing done, this would be them. The sea surface at any given time is a jumble of waves moving in different directions that constructively and destructively interfere with each other to create the dynamic seascape of the wavy ocean. Check out this phenomenon next time you visit a wavy lake or beach.

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13.4: Types of Waves

Oceanographers and mariners use a variety of ways to classify waves—none official that I'm aware of—but we're stuck with what the experts define, so here we go.

The shortest waves—those with wavelengths less than 1.73 centimeters—are called **capillary waves** because they are small, like the capillaries in your body. Capillary waves are most easily recognized as the slight ruffling of the ocean's surface as a wind blows across it. The term "capillary" actually refers to the surface tension of water in a tube that causes the surface of a column of water to form a slight bulge or depression. Sometimes capillary waves are referred to as ripples—a better name, perhaps, but confusing in that the term has also been applied to waves slightly larger than capillary waves.

Capillary waves are the most abundant wave in the world ocean. It takes only the slightest amount of wind to cause them. Their shape is distinctive, with rounded crests and V-shaped troughs. You can easily make your own by blowing on a bowl of water. It's said they resemble cats' paws on water. As an owner of four cats, I really don't see the resemblance, but I guess a thirsty cat's habit of gently pawing a bowl of water to gauge the distance between its face and the water surface may have something to do with it.

Be that as it may, these very short waves behave differently from how larger ocean waves behave because they are under the control of surface tension. When the wind stops, capillary waves disappear immediately as surface tension restores the ocean's surface. Another interesting thing about capillary waves is that as the wind blows harder, their wavelengths become shorter, just the opposite of larger waves. Despite their small size, capillary waves play an important role in the formation of larger waves because the roughness they create over the ocean's surface permits a faster exchange of wind energy into the ocean.

Sailors and ocean folks refer to wind-generated waves, or **wind waves**, by a variety of names. Each roughly corresponds to the wave's size. **Ripples**—a bit larger than capillary waves—and **wind chop**—short and steep irregular waves—represent the waves you see when the wind begins to blow or has been blowing for a short time. **Fully developed seas** refer to the maximum wave size for a given wind speed over a period of several hours or a few days. **Swell** refers to the waves that travel out beyond the winds that generate them. Swell is what you see and experience as the rise and fall of the sea surface before they inter the seafloor. Swell moves the fastest of any wind-generated wave and produces the largest and fastest surf, ideal for **big wave surfers**, defined as surfers who ride waves greater than 20 feet (6.2 m) in height.

Oceanographers and physicists use a more formal classification system for waves based on their forward motion. To understand this system, we need to take a ride on the freeway.

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13.5: The Timing of Waves

The time element of progressive waves turns out to be quite important for surf prediction. When watching waves from the end of a pier, you are likely to notice wave crests passing the end of the pier one after another. If you watch the water level along one of the pier pilings, you'll see the water rise as the crest approaches and fall as the crest passes. After a few to several seconds, it happens again. Seconds later, it happens again, and so on. The time between successive crests is the **wave period**.

One way to understand wave periods is to consider a freeway full of cars barreling down the road. Each car maintains a certain time between it and the car ahead of it. You can measure the time between you and the car ahead of you by asking a passenger in your car to start a stopwatch at the moment the car ahead of you crosses under an overpass. Stop the stopwatch right when you pass under the overpass and you have the time that separates you and the car ahead of you. Think of cars as wave crests, and you have the idea.

Of course, wave periods can be measured using more sophisticated equipment. Ocean-deployed weather buoys digitally record the rise and fall of a float as waves pass by. These real-time wave-monitoring systems are critical for alerting scientists and authorities when potentially destructive big waves are approaching a shoreline. Of course, surfers take an interest in these buoy measurements as well.

Wave periods serve as the basis for a more formal classification system of waves. Capillary waves have the shortest periods, less than 0.1 seconds. Waves with periods of 0.1 to 1 second—what we might call ripples—are classsified as **ultragravity waves**. The kind of waves we experience most often on the ocean—**ordinary gravity waves**—vary from 1 to 30 seconds. Waves with periods from 30 seconds to 5 minutes—**infragravity waves**—originate from interactions between shorter period waves in coastal waters. These waves likely play a role in sediment transport and other nearshore processes (Cook 2018). **Long-period waves**—waves with periods from 5 minutes to 12 hours—include storm waves and tsunami. Beyond that, we venture into tides and other kinds of very long period waves.

Wave periods serve as a proxy for surf conditions. In general, the longer the wave period, the faster and more energetic the wave. Savvy surfers check **surf reports**, internet, app- or even phone-based tools that report information on wave periods, weather, and other surf-related factors. In Southern California wave periods of 10 seconds or more are considered pretty rocking. Wave periods of more than 20 seconds are insane! Some of the most epic surf days have wave periods of more than 20 seconds. Fortunately, such long-period waves are rare. They create very dangerous conditions along the coast and can tear up a coastline and damage property in just a few hours.

Though not wind-driven, **tsunami**—long-period waves generated by vertical motions of the seafloor during shallow earthquakes—have very long periods, on the order of five minutes to an hour. That's why it's important to remain out of harm's way after the first arrival of a tsunami. There are more waves to come! Tsunami may travel the ocean for days.

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13.6: The Speed of Waves

Wave periods and wavelengths vary according to the **wave speed**—the forward motion of a wave crest over time. Following Knauss and Garfield (2017), their relationship may be expressed mathematically as wave speed (S) equals wavelength (L) divided by wave period (T), or:

$$S = L / T$$

(Eq. 19.1)

These equations are easily rearranged to:

$$L = S \times T \text{ or } T = L / S$$

(Eqs. 19.2 and 19.3)

These equations should make sense to you in that the crest of a progressive wave has a particular length to travel in a particular time period—the wave period. It's important to note that the wavelength and period (and thus wave speed) vary in proportion to each other. The longer the period, the longer the wavelength, and the faster the speed of the wave. For example, a wave with a period of 2 seconds will have a wavelength of about 20 feet (6 m) and a speed of 6 knots (nautical miles per hour) while a 14-second wave will have a wavelength of 1,000 feet (305 m) and a wave speed of more than 40 knots.

One interesting fact about wave periods is that once a wave forms, its period remains constant. This is best observed along a shoreline where waves are approaching straight on. Interactions of the waves with the seafloor cause them to slow down. As a result, the waves begin to bunch up because their wavelengths shorten to compensate for the slower wave speed.

Because wave period is simple to measure—just measure the time between one crest and the next—some rules of thumb have been developed to estimate wavelength and wave speed from wave period. For example, the speed of a wave in knots is approximately three times the wave period. So a wave with a 7-second period has a speed of roughly 21 knots. Wavelength in feet can be estimated by taking the square of the period (in seconds) and multiplying the result by 5. For a 7-second wave, the square is 49, so its length would be 49 × 5, or 245 feet. These approximations help sailors or surfers who want to calculate when a given set of waves will arrive at a location any known distance from the source (e.g., Smith 1973).

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13.7: Wave Orbitals

One other aspect of waves, mentioned above, deserves our attention. The water particles in a wave move in a circular orbit—the wave orbital—as the energy of the wave passes through the surface of the ocean. This is really important to recognize because the water is not moving at the speed of the wave!

If you have ever sat in the water on a raft, or watched a seabird floating on the water, you've noticed that you (or the bird) move up and forward as the wave approaches and down and backward as the wave passes. If you can imagine a dot on the surface of the ocean, the path of the dot will trace a circle as the waves pass by. The rotation of the dot is in the same direction of the wave at the crest; at the trough the dot is moving in the opposite direction.

The diameter of the circle traced by the dot will be equal to the height of the wave. However, water particles below the surface will trace progressively smaller circles. Wave orbitals decrease in diameter from the ocean surface to a depth of one-half the wavelength of the wave. At this depth, called the **wave base**, the orbital motion is negligible (about 1/23 the surface diameter; Bascom and McCoy 2021).

The vertical distance from the surface to the depth where particle motions cease defines the boundaries of the energy of the wave. Not surprisingly, the energy of a wave is concentrated at the surface and diminishes with depth. For a wave with a wavelength of 20 feet (6 m), this depth would be 10 feet (3 m). For a 1,000-foot wave (305 m), the energy of the wave would be present in waters shallower than 500 feet (152 m). Surfers and scuba divers know the main energy of a wave is at the surface. Scuba divers entering from the beach get shoved back and forth along the seafloor until they reach a depth where the wave energy no longer penetrates. Surfers perform a **duck dive**, a skillful maneuver to propel a board underneath a wave to avoid being pushed backward or worse (e.g. Brander 2010). Submarines, too, can avoid storm waves by submerging to a depth where the wave energy disappears.

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13.8: Wind Stress- A Transfer of Energy

As we learned in Chapter 15, winds—movements of air—are caused by differences in air pressure at different locations in the atmosphere. Air, of course, is a mixture of gases, including nitrogen (N_2), oxygen (O_2), water vapor (H_2O), argon, carbon dioxide, and others. So when we talk about air molecules, we are talking about these molecules collectively.

Wind represents molecules of air in motion. These moving molecules contain a form of energy known as **kinetic energy**—energy in motion. Lots of things have kinetic energy: the air around you, winds, a flying insect, a hurled rock, an automobile speeding down the highway, or people at a rave, for example. The ripples that you notice when the wind interacts with the ocean surface result from collisions between air molecules and water molecules. Literally, an air molecule bangs into a water molecule.

The transfer of energy from the wind to the ocean surface along the horizontal plane of the ocean (parallel to the ocean surface) is known as **surface wind stress** (e.g., Jones et al. 2001). It's the surface wind stress that sets the ocean in motion. Most of the energy transferred by surface wind stress makes waves, but a small amount of it causes currents (movements of water, the ocean analog of wind). Some energy is also dissipated as heat.

The banging of molecules transfers energy from the moving molecule to the unmoving molecule. The energy transfer sets the previously unmoving molecule in motion. The amount of energy transferred from the moving molecule to the unmoving molecule depends on **momentum**—the product of a molecule's mass and its velocity. The larger a molecule (the greater its mass), the greater its momentum. Alternatively, or additionally, the faster a molecule (the greater its velocity), the greater its momentum. A good way to think about momentum is to think about the difference between an insect hitting your windshield at 75 mph or a rock hitting your windshield at that speed. The insect, with little mass, makes a splat, but no harm done other than a dirty windshield. A rock, on the other hand, with a larger mass and greater momentum, can put a crack in your windshield. If the rock is a meteorite, fuhgeddaboudit! (Your car is toast.)

When a moving molecule of air bangs into an unmoving molecule of water, a transfer of momentum occurs from the moving molecule to the unmoving molecule—an act of physics known as **momentum transfer**. The formerly unmoving molecule gains kinetic energy and begins to move. Of course, the now-energized water molecule is going to transfer momentum to surrounding water molecules because there will be collisions and transfers of kinetic energy from moving water molecules to other water molecules. So kinetic energy is passed from molecule to molecule within the upper ocean.

At the same time, some of the energy transferred through momentum causes vertical displacement of water molecules. The lifting or lowering of water molecules at the surface will change their **potential energy**, which is energy contained in an object or system due to its position or placement. When raised above the resting sea level, such as at the crest of a wave, a water particle gains potential energy in proportion to its height above the resting level. When that water particle moves downward, it releases that potential energy as kinetic energy. The same is true when lowering a water particle below the resting state. At the trough of a wave, the buoyancy of the water beneath the water particle will force it upward. As it moves, it will release potential energy.

In general, about half the energy in a wave is in the form of kinetic energy, and the other half is in the form of potential energy. Because the orbital motions of water particles represent kinetic energy, and the height of a wave determines the diameter (and circumference) of the wave orbital, and because the height of a wave determines the potential energy in a wave (the displacement of a water particle above or below the resting level), the total energy in a wave—kinetic plus potential—can be described in terms of the wave height (e.g., Knauss and Garfield 2017), as:

$$E = 1/8 \times \rho \times g \times H^2$$

(Eq. 19.4)

Total energy in a wave equals 1/8 times the water density (ρ, pronounced rho) times acceleration due to gravity (g, which is 9.8 meters per second squared) times the height of the wave squared (H^2).

The take-home message here is that a 6-foot wave has four times the energy of a 3-foot wave. A 12-foot wave has 16 times the energy of a 3-foot wave. Waves are extremely powerful, and now you know why.

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13.9: The Wind-Stressed Sea Surface

When the wind begins to blow over the surface of a calm ocean, there is a transfer of momentum from the air molecules to the water molecules. The first waves that we notice are capillary waves, the ripples that move like a shadow across the ocean's surface. Often the wind is uneven or moving slightly upward and downward, so looking out across an expanse of ocean, you see several patches of capillary waves moving, disappearing, and appearing again somewhere else. When the wind stops, the capillary waves disappear as the surface tension of water immediately restores the ocean surface to its level state.

However, if the wind keeps blowing, enough energy is transferred across the air–sea interface to generate gravity waves. Unlike capillary waves, gravity waves are not counteracted by surface tension; they are counteracted by gravity. These waves travel outward from the location where they are formed. Waves of a decent size can travel thousands of miles across the ocean. One of the earliest studies of ocean wave propagation detected waves in Southern California that originated in the Indian Ocean (e.g., Snodgrass et al. 1966).

The prolonged blowing of the wind continues the transfer of energy into the ocean, and the waves continue to grow. Ripples turn into wavelets, which turn into chop and larger waves. But there are limits to the size of waves that can be produced under a given set of wind conditions.

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13.10: Factors Affecting Wave “Size”

First, and perhaps most obvious, the **wind speed** plays a role in determining the size of waves that may be produced on the ocean. The faster the winds, the faster the transfer of energy to the ocean’s surface, and the bigger and more energetic the waves that are formed. Makes sense, right? There’s more energy transferred to the upper ocean.

The length of time that the wind blows, **wind duration**, is also important. A short, sharp wind, no matter how fast, isn’t going to produce very big waves. You can sneeze on an aquarium—a sneeze has been clocked at about 40 mph—but you’re still not going to produce much in the way of waves. It takes time. So the longer the wind blows, the bigger and more energetic are the waves formed. But wait! There’s more.

The distance over which the wind blows in the same direction, something called the **fetch**, also makes a difference. Long fetches mean that a larger area of the ocean receives energy from the wind; the ocean surface becomes more energetic. The greater the fetch, the bigger and more energetic the waves that are formed. Fetch explains why hurricanes with the fastest winds don’t always generate the biggest waves. Typically, the size of the wind field in a hurricane is smaller and the fetch shorter and more variable (because winds rotate around a hurricane) than the wind field in a large storm system. Low-pressure systems over the ocean may have fetches of hundreds of miles and wind speeds near hurricane strength. As a result, storms at sea tend to produce the largest waves observed in the ocean. Wind speed, wind duration, and fetch contribute to the formation of ocean waves. They act in combination to deliver energy to the ocean surface.

Some forces remove energy from a wave. Progressive waves must contend with friction from the atmosphere as they move forward. Friction drains the energy from a wave. Strong winds may create **whitecaps**, the broken tops of wave crests that appear white because of the bubbles and foam present within them. Whitecaps remove energy from a wave. Other factors within the waves tend to dissipate their energy as well. At some point the energy transferred to the ocean at a given wind speed is balanced out by the energy lost by the waves. The steady state between energy-intensifying factors and energy-dissipating factors produces a fully developed sea. When this occurs, continued blowing of the wind at the same speed will produce no additional gains in wave height or energy. For these reasons waves always move at speeds slower than the wind speeds.

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13.11: The Beaufort Wind Force Scale

The concept of a fully developed sea has important implications for sailors. It means that there are limits to how bad the ocean will get for a given wind speed. How long it takes to reach a fully developed sea depends on the wind speed, duration, and fetch. A fully developed sea may take only a few hours under light winds, but it can be two to three days for a fully developed sea to develop in strong winds.

Recognition of the relationship between wind speeds and a fully developed sea state led to development of the **Beaufort wind force scale**, a visual guide for determining wind speed from sea state. Adapted from existing wind scales by Sir Francis Beaufort (1774–1857) and formally adopted by the Royal Navy in 1838 (e.g., Wheeler and Wilkinson 2004), the Beaufort scale allows a mariner to estimate the wind speed from wave conditions. Sea and atmospheric (and land) conditions are scaled from 0 to 12 "forces," where Beaufort force 0 represents the calmest air, and Beaufort force 12 signals a hurricane. For example, knowing that a Beaufort force 5 is in effect, a ship's captain can prepare the ship and crew and decide whether it's safe to sail or wait for the seas to subside.

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13.12: Dispersion of Waves

Once formed, gravity waves keep on truckin', even after the wind has subsided. The most energetic waves—the longest waves with the longest wave periods—move away from their point of origin faster than shorter waves. Thus, ocean swell with the longest wavelengths and periods separates from the slower waves with short wavelengths and periods, a process called **wave dispersion**. Most times, short-wavelength waves dissipate near the storm center. But fast-moving ocean swell will continue across the ocean until it meets an obstacle, such as a seamount, an island, or a distant beach.

Because swell sorts out according to its speed, waves of the same speed tend to travel together in a group called a **wave train**. Depending on the conditions that create swell, wave trains may have anywhere from 3 to 15 waves associated with them. Surfers know a wave train as a **wave set**, or simply a set—a series of similarly sized waves that arrive at the shore in close progression, one right after the other. Wave trains are the origin of sets. However, it's simply not true that the seventh wave or the fifth wave or the third wave of a set is the largest. For a number of reasons, there will always be a wave or two that are bigger than the others in a set, but there is no mathematical consistency to which wave it will be. Sorry, dudes.

One of the interesting things about wave trains is that the train moves at half the speed of the individual waves. It's not terribly important that you know why, but it has to do with the distribution of energy in the wave train. Just like a Tour de France cyclist, the lead wave does all the work.

In any wave the kinetic energy goes into moving water particles in their orbits. As they move, they lift the sea surface and create potential energy. The potential energy of the wave is released when the crest drops, and the released potential energy supplies energy to making wave orbitals—generating kinetic energy—and so on. In a wave train, the first wave has to lift the sea surface on its own. It uses kinetic energy to do that. But the second wave is the recipient of the potential energy generated by the first wave; the raised sea surface falls and releases energy to the second wave. In a wave train, the leading wave diminishes and disappears, but a new wave appears at the end of the train, because potential energy is released by the last wave in the train. In short, this backward trading of energy that goes on in a wave train results in the first wave disappearing and a new wave appearing at the end of the train, so that the forward progress of the entire train is slower. As a result, the **group speed**—the speed of the wave train—is half the speed of the individual waves.

One way to visualize a wave train is to imagine a conga line of dancers where the lead dancer exits and a new dancer joins the line at the rear when the line advances two steps. Even though individuals advance by two steps, the whole line only makes forward progress one step at a time. Try it at home with friends. Do the conga wave train. ("Come on, shake your body, baby, do the conga wave train!")

Though swell moves hundreds to thousands of miles across the ocean, there is some loss of energy along the way. Frictional forces will dissipate some of the energy. But energy also dissipates by elongation of the **wave front**, the "edge" of the wave perpendicular to its direction of travel. The loss of energy due to expansion of the wave front is called **spreading loss**. Most of the energy generated by a storm, some 90 percent, will travel outward in a cone with an angle of about 30° to 45°. So the greater the distance you are from the vertex (the location where the two rays of the angle intersect), the greater the distance between the two rays, or sides, of the angle.

You can easily see this by making a peace sign with your hand. The distance between the knuckles of your fingers is shorter than the distance between your fingertips. Because swell has a fixed amount of energy, the widening of the wave front causes a reduction in the energy at any point along the wave front. The energy per unit length of wave front decreases with distance from the point of origin of the wave.

Close to the point of origin, spreading loss is minimal. Farther away from the point of origin, spreading loss can be significant. Some 60 percent of the energy of swell (per unit length of wave front) may be lost within the first 500 miles (805 km). That's why killer surf for Hawaii might not be so epic once it reaches the US West Coast. Spreading loss reduces the size of the swell as it travels outward. The width of the wave front depends on the width of the fetch that created it, the **fetch width**. Typical storm systems across the ocean may range from 600 to nearly 2,000 miles in horizontal diameter (1,000–3,000 km; e.g., Bierly 2005). Swell-generating fetch will be on a similar scale. Thus, wave fronts for a typical ocean swell may extend hundreds of miles, if not a thousand miles or more, in length. What that means is that waves from a single storm system can affect the entire coastline of the western United States.

Storm systems rarely remain in one place. Generally, storm systems move west to east in both hemispheres, in the direction of the jet streams. Thus, the effective fetch of a storm may be much greater. The swell generated over a period of days will travel outward for the duration of the storm. Large storm systems at great distance may send waves for several days toward coastlines (e.g., Butt 2021).

The movement of storm systems also affects the **swell direction**—the direction the swell is coming from. Swell direction is identified according to directions on a **compass rose**, an illustration that depicts the **cardinal directions**—north, east, south, and west—and the **ordinal directions**, the points between the cardinal directions—northeast, southeast, southwest, and northwest. Compass directions are always given in degrees of a circle, where north is 0°, east is 90°, south is 180°, and west is 270°. The range of compass directions from which swell may arrive is known as the **swell window**. Surf forecasters calculate swell windows to determine which beaches may offer the best surfing conditions on a given day.

In California, swell windows may change from northwest to southeast, depending on the time of year. Storms in the North Pacific often occur in the winter and generate swell from west to northwest. In summer, winter storms in the Southern Hemisphere produce swell from the southwest to southeast. Hurricanes off the coast of Mexico swing into action in the summer and occasionally send swell our way. Of course, California has a tough time competing with Hawaii, which has to be one of the best places for surfing in the world. Situated in the middle of the Pacific, Hawaii can experience swell from just about any direction. As a result, there are surfable waves nearly year-round in Hawaii.

Swell direction also proves critical for places where islands or other land features may interfere with swell. Islands can block swell or change its direction. Gaps between the islands mean that some spots are going off, while other spots are snoozy. Because of the Channel Islands, it's not uncommon for San Diego to experience big waves while Orange County is quiet, or vice versa. The islands produce what is called a **swell shadow**—a region over which swell is blocked from a particular direction.

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13.13: Deep- and Shallow-Water Waves

Ultimately, the swell reaches shallower water. Remember the orbitals in a wave that extend to a depth of about one-half the wavelength? Waves traveling in water depths deeper than one-half the wavelength—like ocean swell—are called **deep water waves**. Their progress is unimpeded by the seafloor. But as waves approach water depths less than one-half the wavelength, the wave orbitals begin to interact with the seafloor. The orbitals at the bottom of the wave are unable to complete their orbits, and they assume a more elliptical path. When the seafloor begins to interfere with the wave orbitals, the wave is said to "feel bottom." It's at this point that the life of a deep water wave ends.

Waves traveling in water depths less than 1/20 of their wavelength are classified as **shallow water waves**. Now, let's take a minute to think about what that means. If a wavelength is 100 feet, then 1/20 of its wavelength is 5 feet because 100 / 20 = 5. So that means that when a wave with a wavelength of 100 feet reaches a water depth of 5 feet or shallower, it is officially designated as a shallow water wave. What is the depth of "shallow water" for a 1,000-foot-wavelength wave? (Hint: divide 1,000 by 20. Simple, huh?)

The behavior of shallow water waves is much different from that of deep water waves. In addition to the Eq. 19.1 above (S = L / T), we can express the speed of a deep water wave as (e.g., Knauss and Garfield 2017):

$$S_{deep} = 1.56 \times T$$

(Eq. 19.5)

where S is the speed of the wave and T is the wave period. S here gives the speed at which some part of the wave—the crest, for example—is moving forward. (Officially, it's called the wave's phase speed.) It's this relation that tells us that longer-period waves travel faster. Deep water waves disperse (see wave dispersion above) because they separate according to their speed.

Shallow water waves behave differently. The speed of shallow-water waves depends solely on the water depth, according to:

$$S_{shallow} = \sqrt{(g \times z)}$$

(Eq. 19.6)

The speed of a shallow water wave equals the square root of the gravitational constant (g, or 9.8 m/s^2) times water depth (z).

What that means is that the speed of a shallow water wave depends solely on depth. Neither wavelength nor wave period makes any difference. For this reason, shallow water waves are **nondispersive**—they do not separate according to wavelength or wave period.

One surprising thing about shallow water waves is that they include some waves you would never suspect—tsunami, for example. The wavelength of a large tsunami can be up to 300 miles (482 km). The deepest place in the world ocean, the Mariana Trench, is only 6.79 miles deep (10.9 km). That means tsunami act like shallow water waves everywhere in the ocean. Their speed, then, is governed by the depth of the water. What is the speed of a tsunami traveling across the Mariana Trench? It's over 700 mph. Cowabunga, indeed!

For the sake of completeness, waves between wavelengths ½ L and 1/20 L are called **intermediate** (or transitional) **waves**. They have a different set of equations that govern their behavior, which, because of their mathematical complexity, we are not going to discuss here.

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13.14: The Making of Surf

Interesting things happen when waves enter shallow water. When a wave begins to feel bottom, it begins to interact with the seafloor. Friction causes the wave to move slower. The geometry of wave orbitals becomes flattened as their vertical motion is hindered. With nowhere to go but up, the energy of the wave is directed upward. As a result, the wave gains height. Viewed from the shore or a pier, you can see the swell get bigger as it approaches the shore.

Eventually, the water particles in a wave can't even complete an orbit, and they simply move back and forth. If you've ever dived beneath the waves or sat on the bottom as a scuba diver, you can attest to the strength of the back-and-forth motion of waves in shallow water. At some point in the wave's progress into shallow water, the crest topples forward—sometimes with fury—and the wave breaks. This usually happens at a point when the wave height becomes too steep.

Oceanographers define the ratio between a wave's height (H) and its wavelength (L) as **wave steepness**, which we'll symbolize as Z (e.g., Bascom 1980):

$$Z = H / L$$

(Eq. 19.7)

In general, waves break when their height exceeds their wavelength by about 1/7 (0.142; Michell 1883; but see Perlin et al. 2013). A 7-foot wave will break when its height reaches 1 foot. Generally that happens when the water depth becomes less than about 1.3 times the wave height (e.g. Butt 2014). So a 3-foot wave will break when the water depth reaches 3.9 feet.

Types of Breaking Waves

Breaking waves are generally called surf or **breakers**. And as everyone who watches waves knows, no two breakers are alike. This is partly due to the characteristics of the waves themselves, but the slope of the seafloor also makes a difference. A gently sloping nearshore will slow down the wave gradually, and its energy will be expended along a greater distance in its progress toward the shore. A steeply sloping nearshore will permit a wave to approach a beach at near top speed. The differences between the waves breaking on a gradual versus a steep beach slope can be dramatic.

In general surf may be classified into one of four categories depending on the characteristics of its break. A wave whose lip trickles down the front of the wave as it approaches is called a **spilling breaker**. The top of the crest of the wave spills down the front of the wave. This type of wave generally occurs on a gently sloped bottom. Most of the small waves you'll see in Florida are of this type. A wave that creates a tube with a lip that shoots over the face of the wave in a kind of waterfall is called a **plunging breaker**. This is the kind of wave most sought after by surfers. The waves at Pipeline in Hawaii and Teahupo'o in Tahiti are great examples of plunging breakers. These locations produce the much-coveted barrels. Plunging breakers can be found on shallow- to intermediate-sloped seafloors. More steeply sloped seafloors produce **collapsing breakers**, where the entire wave face disintegrates into foam. The steepest nearshore bottoms produce waves that don't even break; they slide up onto the beach in a swoosh. Swooshy waves are called **surging breakers** (e.g., Butt 2014).

The speed and shape of the incoming wave, the dynamics of the nearshore that change the slope and depth of the seafloor, tides, and winds, among other factors, ultimately determine the way the wave breaks. Many waves are a combination of these types. For example, in Southern California, we often see breakers that spill and plunge. And really, when you're out enjoying the waves, it doesn't matter what you call them. They're simply fun!

Wave–Seafloor Interactions

Often waves approach the beach at an angle, meaning the wave front doesn't arrive parallel to the shoreline. This can occur because waves generated far out to sea come from different directions and because the direction a beach faces depends on where it's located. Most beaches in Orange County face southwest. (The Huntington Beach pier points to about 220°, per Google Earth.) Further up the coast in the South Bay, Hermosa and Manhattan Beaches face almost due west. When waves approach at an angle, one part of the wave front may enter shallower water earlier than the rest. The part entering shallow water slows down, but the part in deeper water continues at full speed. The result is a bending of the wave, something known as **wave refraction**.

As a wave approaches a beach and refracts, the wave front will bend and align with the depth contours of the bottom—the **isobaths**. You can actually figure out which parts of the nearshore are deeper and which are shallower simply by watching the

approaching waves. As waves approach the shore at an angle, the wave front bends and becomes more parallel to the beach, but rarely becomes perfectly parallel. If you watch carefully, you will see that one part of the wave begins to break before the other parts. The places where the wave breaks first are the shallowest parts of the nearshore. If the depth of the nearshore has a constant slope (no spots deeper or shallower than others), the wave will break right to left or left to right, depending on whether it's coming from the right or the left of the direction the beach is facing, respectively.

Headlands—points of land that jut out into the ocean—are a great place to observe wave refraction. A wave approaching a headland straight on will slow down in the shallower water surrounding the headland, but because the extremities of the wave front are traveling faster, the wave will refract. The result is a wave front that bends toward the headland. If the wave approaches the headland at an angle, it will bend around the headland and produce something known as a **point break**. Point breaks produce some of the best surfing in Southern California. Dana Point once had the best point break in the world, until someone decided to build a jetty. (I hate it when that happens.) Similarly, a wave entering a bay will slow down at its extremities so that the wave bends and takes on the shape of the bay as it nears the shore.

Between islands or inside boat harbors, boat owners have to worry about something called **wave diffraction**, the lateral shifting of wave energy along the wave front. It gets complicated because it depends on the wavelength of the approaching wave relative to the width of the opening, and constructive and destructive interference can play a role, but wave diffraction will cause a wave front to arc and expand as it enters the opening. This can result in waves coming from an unexpected direction in what is supposed to be a safe harbor. Between islands the effects can be dramatic as wave patterns become fanlike and superimpose on each other.

When waves approach an underwater reef or seamount, wave refraction may cause the energy of the wave to converge on the reef or seamount. This concentration of energy is known as **wave focusing** (e.g., Butt 2014). Extreme surf spots such as Jaws, Mavericks, Cortes Bank, and Shark Park produce epic waves as a result of wave focusing around an underwater obstacle. Ranging in size from 50 to 100 feet (15–30 m; e.g., Smith 2006), these are waves to die for—literally, as most of us would be dead if caught in a wave of this magnitude. Next time you're standing next to an eight-story building, look up. The wall next to you is about the same height as a wave you might experience at one of these places. Except that in an extreme wave, the wall is moving 20 to 30 mph and falling down on top of you. Yikes!

One Southern California extreme wave spot—featured in Bruce Brown's classic film *The Endless Summer* (1966)—serves as a perfect example of wave reflection—the change in direction of a wave front when it encounters an obstacle such as an island, beach, seawall, or jetty. If swell period and swell direction are ideal, the Wedge, at the south end of Newport Beach on the Balboa Peninsula, can produce 20-foot (6 m) waves (e.g., Surfline 2023). Waves at the Wedge result from the interaction of incoming waves with waves reflected off the Newport Inlet jetty. When waves approach from the SSW, they bounce off the jetty, which extends from the shore about 1,800 feet (549 m), and reflect 90° (NNW), where they interfere with the incoming waves. Where the crests of the incoming and reflected waves meet (constructive interference), a towering "wedge" of water is produced, hence the name. Next to Hawaii's Banzai Pipeline, the Wedge rates as one of the best places to watch extreme wave surfing. On a summer day with a large SSW swell, hundreds of onlookers will gather at the Wedge to watch bodyboarders, bodysurfers, and even board surfers take their chances on the waves.

All of the science aside, ocean waves captivate our attention, whether we're at the beach or simply watching a surf cam from home. Waves reflect the moods of the ocean—perhaps our own, as well. As the fictional teen "surfer girl" Gidget puts it, "Surfing is out of this world. . . . It positively surpasses every living emotion I've ever had" (Wendkos 1959).

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13.15: Chapter References

Bascom, Willard. 1964. *Waves and Beaches: The Dynamics of the Ocean Surface*. Garden City: Anchor Press. https://archive.org/details/wavesbeaches00doub

———. 1980. *Waves and Beaches: The Dynamics of the Ocean Surface*. Revised, updated, and enlarged. Garden City: Anchor Press. https://archive.org/details/wavesbeachesdyna0000basc

Bascom, Willard, and Kim McCoy. 2021. *Waves and Beaches: The Powerful Dynamics of Sea and Coast*. Ventura: Patagonia. https://www.patagonia.com/product/waves-and-beaches-the-powerful-dynamics-of-sea-and-coast-book/BK855.html

Bierly, Greg. 2005. "Extratropical Cyclones." In *Encyclopedia of World Climatology*. Edited by J. E. Oliver. Dordrecht: Springer. https://doi.org/10.1007/1-4020-3266-8_80

Brander, Rob. 2010. *Dr. Rip's Essential Beach Book: Everything You Need to Know About Surf, Sand, and Rips*. Sydney: University of New South Wales Press. https://www.scienceofthesurf.com/books

Brown, Bruce. 1966. *The Endless Summer*. Cinema V. Film. 95 minutes. https://www.imdb.com/title/tt0060371/

Butt, Tony. 2014. *Surf Science: An Introduction to Waves for Surfing*. Honolulu: University of Hawaii Press. https://uhpress.hawaii.edu/title/surf-science-an-introduction-to-waves-for-surfing/

———. 2021. "Hurricane Larry: How to Track Swells and Calculate Storm Distance." Magicseaweed. September 7, 2021. https://magicseaweed.com/news/hint-you-can-use-our-swell-charts-to-tell-how-far-away-a-storm-is/11738/

Center for Western Weather and Water Extremes (CW3E). 2021. "CW3E Event Summary: 19-26 October 2021." October 23, 2021. CW3E. https://cw3e.ucsd.edu/cw3e-event-summary-19-26-october-2021/

Dally, William R. 2001. "The Maximum Speed of Surfers." *Journal of Coastal Research* 29: 33–40. https://www.jstor.org/stable/25736203

do Carmo, José Simão Antunes. 2022. "Dominant Processes that Amplify the Swell Towards the Coast: The Nazaré Canyon and the Giant Waves." *Research, Society, and Development* 11(11): e578111133804. https://doi.org/10.33448/rsd-v11i11.33804

Google Earth. 2023. "Huntington Beach Pier." Google Earth, version 9.181.0.1. Accessed January 31, 2023. https://earth.google.com/web/search/Huntington+Beach+Pier,+Huntington+Beach,+CA

Jones, Ian S. F., Y. Volkov, Y. Toba, S. Larsen, and N. E. Huang. 2001. "Overview." In *Wind Stress Over the Ocean*. Edited by Ian S. F. Jones and Yoshiaki Toba, 1-34. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511552076.002

Knauss, John A., and Newell Garfield. 2017. *Introduction to Physical Oceanography*. Long Grove: Wavelend Press. https://www.waveland.com/browse.php?t=504

Michell, J. H. 1893. "XLIV. The Highest Waves in Water." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 36(222): 430-437. https://doi.org/10.1080/14786449308620499

Perlin, Marc, Wooyoung Choi, and Zhigang Tian. 2013. "Breaking Waves in Deep and Intermediate Waters." *Annual Review of Fluid Mechanics* 45: 115–145. https://doi.org/10.1146/annurev-fluid-011212-140721

Pilastro, Eleonora. 2022. "Sebastian Steudtner Surfs Giant Wave and Smashes World Record." Guiness World Records. May 25, 2022. https://www.guinnessworldrecords.com/news/2022/5/sebastian-steudtner-surfs-giant-wave-and-smashes-world-record-705874

Smith, Craig B. 2006. *Extreme Waves*. Washington, DC: Joseph Henry Press. https://doi.org/10.17226/11635

Smith, F. G. Walton. 1973. *The Seas in Motion: Waves, Tides, and Currents—How They Work; Their Causes and Effects*. New York: Thomas Y. Crowell. https://archive.org/details/seasinmotion00fgwa

Snodgrass, F. E., K. F. Hasselmann, G. R. Miller, Walter Heinrich Munk, and W. H. Powers. 1966. "Propagation of Ocean Swell across the Pacific." *Philosophical Transactions of the Royal Society A* 259(1103): 431–497. https://doi.org/10.1098/rsta.1966.0022

Statista. 2022. Surfing—Statistics and Facts. Statista. https://www.statista.com/topics/9833/surfing/#topicOverview

Surfer Today. 2023. “Big Wave Surfer Márcio Freire Dies in Nazaré.” Surfer Today. January 6, 2023. https://www.surfertoday.com/surfing/big-wave-surfer-marcio-freire-dies-in-nazare

Surfline. 2023. “The Wedge.” Surfline. Accessed January 31, 2023. https://www.surfline.com/surf-report/the-wedge/5842041f4e65fad6a770882b

Warshaw, Matt. 2011. *The History of Surfing*. San Francisco: Chronicle Books. https://www.chroniclebooks.com/products/the-history-of-surfing

Wendkos, Paul. 1959. *Gidget*. Columbia Pictures. Film. 95 minutes. https://www.imdb.com/title/tt0052847/

Wheeler, Dennis, and Clive Wilkinson. 2004. “From Calm to Storm: The Origins of the Beaufort Wind Scale.” *Mariner's Mirror* 90(2): 187–201. https://doi.org/10.1080/00253359.2004.10656896

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CHAPTER OVERVIEW

14: Ocean Tides and Sea Level Rise

Long before clocks were invented, long before people were invented, and long before the first microbe snuggled up to a scalding vent of water, the Earth and the Sea heaved up and down at precise intervals, like clockwork. The heavings continue to this day, rising and falling, sometimes higher than the time before, sometimes lower, but timed to precision. Of course, we're talking about daily changes in **sea level**—the theoretical height of the ocean at rest. The rising and falling occur as a result of the **ocean tides**—the changes in sea level caused by the gravitational forces of the Earth, Sun, and Moon.

The tides have existed since the moment that the Moon fell into orbit around the Earth, about 4.53 billion years ago, some 20 million years after the Earth gained most of its mass. Subsequently, organisms evolved adaptations and behaviors synchronized with the tides. They tolerate exposure to the air during **low tides**, when sea level reaches its lowest extent during the day. They carry out metabolic and reproductive activities when submerged during **high tides**, when sea level reaches its highest extent.

The tides also play a part in the everyday lives of people and have done so since antiquity. The Indians, Greeks, Romans, Babylonians, and Chinese described and predicted the tides. As early as 325 BCE, the height of the tides was proposed to depend on the phases of the Moon (Cartwright 2000). Tides made navigation of shallow seas perilous. Certain places were to be avoided at low tides. Swiftly rising tides created dangerous currents and ferocious whirlpools that could wreck an unsuspecting captain. The success of military operations in coastal waters hinged on the navigability of the waters and beaches at high or low tide.

Knowledge of tides assisted the hunting and gathering of seafood along shorelines, where abundant beds of oysters and mussels, or buried clams, might be found at low tide. The people of the Republic of Palau in the western North Pacific express their relationship with the tides in this way:

The rhythm of our life is the rhythm of the sea. We are born on a certain tide; we die on another. The tide carries our boats out to the fish and brings us back to feed our families. The seasons of our lives depend on different currents that guide us to the schools of feeding fish. (MacGillivray 1995)

Our study of tides here has two aims: (1) to help you better appreciate the importance of tides for human activities; and (2) to help you better understand discussions about changes in sea level. We're especially concerned about sea level rise—caused by global warming—which already affects coastal cities around the world. Will your favorite seaside hangout be affected? Let's find out.

14.1: The Tide-Causing Forces
14.2: The Tides Follow the Moon
14.3: Measuring and Predicting Tides
14.4: Classification of Tides
14.5: Tidal Height
14.6: Spring and Neap Tides
14.7: Practical Applications of Tide Knowledge
14.8: An Ever-Changing Sea Level
14.9: How Do We Measure Sea Level?
14.10: What Causes Sea Level Change
14.11: What Have We Learned About Global Sea Level Rise?
14.12: What Have We Learned About Local Sea Level Rise?
14.13: It's Not Just Sea Level Rise
14.14: Chapter References

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14.1: The Tide-Causing Forces

If tides may be considered Mother Nature's clock, then the Moon is the tides' clockkeeper, with a little help from the Sun. The gravitational forces of the Moon and the Sun, primarily, and other planetary bodies, to a lesser extent, cause the tides. Textbooks and the internet abound with explanations of the tide-causing forces, many of which are confusing or conceptually incorrect. Here we follow the reasoning provided by Dutch physical oceanographer Theo Gerkema, who has written a highly readable text on ocean tides (Gerkema 2019). (See also Donald Simanek's website and Steve Hurley's Explaining Science website for good treatments.)

We start with an Earth completely covered by ocean without friction and where the ocean responds immediately to gravitational forces. We'll also ignore the Sun for the moment and only consider the Moon. The Earth will remain motionless in this model, other than its rotation on its axis. This simplified model of ocean tides is known as the **equilibrium model of tides**, and it gives us an intuitive understanding of the tide-causing forces without resorting to mathematics. We will not consider the more realistic dynamic model of tides here (but see Gerkema 2019).

From Newton's law of gravity, we know that the **gravitational force** between two objects varies with their mass and distance. This is why the Earth and the Moon orbit the Sun, which is 333,000 times more massive than Earth (and 27 million times more massive than the Moon). However, because the Moon is closer to the Earth than the Sun (238,855 miles versus approximately 93 million miles; e.g., NASA 2023a), the Moon exerts a greater influence on Earth's tides, nearly twice as much as the Sun. Let's be clear: Earth and the Moon orbit the Sun. It's massive and exerts the strongest gravitational force of any object in our solar system. But the Moon's close proximity to Earth gives it an edge when it comes to the tide-causing forces.

Now, the important part of this discussion comes down to this: the Moon's gravitational attraction varies for different points on Earth's surface. Because gravitational attraction depends on distance between two bodies, points nearer the Moon experience a stronger attraction while points farther away experience less of an attraction. These variations give rise to a non-uniform force (a force that varies) across Earth's surface. Oceanographers refer to these variations in the Moon's gravity across Earth's surface as the the **tidal forces** (Gerkema 2019; Simanek 2022).

The tidal forces cause movements of water. Tidal forces have a **radial component**—acting vertically—and **tractive component**—acting horizontally. Radial forces pull upward or downward. Tractive forces pull back and forth. Because Earth's gravity acts downward (vertically) with a force about 10 million times greater than the upward gravitational force of the Moon, the Moon's vertical forces are dwarfed by Earth's gravity. Thus—and this is important—only the tractive (horizontal) forces cause tides. Earth's tides result from water moving toward or away from different locations depending on the magnitude of the tractive forces. The vertical component of the tidal forces has about as much effect on the ocean as does a seagull landing on or taking off from a cruise ship.

I want to emphasize that the ocean is not lifted by the gravitational attraction of the Moon (or Sun). The tidal forces are horizontal forces. They act tangential to the Earth's surface (i.e., horizontally), not perpendicular (i.e., vertically). The "bulges" featured in many textbook illustrations of tides represent points toward which the ocean flows. They are not real bulges and they certainly don't result from water being "pulled up" (on the near-Moon side) or "flung" off (on the opposite-Moon side) of the Earth.

The horizontal movements of water caused by tidal forces are called **tidal currents**. These tidal currents—water flowing toward or away from different points on Earth—cause the periodic rise and fall of sea level that we experience as tides. The ocean flows toward certain points and away from others at regular intervals. Along a shoreline, we observe sea level rising—the tide coming in—or falling—the tide going out.

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14.2: The Tides Follow the Moon

Because Earth rotates on its axis, the locations beneath (and opposite to) the Moon (and Sun) rotate with the Earth. Every 24 hours, the Earth rotates on its axis, but a point on Earth's surface directly beneath the Moon will take 24 hours and 50 minutes to rotate directly beneath the Moon the following day. That's because the Moon orbits the Earth, and advances in its orbit by 50 minutes each day.

If the Earth was not orbiting the Sun, the Moon would complete one orbit around the Earth in 27 days, what's called a **sidereal month**. But the Earth does move and by the time the Moon makes a complete circle around the Earth, the Earth has moved forward in its orbit, too. For the Moon to reach the same point with respect to the Sun and Earth (i.e., to move into the same configuration as 27 days earlier), an additional 2.5 days are required. So, the complete cycle of the tides requires 29.5 days, what's known as the **synodic month**, the time it takes for the Moon to transit around the Earth and return to its starting point relative to the Earth and Sun.

The phases of the Moon mark different waypoints in the Moon's orbit during the synodic month. When the side of the Moon facing Earth is fully illuminated by the Sun, the Moon is said to be full; it's a **full Moon**. When the Moon is not visible at all, the Moon is said to be new; it's a **new Moon**. The point halfway between new and full is called the first quarter. The right half of the Moon is illuminated during the **first quarter** (in the Southern Hemisphere, it's the left half). Following the full Moon, at the halfway point between the full Moon and the new Moon, the left half of the Moon is illuminated at the **third quarter**. From the new Moon to the full Moon, the Moon grows brighter each night; the Moon is **waxing**. When the Moon grows dimmer, as it does during the transition from full to new Moon, the Moon is **waning**.

Though not necessary for an understanding of tides, we can divide the Moon's orbit even further, and it's fun to do so because the Moon is the most visible object in the night sky. The sliver of Moon between the new Moon and first quarter, and between the third quarter and new Moon, is called a **crescent Moon**. We distinguish the two crescent moons as a **waxing crescent**—from new to first quarter—and a **waning crescent**—from third quarter to new. Similarly, the three-quarters-full Moon is called a **gibbous Moon**. From first quarter to full, it's a **waxing gibbous**, and from full to third quarter, it's a **waning gibbous**. Feel free to use these terms next time you are out beneath the Moon with someone special. They are sure to be impressed.

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14.3: Measuring and Predicting Tides

Tides and their measurement represent “the oldest and longest oceanographic records” in existence (Cartwright 2000). To keep track of tides, oceanographers employ an instrument known as a **tide gauge**, an instrument that tracks and records sea level continuously usually with a float and recording device (e.g., a paper chart recorder pre-1970s and a computer since the 1970s). Tide gauges developed in the 1830s (e.g., Matthäus 1972) permitted measurement and recording of the position of sea level 24 hours a day, seven days a week.

In their most basic form, tide gauges record the position of a float at regular intervals throughout the day. The characteristic shape that emerges from measurements of tides, a **tide graph**, illustrates the principles of tides. The x-axis of the graph represents time, while the y-axis of the graph represents the tide height. The “peak” of the curve represents the time and height of the high tides. The “valley” of the curve represents the time and height of the low tide.

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14.4: Classification of Tides

The phases of the Moon mark the monthly period of the tides. We also need to define some aspects of the daily period of the tides.

A **tidal day** refers to one complete revolution of the Earth beneath the Moon, or 24 hours and 50 minutes. The term **tidal period** refers to the time between one high tide (or low tide) and the next high tide (or low tide). In many locations around the world ocean, the tides rise and fall twice daily, meaning that there are two high tides and two low tides each day. These locations are said to experience **semidiurnal tides**, twice daily tides. Other locations experience only one high tide and one low tide per day. These locations are said to experience **diurnal tides**, once daily tides. The tidal period for semidiurnal tides is half of a tidal day, or 12 hours and 25 minutes. On the other hand, the tidal period is equal to a tidal day for diurnal tides. In some locations, such as the west coast of North America, including Southern California, the height of the two daily high tides differs as does that of the two daily low tides. Regions where successive tides differ in height experience what are called **mixed semidiurnal tides**, or simply mixed tides. Because their heights differ, the high tides and low tides are identified according to their relative heights. The highest of the daily high tides is called the **high high tide**. The lowest of the daily low tides is called the **low low tide**. The lower of the two daily high tides is called the **low high tide**. The higher of the two daily low tides is called the **high low tide**.

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14.5: Tidal Height

The height of tides, the **tidal height**, refers to the vertical distance of sea level above or below a standard baseline. The National Oceanic and Atmospheric Administration (NOAA) is the agency responsible for establishing the definition of this baseline, the **tidal datum**, also known as the **zero tide height**. For reasons beyond our discussion here, NOAA takes a 19-year average of the low water (i.e., low tide height), or low low water (i.e., low low tide height) to set the tidal datum for a location. Tide heights for the mean low water (MLW) at semidiurnal and diurnal tide locations or mean low low water (MLLW) for mixed tide locations establish the **National Tidal Datum Epoch** (e.g., NOAA 2023a). An actual metal marker, called a **tidal datum benchmark**, provides a reference (with known elevation) for determination of zero tide heights. For all practical purposes, the tidal datum, MLW (semidiurnal and diurnal tides) or MLLW (mixed tides), and zero tide height are all the same thing: they establish the location from which the heights of tides may be determined.

Tides that rise above the zero tide height are called **plus**, or positive, **tides**, while tides that fall below the zero tide height are known as **minus**, or negative, **tides**. For example, a high tide with a height of six feet is six feet above the zero tide height. A low tide with a height of minus two feet is two feet below the zero tide height. The difference between the height of the high and low tides defines the **tidal range**. It can be simply defined as follows:

Tidal range = Height of the high tide – Height of the low tide

(Eq. 20.1)

If the high tide is 6 feet and the low tide is –2 feet, the tidal range would be 8 feet. Tidal range can refer to a high tide and the next low tide or it can refer to the maximum difference in tide heights in a day.

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14.6: Spring and Neap Tides

Tides also exhibit a monthly cycle that corresponds with the positions of the Earth, Moon, and Sun. Although the tidal forces from the Sun are half those of the Moon, they are still significant, and tidal bulges from the Sun affect the tides. When the Sun and Moon are on the same side of the Earth, or on exact opposite sides, the effect of the lunar and solar tidal forces is additive. Tides during these times are more extreme: the highs are higher and the lows are lower. Tidal range is maximal during spring tides. This period of time is called the **spring tides** because the tides appear to spring up faster than normal. Spring tides occur during the new and full moons when the Earth, Moon, and Sun are aligned. Alternatively, when the Earth, Moon, and Sun are at right angles to each other, the tides are less extreme. These are the **neap tides**. Tidal range is minimal during neap tides. Neap tides occur during the first and third quarters of the Moon. Because spring tides occur every time there is a full or new Moon, and neap tides occur every time there is a first quarter or third quarter Moon, there are two spring tides and two neap tides every 29.5 days.

Finally, you may have read or heard about **king tides**, periods when high tides are exceptionally high. At certain times of the year, the positions and alignment of the Earth, Sun, and Moon create a little extra force giving rise to king tides. It's a non-scientific term, but one that has become popular in recent years. Now you know what it means.

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14.7: Practical Applications of Tide Knowledge

Knowledge of tides has enormous practical use. Tide predictions are as important to ship's captains as weather reports. You best know the tides before you set sail! Knowing the height of a tide beforehand is critical for safe navigation of watercraft. During times of extreme minus tides, rocks that may be submerged during normal times can appear above the surface. Many shipwrecks, ferryboat groundings, and other boating accidents happen during extreme low tides.

Tides also affect those of us who spend time near the shore. If you ever do any hiking along the Northern California–Oregon–Washington coasts, tide charts tell you when a particular stretch of beach is passable. For example, along the Lost Coast in Humboldt County, hikers have to wait for a low tide to pass around some of the headlands. Timing your hike with the tides is critical, otherwise you may have to wait several hours, or worse, be tempted to try something stupid like swimming around a point in pounding surf. Some have tried. I don't have to tell you what happened to them.

Fishermen religiously follow the tides. Low tides along sandy coasts mean good clamming. On the Washington coast, people "dig" for razor clams using a **clam gun**, a hollow metal pipe with a handle at one end. By shoving the pipe into the sand at the location of a clam siphon, and pulling it out of the sand, you capture the clam inside a column of sand. All you have to do next is spill the sand onto the beach and grab the clam before it digs back into the sand.

Tide predictions let you know the best times to observe marine organisms in the **rocky intertidal zone**, the region of a rocky shore alternately exposed and submerged due to the tides. You'll also find tidepools, the shallow water-filled depressions in rocks that appear when the tide is low. During minus tides, a dazzling variety of organisms may be observed, including sea anemones, hermit crabs, and sea stars.

Of course, the best reason to own a tide chart is so you know when to see the most fabulous nighttime beach event of all, the **California grunion run**. From March through August, on beaches from Morro Bay, California, to Baja California, these anchovy-sized fish swarm the beach to perform their mating dance. Grunion runs typically occur two to four days after the new Moon or full Moon (i.e., at the time of the spring tide) and one to three hours after the high high tide, which occurs at night in Southern California. Though the entire event may unfold over hours on a given night, the actual mating of a pair (or trio) of grunion takes less than 30 seconds. Because the height of the high high tide following the new or full Moon is lower each night (from spring to neap), the eggs remain covered in sand on the beach for 10-14 days until the next spring tide. When the incoming waves wash up on the beach and soak the eggs, out pops a little larval grunion, not even an inch long. The larval fish swims into the surf, never to be seen until it reaches adult size and is ready for mating.

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14.8: An Ever-Changing Sea Level

It's hard to imagine that the dry ground over which you drive and walk on a daily basis was once covered in hundreds of feet of seawater. Enormous changes in sea level across geologic time have dramatically reshaped coastlines. Sea level changes produced the shallow seas that gave rise to the world's petroleum reserves and enabled (or prevented) human migration across Polynesia. Next time you are in downtown Los Angeles, look up at the US Bank Tower, the tallest building in California at 1,018 feet tall. That's about 198 feet taller than the height of the sea level at its highest extent nearly 100 million years ago (Haq 2014).

Changes in sea level over geologic time are why we find whale bones in Southern California. Only a few million years ago, Southern California was submerged beneath the Pacific Ocean. Sedimentary rocks just a few miles from the Fullerton College campus contain shells of ancient marine organisms and other fossils. The Interpretive Center at Ralph B. Clark Regional Park in Fullerton hosts hundreds of marine and terrestrial fossils, including a gray whale skeleton and a giant sloth, all former residents of the Orange County as sea level rose and fell over geologic time. (See also Lozinsky 2010.)

While natural cycles contribute to sea level changes now and in the past, we focus here on sea level change as a result of human-caused warming of our planet. Sea level rise presents an immediate danger to people and structures along the coastlines of the world. Coastal-dwelling people will be forced to migrate elsewhere. Local, state, and federal governments will bear the cost of measures to adapt to or retreat from sea level rise, costs which are ultimately borne by the taxpayer. Sea level rise affects all of us, whether we live in the path of the rising sea or not.

A Closer Look at the Definition of Sea Level

At first glance, the height of the ocean—sea level—seems a simple enough affair. But upon closer inspection, we realize that a wide number of processes can cause the sea surface and sea level to change. Waves, tides, winds, atmospheric pressure gradients, ocean currents, Earth's rotation, and even Earth's gravitational field, which varies with the bumps and dips of the seafloor (such as seamounts, ridges, trenches), can affect sea level. The ocean is constantly in motion. At the same time, shifts in the height of the land caused by geologic forces—upward or downward—cause vertical motions in shorelines. As the ocean cools down or warms up due to climate change—causing seawater to contract or expand—and as ice caps and glaciers form or melt—changing the amount of water in the ocean—the volume of the ocean changes. At the peak of the last ice age about 20,000 years ago, sea level was lower by nearly 410–440 feet (125–134 m). All that extra seawater was frozen on land as glaciers (e.g., Lambeck et al. 2014). These many processes determine the sea level at any given moment and the rate at which sea level changes over time.

The first problem in estimating true sea level arises from Earth itself: it's lumpy, way lumpy. As you know from Chapter 7, the seafloor boasts majestic mountains, deep and narrow trenches, and a whole host of other features that all impact sea level. And these variations in the shape (and chemical composition) of Earth's crust cause differences in Earth's gravitational field. Gravity, of course, is the restoring force for sea level. So variations in gravity cause variations in sea level.

Scientists define a theoretical surface known as the **geoid** (JEE-oyd; more fun to say than study, I'm afraid), the isosurface (equal magnitude surface) of Earth's gravity. NOAA's National Geodetic Survey defines the geoid as "the equipotential surface of the Earth's gravity field which best fits global mean sea level." The United States Geological Survey is a little less technical, describing the geoid as "the irregular-shaped ball" that serves as "an imaginary sea level surface." Computer-generated images of Earth's geoid resemble the kind of lopsided biscuits my mom used to bake (not the greatest cook but an incredible woman in every other way). The geoid works very well for measurements of sea level from space and computer models. But for establishing local variations in sea level, some oceanographers prefer the **reference ellipsoid**, essentially, "the surface of an ellipsoidal volume that approximates the geoid" (Gregory et al. 2019).

Thankfully, most people (including you and me) don't ever have to think about the geoid or the reference ellipsoid. But it is important that you appreciate the technical difficulty of defining sea level. And important that you understand how scientists go to great lengths to establish criteria for determining the magnitude of changes in sea level and the potential for rising sea level to flood coastlines.

Defining Sea Level Change

Because a number of processes can cause sea level to change, it's important to establish clear benchmarks to assess how much sea level changes at different places and times. A few more definitions help in this endeavor. According to Gregory et al. (2019), the

sea surface can be defined as “the time-varying upper boundary of the ocean” whose height is calculated with respect to the reference ellipsoid. As with tide heights, the height of the sea surface can be positive or negative relative to the ellipsoid. From this definition, they establish **mean sea level** as “the time-mean of the sea surface”—the average of sea level, as it were—with a time period sufficient to average out the effects of waves and atmospheric pressure (among other things) that may cause short-term variations in sea level.

In general, we think of changes in sea level as caused by changes in the volume of the ocean (discussed below). Increases in the ocean’s volume cause sea level rise, while decreases cause sea level fall. However, sea level can change because of movements of Earth’s crust: coastlines can move up or down vertically in response to geologic and tectonic forces (the concept of isostasy referred to in Chapter 7). Because they’re most concerned about how changes in sea level will affect the integrity of beaches and structures at individual locations along coasts, oceanographers define the term **relative sea level rise** (also relative sea level change) as “the change in local mean sea level relative to the solid surface, i.e., seafloor or land.” When referring to the global increase in volume of the ocean—either through the thermal expansion of seawater as it warms or increases in the amount of water due to the melting of ice caps and glaciers into the ocean—oceanographers use the term **global mean sea level rise** (or global mean sea level change), defined as “the increase in the volume of the ocean divided by the ocean surface area” (Gregory et al. 2019). Most of the “sea level rise” that you hear about in the news refers to global mean sea level rise. For variations in sea level along a specific coastline, the term relative sea level rise is more appropriate.

Consideration is also given to the local effects of waves, tides, and storm surge—the change in sea level caused by synoptic-scale weather systems (occurring over hundreds of miles), such as hurricanes. Gregory et al. (2019) define **extreme sea level rise** as events with “an exceptionally high or low local sea-surface height” (emphasis mine).

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14.9: How Do We Measure Sea Level?

To know how much sea level has risen in recent years, you have to know something about how sea level has changed in the past. Measurements of sea level date back to the second century BCE when Greek Stoic philosopher Posidonius (135–51 BCE) reported observations in the Mediterranean Sea. Knowledge of tides and their heights undoubtedly existed in the logbooks, charts, and minds of sailors in ancient times, but systematic measurements of the tides did not begin until the mid-1700s (Cartwright 2000). Daily recording of tides nearly 200 years old can be found for a few locations, such as Boston Harbor (Talke et al. 2018). Unfortunately, many of these measurements are unusable because they remain in analog form (i.e., on a piece of paper) or because they've been stashed away somewhere and forgotten (Talke and Jay 2017). Tide gauges (described above) have proliferated in the last 50 years, and they remain the principal source of information on sea level rise at a local level.

At least 1,355 stations out of more than 2,000 worldwide provide usable records—in terms of climate-relevant analyses—but most of these are coastal and some countries lack many or any stations (e.g., Woodworth et al. 2017). At the same time, local tide stations are subject to land motions and other sources of bias that limit their usefulness for determining global rates of sea level rise (e.g., Thompson et al. 2016). Thankfully, the 1970s ushered in the era of measurement of sea level globally, using, of all things, satellites.

In Chapter 4, we briefly explored the pioneering missions of TOPEX/Poseidon and the Jason satellites. In November 2020, the European Space Agency—in cooperation with NASA and other European partners—launched the first of two satellites to replace the Jason satellites, the Sentinel-6A. Recently renamed after the former director of NASA's Earth Science Division, Michael Freilich (1954–2020)—a "passionate advocate" of measurements of Earth from space (Cook 2020)—the now-Sentinel-6 Michael Freilich will be able to track sea level rise with an error of less than one millimeter per year (Scharroo et al. 2016). The satellite will also map at both high and low resolution to provide a more detailed picture of the sea surface and to permit comparisons with sea surface topography from earlier lower resolution missions. The second satellite, the Sentinel 6B—to be launched in 2026—will extend measurements of sea level until 2030 (NASA 2023b).

One other set of satellite measurements deserve mention here with regard not only to our understanding of sea level rise but also to the distribution of water on our planet and the water cycle. The **Gravity Recovery and Climate Experiment** (GRACE) and the Follow-On mission (GRACE-FO) measure the variations in gravity that result from changes in the distribution of mass across Earth's surface, especially those that result from changes in the volume of water or ice. Launched in 2002, GRACE established "a new field of spaceborne remote sensing" (Rasmussen 2017), the field of satellite gravimetry—the study of mass transport on Earth's surface using gravity measurements (Chen 2019).

GRACE and GRACE-FO accomplish these measurements using a deceptively simple but ingenious method. Immense land features—like mountains—generate a larger gravitational force than flat regions of the world. Smaller features, too, exert a gravitational field, all of which exert an influence on the speed of Earth-orbiting satellites. As a satellite approaches a feature, it speeds up (being attracted by its gravitational pull), and as it passes, it slows down (as the gravitational pull tugs at it from behind). To observe these changes in speed, GRACE uses two satellites in identical orbits separated by a distance of about 137 miles (220 km). As the twin satellites pass over different features, the distance between them changes slightly as one satellite is accelerated and the other is slowed down. Pulses of microwaves between the two satellites provide highly accurate measurements of the distance between them (like a radar gun). Using this information (and well-known physical laws), scientists can produce a map of Earth's gravitational field every month. Differences in the distribution of gravity from month to month reveal movements of water above and below Earth's surface, changes in ice mass, and changes in sea level.

GRACE has revolutionized our understanding of water on our planet. During the 2011 La Niña, scientists used data from GRACE to observe water that evaporated over the tropical Pacific. Sea level dropped as a result, but the water appeared as precipitation over Australia, South America, and Asia (Boening et al. 2012). GRACE and GRACE-FO have also been vital for observing reductions of ice mass in Greenland and Antarctica (e.g., Velicogna et al. 2020). Ultimately, predictions for future impacts of sea level rise—and especially extreme sea level events—will depend on scientists' ability to better measure and quantify factors that cause sea level to change. New approaches and technologies promise to improve our understanding of sea level variability—globally and locally—and to better prepare and implement plans to mitigate sea level rise in the coming decades.

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14.10: What Causes Sea Level Change

Fundamentally, sea level rises or falls as the volume of the ocean changes. That's the simple view. However, on any given shoreline, sea level may change due to changes in the elevation of the land. As we have seen, sea level rise depends on any of a number of factors at any one location.

The global rise in sea level results primarily from two principal processes that increase the volume of the ocean: (1) thermosteric sea level rise; and (2) barystatic sea level rise. **Thermosteric sea level rise** results from the thermal expansion of seawater when heated. Increases in the temperature of seawater cause its volume to expand. **Barystatic sea level rise** comes from the addition of water to ocean basins—an increase in ocean mass—from melting land ice (e.g., ice caps and glaciers), changes in land storage of water (e.g., water formerly stored behind dams), and the atmosphere (e.g., precipitation; Gregory et al. 2019).

Local sea level rise also experiences thermosteric and barystatic sea level rise, but they're also subject to **vertical land movements**, defined as "the change in height of the seafloor or land surface" (Gregory et al. 2019). Upward vertical motions are called **uplift** (or emergence), while downward vertical motions are called **subsidence** (or submergence). Any number of natural and manmade processes may cause uplift or subsidence. What's most important are the effects of vertical land motions on relative sea level rise. Where a coast is uplifted, relative sea level rise may be slower than if the land exhibits no vertical motion. On the other hand, a subsiding coastline may experience an accelerated relative sea level rise because the land is losing height while sea level is increasing.

Understanding the individual contributions of thermal expansion, ocean mass gains, and vertical land movements on sea level rise is important for predicting future changes and impacts. For example, the rate of thermal expansion of seawater increases with increasing temperature. Thus, as the ocean warms, thermal expansion will accelerate (e.g., Widlansky et al. 2020). Similarly, increases in the rate of melting of glaciers and ice caps will accelerate contributions to ocean water mass (e.g., The IMBIE Team 2020). Indeed, thermal expansion and increased ice melt explain the acceleration in global mean sea level rise that has been observed since the 1970s (Frederikse et al. 2020).

Most of the differences in relative sea level along US coastlines and around the world can be explained by vertical land motions. Tectonic compression (pushing land together) may cause uplift of a coastline—essentially reducing the rate of sea level rise—while tectonic extension (pulling land apart) may cause subsidence—making the rate of relative sea level rise faster. At the same time, many coastlines (along the United States and around the world) are still adjusting to the retreat of glaciers at the end of the last ice age some 16,000 years ago. When present, glaciers depress land masses. Once removed, the land masses return to their former position. This movement of land masses in response to the presence or absence of glaciers is known as **glacial isostatic adjustment** (NOAA 2023b). There's also a kind of edge effect with glaciers: the land along their southern terminus—the unglaciated land at the edge of a glacier—experiences an uplift as the land under the glacier sinks. This uplift—known as a **forebulge**—disappears when the glacier retreats. **Forebulge collapse**—the subsidence of land following retreat of a glacier—explains a large part of the subsidence that is happening along the north and central US East Coast. Glacial isostatic adjustments may last tens of thousands of years (Whitehouse 2018).

Human activities also contribute to subsidence. Extraction of underground resources—especially groundwater and hydrocarbons—can cause land to subside. In the 1940s, so much water, gas, and oil had been pumped out from beneath Long Beach, California, that 20 square miles of land sank. Some spots subsided nearly 30 feet (Waldie 2015). Long Beach became popularly known as the "Sinking City" in the '50s. Fortunately, legislation and monitoring have brought the city's subsidence under control.

The same cannot be said for Louisiana, which may now be called the "Sinking State." A recent study along coastal Louisiana revealed land subsidence rates of 0.35 inches (9 mm) per year—not including sea level rise—due to natural and human activities (Nienhuis et al. 2017). Disruptions of natural processes of sediment transport that supply and trap sand—including dams, surface hardening, and sand mining—and any number of other human activities may also contribute to subsidence.

The degree to which any of these processes contribute to local sea level rise will vary across different parts of the world. As noted by the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate, "responses to sea level rise are local and hence always based on relative sea level experienced at a particular location. . . . Extreme sea level events at the coast that are rare today will become more frequent in the future. . . . One important response for preparing for future sea level rise is to improve observational systems" (e.g., Oppenheimer et al. 2019).

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14.11: What Have We Learned About Global Sea Level Rise?

Measurements of sea level over more than a century have revealed two trends: (1) global mean sea level is rising; and (2) the rate at which it is rising is accelerating (Oppenheimer et al. 2019). Over the period from 1901 to 1990, global mean sea level increased at about 0.055 inches (1.4 mm) per year, as measured from tide gauges. Over the period from 1993 to 2015—using data from tide gauges and satellites—scientists measured a rate of global mean sea level rise of about 0.126 inches (3.2 mm) per year, more than double the historical rate. Using data from tide gauges and satellite altimetry with independent estimates based on GRACE and Argo data from 2006 to 2015, scientists determined a rate of rise of global mean sea level of 0.14 inches (3.6 mm) per year (Oppenheimer et al. 2019). If we use these data to calculate how much global mean sea level has risen from 1901 to 2020 (using 0.055 in y^{-1} for 1901–1992, 0.126 in y^{-1} for 1993–2005, and 0.14 in y^{-1} for 2006–2020), we come up with a global mean rise of sea level of about 8.6 inches (218 mm). This roughly matches the eight inches of sea level rise from 1880 to 2009 reported by Church and White (2011). If we assume the fastest rate (no further acceleration) of sea level rise until 2050, we add another four inches (108 mm). And if we project that out to 2100, we get an additional seven inches (180 mm) for a total projected sea level rise of about 19 inches (about 0.5 m).

However, scientists don't expect a constant rate of sea level rise; they expect it to continue to accelerate as the data above show (e.g., Nerem et al. 2018). Assuming a slow-but-steady acceleration of sea level rise, scientists project a range of two to four feet (0.61–1.1 m) of global mean sea level rise by 2100 (Oppenheimer et al. 2019; Palmer et al. 2020). Of course, projected global sea level rise depends on whether we begin to reduce atmospheric greenhouse emissions or not. If we start on a path toward reductions, sea level rise may be more modest. If not, then it could be even worse. Under the worst-case scenario, sea level could rise by as much as 6.5 to 10 feet (2–3 m; e.g., Jevrejeva et al. 2014; Le Bars et al. 2017).

To give these numbers a little perspective, imagine that you're on the freeway going 40 mph to a special someone's house for Thanksgiving. If your destination is 120 miles away, it will take you three hours to get there at 40 mph. That's a steady speed with no acceleration, like what would happen if sea level simply rose eight inches every 100 years or so. But imagine that your rate of speed doubles every hour. In your first hour you'll travel 40 miles, but in your second hour—traveling at 80 mph (double your previous speed)—you'll make 80 miles and be done with your trip (40 mi + 80 mi = 120 mi). What would have taken three hours only takes two hours when your speed is accelerating. Imagine the surprise of that special someone when you arrive an hour early. This is what happens when a process accelerates with time. Acceleration makes things happen faster than we might otherwise have expected. Faster-than-expected sea level rise falls into this category.

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14.12: What Have We Learned About Local Sea Level Rise?

In the world of sea level rise—as in the world of real estate—it's all about location, location, location (a phrase in use since at least 1926; e.g., Safire 2009). While the average global rate of sea level rise is about 0.11 inches per year (3 mm y^{-1}), the relative sea level rise at different locations around the world varies from 0.02 to 0.5 inches per year (0.5 to 12.5 mm y^{-1}; e.g., Brown et al. 2012). Not everywhere experiences the same degree of sea level rise.

Among the world's 33 **megacities**—defined as urban regions with more than 10 million people—at least 15 occur along coastlines (e.g., Blackburn et al. 2019; Institute for Economics & Peace 2022) Moreover, these coastal megacities include lands with an elevation of less than 10 meters—the so-called **Low Elevation Coastal Zone** (e.g., McGranahan et al. 2007). This is the region considered most vulnerable to impacts from sea level rise. An estimated 600 million (Neumann et al. 2015) and perhaps as many as one billion people (e.g., Kulp and Strauss 2019) live in the Low Elevation Coastal Zone.

In the United States, an estimated 3.7 million people live within one meter of mean high tide and 22.9 million within six meters, all of which may be impacted by sea level rise, especially when other factors (storm surge, waves, subsidence, etc.) are considered. The US East and Gulf Coasts face the greatest risks—especially Florida, New York, New Jersey, and Louisiana—but parts of California may also be vulnerable, especially Southern California (Strauss et al. 2012).

South of Cape Mendocino (about 200 miles north of San Francisco), tectonic-driven subsidence and human activities are causing coastlines to sink at an average rate of 0.04 inches per year (1 mm y^{-1}). Coastlines subject to sea level rise of 0.012 inches per year (3 mm y^{-1}) will experience 0.016 inches (4 mm) of additional sea level rise annually because the land is sinking at the same time the sea is rising. Talk about a double whammy. By 2100, relative sea level rise could exceed five to six feet for much of California (National Research Council 2012). If anyone is interested in glass bottom boat tours of sunken California cities, hit me up in 2100.

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14.13: It's Not Just Sea Level Rise

Unfortunately, sea level rise—even when accounting for vertical land motion—isn't the only factor to affect flooding of coastlines. Short-term events lead to temporary and extreme sea level rise. Factors that cause rapid sea level rise include climate cycles (e.g., El Niño), tidal cycles (e.g., king tides), storm surges (e.g., hurricanes), and large ocean waves (e.g., storm swell). Each of these factors may add additional and significant increases to sea level over timescales from days to months and longer. If they overlap—for example, if a king tide coincides with the arrival of storm surge and wave swell from a hurricane—significant damage is a greater possibilty.

Sea level rise has already contributed to the phenomenon known as **nuisance flooding**—a (usually) tidally driven rise in sea level that causes seawater to inundate coastal areas. NOAA defines nuisance flooding as water levels that exceed the mean high high water by 1.6 to 2.1 feet (0.5–0.65 m; e.g., Sweet et al. 2020). Though considered minor in terms of harm to citizens or damage to properties, nuisance flooding can disrupt daily activities, damage property and infrastructure, and threaten human health (Mofktakhari et al. 2018). In Miami, Florida—which has become a kind of poster child for nuisance flooding—city streets and sidewalks become impassable, parking garages and landscapes flood, and septic systems leak into the streets during king tides (e.g., Loria 2018). By NOAA's definition, Miami experienced nine days of nuisance flooding in 2019. In Southern California, many locations—especially Newport Beach (Orange County) and Imperial Beach (San Diego)—regularly experience nuisance flooding during king tides (Jones-Bateman 2019). Researchers expect the frequency of nuisance flooding to double every five years for locations already vulnerable to nuisance flooding (Taherkhani et al. 2020). NOAA's Margaret Davidson (1950–2017) put it this way: "Today's flood will become tomorrow's high tide" (e.g., Sweet et al. 2018).

Definitions based on fixed tide heights don't always reflect conditions on the ground. One neighborhood in Key Largo—about an hour's drive south of Miami—experienced more than 90 days of nuisance flooding in 2019 as a result of king tides (e.g., Mazzei 2019). To protect their cars from saltwater corrosion, residents drive on top of lawn sprinklers to wash away the salts (e.g., The Weather Channel 2019). The challenge of adequately describing hyperlocal impacts of nuisance flooding has led one group of researchers to turn to social media. Using number of tweets and geographic information, the researchers found that users generally did a good job of tracking flooding events (Moore and Obradovich 2020). Some researchers have begun to promote **citizen science**—reporting and collection of scientific data from the public—to expand flood monitoring and even flood model calibration (e.g., Reineman et al. 2017; Loftis et al. 2019; Golparvar and Wang 2020).

Oceanographers are also concerned about extreme events. When high tides coincide with other phenomena that increase sea level, potentially catastrophic sea level rise may occur. Two of the three strongest El Niños on record—1982–1983 and 1997–1998—resulted in millions of dollars of damage through loss of homes, businesses, and infrastructure, in part, due to increases in sea level (e.g., Cayan et al. 2008; NRC 2012).

The descriptions here only briefly touch on the various causes and consequences of sea level rise globally and locally. While efforts are underway to develop tools, strategies, and solutions for mitigating and adapting to sea level rise, it is unclear whether the public's sense of urgency has yet been sufficiently awakened. In an October 16, 2020, commentary in the *San Diego Tribune*, Scripps oceanographer Richard Norris writes:

A recent state report notes that, in 10 years, sea level will be up to a foot higher than it is now. That is not enough to flood much, but add to that the seven additional feet of king tides every spring, and the foot or so of flooding from an El Niño, and even several feet of ocean swell from an ill-timed storm surge, and we step into dangerous territory. In 30 years, the high school fields, the golf course and Campland on the Bay could well be repeatedly underwater along with areas of Pacific Beach, Mission Beach Park, and Marina Village. The time to fix this costly situation is now, so we can make considered plans, instead of being faced with an emergency.

Underscoring these concerns, a recently published paper reported more than half of US coastal communities underestimate the extent of future sea level rise (e.g., Garner et al. 2023). With the ocean already knocking on the door, it's more important than ever for citizens and policymakers to adopt strategies that ensure the well-being of those who live and work along our coastlines. The coastline is changing, and we're going to have to change with it.

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14.14: Chapter References

Bentley, M. G., P. J. W. Olive, and K. Last. 2001. “Sexual Satellites, Moonlight, and the Nuptial Dances of Worms: The Influence of the Moon on the Reproduction of Marine Animals.” In *Earth-Moon Relationships*. Edited by C. Barbieri, and F. Rampazzi, 67–84. Dordrecht: Springer. https://doi.org/10.1007/978-94-010-0800-6_7

Blackburn, Sophie, Mark Pelling, and César Marques. 2019. “Megacities and the Coast: Global Context and Scope for Transformation.” In *Coasts and Estuaries: The Future*. Edited by Eric Wolanski, John W. Day, Michael Elliott, and Ramesh Ramachandran, 661–669. Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-814003-1.00038-1

Boening, Carmen. 2012. “The 2011 La Niña: So Strong, the Oceans Fell.” *Geophysical Research Letters* 39(19): L19602. https://doi.org/10.1029/2012GL053055

Brown, Sally, Robert J. Nicholls, Colin D. Woodroffe, Susan Hanson, Jochen Hinkel, Abiy S. Kebede, Barbara Neumann, and Athanasios T. Vafeidis. 2012. “Sea-Level Rise Impacts and Responses: A Global Perspective.” In *Coastal Hazards*. Edited by Charles Finkl, 117–149. Dordrecht: Springer. https://doi.org/10.1007/978-94-007-5234-4_5

Cartwright, David Edgar. 2000. *Tides: A Scientific History*. Cambridge: Cambridge University Press. https://www.cambridge.org/us/academic/subjects/earth-and-environmental-science/oceanography-and-marine-science/tides-scientific-history

Cayan, Daniel R., Peter D. Bromirski, Katharine Hayhoe, Mary Tyree, Michael Dettinger, and Reinhard E. Flick. 2008. “Climate Change Projections of Sea Level Extremes along the California Coast.” *Climatic Change* 87: 57–73. https://doi.org/10.1007/s10584-007-9376-7

Chen, Jianli, Byron Tapley, Ki-Weon Seo, Clark Wilson, and John Ries. 2019. “Improved Quantification of Global Mean Ocean Mass Change Using GRACE Satellite Gravimetry Measurements.” *Geophysical Research Letters* 46(23): 13984–13991. https://doi.org/10.1029/2019GL085519

Church, John A., Neil J. White, Leonard F. Konikow, Catia M. Domingues, J. Graham Cogley, Eric Rignot, Jonathan M. Gregory, Michiel R. van den Broeke, Andrew J. Monaghan, and Isabella Velicogna. 2011. “Revisiting the Earth’s Sea-Level and Energy Budgets from 1961 to 2008.” *Geophysical Research Letters* 38(18): L18601. https://doi.org/10.1029/2011GL048794

Cook, Terri. 2020. “Obituary: Michael Freilich (1954-2020).” European Geosciences Union. August 7, 2020. https://www.egu.eu/news/678/obituary-michael-freilich-1954-2020/

Frederikse, Thomas, Felix Landerer, Lambert Caron, Surendra Adhikari, David Parkes, Vincent W. Humphrey, Sönke Dangendorf, Peter Hogarth, Laure Zanna, Lijing Cheng, and Yun-Hao Wu. 2020. “The Causes of Sea-Level Rise since 1900.” *Nature* 584: 393–397. https://doi.org/10.1038/s41586-020-2591-3

Garner, Andra J., Sarah E. Sosa, Fangyi Tan, Christabel Wan Jie Tran, Gregory G. Garner, and Benjamin P. Horton. 2023. “Evaluating Knowledge Gaps in Sea-Level Rise Assessments from the United States.” *Earth’s Future* 11(2): 22022EF003187. https://doi.org/10.1029/2022EF003187

Gerkema, Theo. 2019. *An Introduction to Tides*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781316998793

Golparvar, Behzad, and Ruo-Qian Wang. 2020. “AI-Supported Citizen Science to Monitor High-Tide Flooding in Newport Beach, California.” *ARIC ‘20: Proceedings of the 3rd ACM SIGSPATIAL International Workshop on Advances in Resilient and Intelligent Cities*, 66–69. https://doi.org/10.1145/3423455.3430315

Gregory, Jonathan M., Stephen M. Griffies, Chris W. Hughes, Jason A. Lowe, John A. Church, Ichiro Fukimori, Natalya Gomez, Robert E. Kopp, Felix Landerer, Gonéri Le Cozannet, Rui M. Ponte, Detlef Stammer, Mark E. Tamisiea, and Roderik S. W. van de Wal. 2019. “Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global.” *Surveys in Geophysics* 40: 1251–1289. https://doi.org/10.1007/s10712-019-09525-z

Haq, Bilal U. 2014. “Cretaceous Eustasy Revisited.” *Global and Planetary Change* 113: 44–58. https://doi.org/10.1016/j.gloplacha.2013.12.007

Hurley, Steve. 2022. "Overview of Tides." Explaining Science. January 4, 2022. https://explainingscience.org/2022/01/04/overview-of-tides/

IMBIE Team. 2020. "Mass Balance of the Greenland Ice Sheet from 1992 to 2018." *Nature* 579: 233–239. https://doi.org/10.1038/s41586-019-1855-2

Jevrejeva, S., J. C. Moore, A. Grinsted, A. P. Matthews, and G. Spada. 2014. "Trends and Acceleration in Global and Regional Sea Levels since 1807." *Global and Planetary Change* 113: 11–22. https://doi.org/10.1016/j.gloplacha.2013.12.004

Jones-Bateman, John. 2019. "NASA Helps California Get Ahead of Coastal Flooding." *NASA*. August 23, 2019. https://www.nasa.gov/feature/nasa-helps-california-get-ahead-of-coastal-flooding

Kulp, Scott A., and Benjamin H. Strauss. 2019. "New Elevation Data Triple Estimates of Global Vulnerability to Sea-Level Rise and Coastal Flooding." *Nature Communications* 10: 4844. https://doi.org/10.1038/s41467-019-12808-z

Lambeck, Kurt, Hélène Rouby, Anthony Purcell, Yiying Sun, and Malcolm Sambridge. 2014. "Sea Level and Global Ice Volumes from the Last Glacial Maximum to the Holocene." *PNAS* 111(43): 15,296–15,303. https://doi.org/10.1073/pnas.1411762111

Le Bars, Dewi, Sybren Drijfhout, and Hylke de Vries. 2017. "A High-End Sea Level Rise Probabilistic Projection including Rapid Antarctic Ice Sheet Mass Loss." *Environmental Research Letters* 12(4): 044013. https://doi.org/10.1088/1748-9326/aa6512

Loftis, Jon Derek, Molly Mitchell, Daniel Schatt, David R. Forrest, Harry V. Wang, David Mayfield, and William A. Stiles. 2019. "Validating an Operational Flood Forecast Model Using Citizen Science in Hampton Roads, VA, USA." *Journal of Marine Science Engineering* 7(8): 242. https://doi.org/10.3390/jmse7080242

Loria, Kevin. 2018. "Cities Around the US Are Flooding at High Tide and on Sunny Days at Record Rates—Here's What It's Like." *Business Insider*. June 12, 2018. https://www.businessinsider.com/sea-level-rise-high-tides-sunny-day-flooding-coastal-cities-2018-4

Lozinsky, Richard. 2016. *Our Backyard Geology in Orange County, California*. 3rd ed. New York: McGraw Hill Education. https://www.google.com/books/edition/Our_Backyard_Geology_in_Orange_County_Ca/XsmLrgEACAAJ

MacGillivray, Greg. 1995. *The Living Sea*. MacGillivray Freeman Films. Film. 40 minutes. https://www.imdb.com/title/tt0113676/

Matthäus, Wolfgang. 1972. "On the History of Recording Tide Gauges." *Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences* 2: 26–34. https://doi.org/10.1017/S0080455X00002083

Mazzei, Patricia. 2019. "82 Days Underwater: The Tide Is High but They're Holding On." *New York Times*. November 24, 2019. https://www.nytimes.com/2019/11/24/us/florida-keys-flooding-king-tide.html

McGranahan, Gordon, Deborah Balk, and Bridget Anderson. 2007. "The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones." *Environment and Urbanization* 19(1): 17–37. https://doi.org/10.1177/0956247807076960

Moftakhari, Hamed R., Amir AghaKouchak, Brett F. Sanders, Maura Allaire, and Richard A. Matthew. 2018. "What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge." *Water Resources Research* 54(7): 4218–4227. https://doi.org/10.1029/2018WR022828

Moore, Frances C., and Nick Obradovich. 2020. "Using Remarkability to Define Coastal Flooding Thresholds." *Nature Communications* 11: 530. https://doi.org/10.1038/s41467-019-13935-3

NASA. 2023a. "Earth's Moon." NASA Solar System Exploration. Accessed February 3, 2023. https://solarsystem.nasa.gov/moons/earths-moon/in-depth/

———. 2023b. "Sentinel-6B." NASA's Earth Observing System. Accessed February 2, 2023. https://eospso.nasa.gov/missions/sentinel-6b

National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: National Academies Press. https://doi.org/10.17226/13389

Neumann, Barbara, Athanasios T. Vafeidis, Julianne Zimmerman, and Robert J. Nicholls. 2015. "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment." *PLoS ONE* 10(6): e0131375.

https://doi.org/10.1371/journal.pone.0118571

Nienhuis, Jaap H., Torbjön E. Törnqvist, Krista L. Jankowski, Anjali M. Fernandes, and Molly E. Keogh. 2017. "A New Subsidence Map for Coastal Louisiana." *GSA Today* 27(9): 58–59. https://doi.org/10.1130/GSATG337GW.1

NOAA. 2023a. "Tidal Datums." NOAA Tides and Currents. Accessed February 3, 2023. https://tidesandcurrents.noaa.gov/datum_options.html

———. 2023b. "What Is Glacial Isostatic Adjustment?" NOAA National Ocean Service. Accessed February 2, 2023. https://oceanservice.noaa.gov/facts/glacial-adjustment.html

Norris, Richard D. 2020. "Commentary: We Need to Rethink Our San Diego Coast to Deal with Sea Level Rise before It's Too Late." *San Diego Union-Tribune*. October 16, 2020. https://www.sandiegouniontribune.com/opinion/commentary/story/2020-10-16/sea-level-rise-climate-change

Oppenheimer, M., B. C. Glavovic , J. Hinkel, R. van de Wal, A. K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R. M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. 2019. "Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities." In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Edited by H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. M. Weyer, 321-445. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157964.006

Palmer, M. D., J. M. Gregory, M. Bagge, D. Calvert, J. M. Hagedoorn, T. Howard, V. Klemann, J. A. Lowe, C. D. Roberts, A. B. A. Slangen, and G. Spada. 2020. "Exploring the Drivers of Global and Local Sea-Level Change Over the 21st Century and Beyond." *Earth's Future* 8(9): e2019EF001413. https://doi.org/10.1029/2019EF001413

Rasmussen, Carol. 2017. "GRACE Mission: 15 Years of Watching Water on Earth." *NASA*. March 15, 2017. https://www.nasa.gov/feature/jpl/grace-mission-15-years-of-watching-water-on-earth

Reineman, Dan R., Leif N. Thomas, and Margaret R. Caldwell. 2017. "Using Local Knowledge to Project Sea Level Rise Impacts on Wave Resources in California." *Ocean and Coastal Management* 138: 181–191. https://doi.org/10.1016/j.ocecoaman.2017.01.020

Safire, William. 2009. "Location, Location, Location." *New York Times Magazine*. June 26, 2009. https://www.nytimes.com/2009/06/28/magazine/28FOB-onlanguage-t.html

Scharroo, Remko, Hans Bonekamp, Christelle Ponsard, François Parisot, Axel von Engeln, Milen Tahtadjiev, Kristiaan de Vriendt, and François Montagner. 2016. "Jason Continuity of Services: Continuing the Jason Altimeter Data Records as Copernicus Sentinel-6." *Ocean Science* 12(2): 471–479. https://doi.org/10.5194/os-12-471-2016

Simanek, Donald E. 2022. "Tidal Misconceptions." Donald E. Simanek. Accessed February 3, 2023. https://dsimanek.vialattea.net/scenario/tides.htm

Strauss, Benjamin H., Remik Ziemlinski, Jeremy L. Weiss, and Jonathan T. Overpeck. 2012. "Tidally Adjusted Estimates of Topographic Vulnerability to Sea Level Rise and Flooding for the Contiguous United States." *Environmental Research Letters* 7(1): 014033. https://doi.org/10.1088/1748-9326/7/1/014033

Sweet, William V., Gregory Dusek, Greg Carbin, John Marra, Doug March, and Steven Simon. 2020. "2019 State of US High Tide Flooding with a 2020 Outlook." NOAA Technical Report NOS CO-OPS 092. Silver Spring: NOAA. 17 pages. https://doi.org/10.25923/q56g-ba90

Sweet, William V., Gregory Dusek, Jayantha Obeysekera, and John J. Marra. 2018. "Patterns and Projections of High Tide Flooding along the US Coastline Using a Common Impact Threshold." NOAA Technical Report NOS CO-OPS 086. Silver Spring: NOAA. http://doi.org/10.7289/V5/TR-NOS-COOPS-086

Taherkhani, Mohsen, Sean Vitousek, Patrick L. Barnard, Neil Frazer, Tiffany R. Anderson, and Charles H. Fletcher. 2020. "Sea-Level Rise Exponentially Increases Coastal Flood Frequency." *Scientific Reports* 10: 6466. https://doi.org/10.1038/s41598-020-62188-4

Talke, Stefan, and David A. Jay. 2017. *Archival Water-Level Measurements: Recovering Historical Data to Help Design for the Future*. Civil and Environmental Engineering Faculty Publications and Presentations. 412. Portland: PDXScholar. http://archives.pdx.edu/ds/psu/21294

Talke, S. A., A. C. Kemp, and J. Woodruff. 2018. "Relative Sea Level, Tides, and Extreme Water Levels in Boston Harbor from 1825 to 2018." *Journal of Geophysical Research Oceans* 123(6): 3895–3914. https://doi.org/10.1029/2017JC013645

Thompson, P. R., B. D. Hamlington, F. W. Landerer, and S. Adhikari. 2016. "Are Long Tide Gauge Records in the Wrong Place to Measure Global Mean Sea Level Rise?" *Geophysical Research Letters* 43(19): 10,403–10,411. https://doi.org/10.1002/2016GL070552

Velicogna, Yara Mohajerani, Geruo A. Felix Landerer, Jeremie Mouginot, Brice Noel, Eric Rignot, Tyler Sutterley, Michiel van den Broeke, Melchior van Wessem, and David Wiese. 2020. "Continuity of Ice Sheet Mass Loss in Greenland and Antarctica from the GRACE and GRACE Follow-On Missions." *Geophysical Research Letters* 47(8): e2020GL087291. https://doi.org/10.1029/2020GL087291

Waldie, D. J. 2015. "Incredibly Sinking State: The Lowdown on Subsidence." KCET. June 10, 2015. https://www.kcet.org/history-society/incredibly-sinking-state-the-lowdown-on-subsidence

Weather Channel. 2019. "King Tides Near Month Two in Key Largo." The Weather Channel. October 23, 2019. https://weather.com/safety/floods/news/2019-10-23-florida-king-tides-photos

Whitehouse, Pippa L. 2018. "Glacial Isostatic Adjustment Modelling: Historical Perspectives, Recent Advances, and Future Directions." *Earth Surface Dynamics* 6: 401–429. https://doi.org/10.5194/esurf-6-401-2018

Widlansky, Matthew J., Xiaoyu Long, and Fabian Schloesser. 2020. "Increase in Sea Level Variability with Ocean Warming Associated with the Nonlinear Thermal Expansion of Seawater." *Communications Earth and Environment* 1: 9. https://doi.org/10.1038/s43247-020-0008-8

Woodworth, P. L., J. R. Hunter, M. Marcos, P. Caldwell, M. Menédez, and I. Haigh. 2017. "Towards a Global Higher-Frequency Sea Level Dataset." *Geoscience Data Journal* 3(2): 50–59. https://doi.org/10.1002/gdj3.42

Zimecki, Michał. 2006. "The Lunar Cycle: Effects on Human and Animal Behavior and Physiology." *Advances in Hygiene and Experimental Medicine* 60: 1–7. https://pubmed.ncbi.nlm.nih.gov/16407788/

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SECTION OVERVIEW

Voyage IV Ocean Biology

15: The Living Sea

15.1: Systems of Classification
15.2: A Quick Lesson in Classification
15.3: Two or Three Domains?
15.4: A Brief History of Life on Earth
15.5: Life and Earth as One?
15.6: Chapter References

16: Ocean Depth Zones

16.1: Defining an Organism’s Habitat
16.2: Marine Biogeography
16.3: Oceanic Environments
16.4: Pelagic Depth Zones
16.5: Benthic Depth Zones
16.6: Ocean Depth Zoning Out
16.7: Chapter References

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CHAPTER OVERVIEW

15: The Living Sea

If anything draws people to the sea—to walk beside its shores, ride along its surface, or plunge into its depths—surely it must be the otherworldly creatures that dwell within it. Part enchanting, part terrifying, the living sea offers an extraterrestrial world on our own planet. Sir Arthur Clarke (1917–2008), creator of numerous fictional extraterrestrial worlds and an avid scuba diver, opined, “No beings from outer space could be more weird than some of the plants and animals that inhabit the oceans of our own world” (Clarke 1960). Indeed, the more we poke, prod, and explore, the weirder the ocean seems: 440-pound jellies with deadly venom, crabs that gather on boiling vents, sea lions that herd oceanic tuna, and octopuses that become friends with humans.

With much of the ocean unexplored—especially midwater and abyssal regions—it should come as no surprise that we continue to make new discoveries on every expedition. Yet in recent decades oceanographers haven’t had to travel too far to make the most startling of discoveries. By probing the genetic makeup of the “invisible” life-forms in seawater—the microbes—a world beyond our imagination has been discovered. Microbes trade molecules, team up to work, sport enormous metabolic toolboxes, thrive everywhere, and are possibly more diverse than all other marine life-forms combined. What’s more, a good percentage of them are completely new to science, life-forms only recently discovered in the ocean. Our newfound understanding of the importance of viruses in the ocean, our increased recognition of the role of diverse feeding modes, and an emerging perspective of the ocean as a microbial network that responds holistically to changes in the environment—a microbial interactome—have radically changed our view of the ocean in just a few decades.

In the chapters that follow, we explore the **living sea**, the interconnected, self-replicating, and self-sustaining network of diverse life-forms that inhabit the world ocean. Arguably, the living sea constitutes the most important part of Earth’s biosphere, dominating cycles of carbon, nitrogen, and oxygen. And while it may or may not be as diverse as the terrestrial biosphere—the question remains unsettled—it certainly is the most ancient biological system on our planet. The present-day inhabitants of the ocean and the roles they play in the modern living sea emerge from their evolution over billions of years. We’ll get to that history in a bit. But first we must try to make some sense of the living world, bring some order to the living sea so that we may better appreciate their diversity and function.

15.1: Systems of Classification

15.2: A Quick Lesson in Classification

15.3: Two or Three Domains?

15.4: A Brief History of Life on Earth

15.5: Life and Earth as One?

15.6: Chapter References

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15.1: Systems of Classification

The science of **systematics** aims to discover the diversity of organisms and their relationships with each other (e.g., Raven et al. 2020). As Narendran (2000) expresses it, "Systematics is nothing less than a thorough and complete study of the diversity of living forms." Not only is systematics useful for understanding the evolution and history of life, it also provides a kind of biological parts list for the Earth system. Knowing who's who—differentiating one species from another—helps scientists determine who is doing what and where and when they are doing it (Yilmaz et al. 2016). Discovery of abundant cyanobacteria in the 1970s completely changed our ideas about oceanic food webs. Had we not known these organisms existed, our ideas would have been incomplete, if not fundamentally wrong. Systematics has enabled oceanographers to piece together the microbial machinery that underpins how the ocean works as a system.

Systematics proceeds in part through **classification**, the organization of life into groups that share certain characteristics. Most of us regularly classify things. For example, when you sort laundry, you separate clothes by color or material. When you put away dishes, you typically place glassware, silverware, and plates in specific locations.

Scientific classification involves the naming of things, a science called **taxonomy** (e.g., Raven et al. 2020). Traditional rank-based taxonomy, or Linnaean taxonomy, popularized by Swedish naturalist Carl Linnaeus (1707–1778), categorizes life into a series of ever-larger groups from most similar to least similar. The **domain** category represents the largest grouping of organisms. Wholly related organisms, individuals that share near-identical genetic codes and can produce fertile offspring with each other, are called **species**. Every species of organism on Earth receives a standardized name—a **scientific name**—that connects it with its closest relatives—the next highest level of organization, the **genus**. Scientific names follow **binomial nomenclature**, a two-part naming system that includes the genus as the first part of the name and the species as the second part. Scientific names also follow strict formatting guidelines: the genus is always capitalized, and both the genus and species are italicized. For example, the properly formatted genus and species for humans appears as *Homo sapiens*. Additional information may appear as part of a scientific name, but that's beyond our discussion here.

Higher levels of organization provide additional information on the relatedness of species (see below). Because each of these groupings represents a kind of rank—domains are the highest level of classification—the rank-based system is called a **hierarchical system**, a system ordered by different levels. The military, with its ranks of personnel, and traditional corporations, with CEOs and managers, use hierarchical systems. However, unlike the military and corporate hierarchies, rank-based taxonomy doesn't necessarily imply levels of importance in the same way (but see Wilcox 2019). There are no generals in Linnaean taxonomy. In this sense, rank-based taxonomy is a nested hierarchy, like the Russian matryoshka, or nesting dolls—where one rank fits within another.

Rank-based classification helps organize living things into intuitive categories—what biologists refer to as "natural kinds" (e.g., Doolittle 2014). But this system has drawbacks for exploring the evolutionary relationships of organisms, such as who evolved from whom. And it can give a false sense of equivalency between ranks. For example, whereas we find about 89 species of cetaceans (i.e., whales, dolphins, and porpoises) on Earth (Fordyce and Perrin 2023), marine mollusks (i.e., bivalves, shells, octopuses, squids) number in the vicinity of 50–55,000 species (Molluscabase 2023). Mollusks have also lived on Earth about 500 million years longer than cetaceans, having evolved 550 million years ago (e.g., Wanninger and Wollesen 2018) versus 50–53 million years ago for cetaceans (e.g., Bajpai and Gingerich 1998; Thewissen et al. 2007). Though species occupy the same rank, they represent very different evolutionary histories (Understanding Evolution 2023).

With a desire for a more objective and quantitative means of classification, German zoologist Willi Hennig (1913–1976) developed phylogenetic systematics, also known as **cladistics** (e.g., Lipscomb 1998), a method of classification that uses measurable characteristics to determine degrees of similarity between organisms (Oxford Languages 2023). Cladistics excels at determining who is descended from whom in a more quantitative way than traditional classification. We won't delve into the details, but a couple terms prove useful for discussing classification based on cladistics. Organisms that share a common ancestor belong to a group called a **clade**. By definition, a clade includes all members descended from the common ancestor. A group that contains all descendants from a common ancestor is said to be **monophyletic**. Ideally, all classification would be based on monophyletic clades. But this is easier said than done.

In many instances, a **paraphyletic** classification—a clade that doesn't include all descendants from a common ancestor—is desirable. For example, birds and dinosaurs had been traditionally considered separate groups. As it turns out, however, based on discoveries of feather-adorned dinosaurs in China, scientists now believe that birds and dinosaurs share a common ancestor (e.g., Bhullar et al. 2012; Singer 2015). A long history of distinction between birds and reptiles makes it unlikely that we'll lump birds in with reptiles anytime soon. And there's practical reasons to maintain separate classifications: birds do different things than reptiles. Ecologically, the two groups are distinct. Thus, because it doesn't include all descendants from a common ancestor, the clade "dinosaurs" (or non-avian dinosaurs) is paraphyletic. Similarly, the clade "birds" is paraphyletic (because it doesn't include dinosaurs). Arizona State University's Dr. Biology (2017) offers this distinction: if you used phylogenetic classification for storing peanut-derived products in your pantry, you'd put peanut butter, peanut oil, and Cracker Jacks on the same shelf. But if you wanted a more functional system, you'd probably separate these items and group them according to how you use them: peanut butter for sandwiches, peanut oil for cooking, and Cracker Jacks for snacks.

Both rank-based classifications and cladistics can be used to construct **phylogenetic trees**, also known as trees of life. These branching diagrams illustrate the hypothetical evolutionary relationships between organisms. They're like a family tree that shows your ancestors and relatives, except in this case, the relatives and ancestors are different species. Phylogenetic trees depict the evolutionary history of a clade of organisms (or all organisms; see below) based on their **inherited characters**—the traits of organisms coded in genes passed down by their ancestors. Choosing different characters can yield different trees. Much of the research on the evolution of life on Earth concerns finding the characters that yield the simplest or most statistically likely tree.

Though many types of trees exist, two types are most common: (1) **rooted**, like a tree with a main trunk and branches; and (2) **unrooted**, which resembles a starburst pattern. Rooted trees provide a road map of the ancestry of organisms and their evolution from a common ancestor. Unrooted trees illustrate the relationships between organisms without regard to a common ancestor. A three-branch tree—representing the three domains of life—is perhaps the most common (e.g., Woese et al. 1990). Ever smaller and more numerous branches represent groupings based on more specific characteristics and genomes. (See Understanding Evolution for more details on different types of trees and their uses.)

Of course, without time travel or photos provided by extraterrestrials who visited Earth billions of years ago, we can never be absolutely certain who evolved from whom. That's why phylogenetic trees are considered hypothetical. Nevertheless, they offer enormous insights into the evolution of life and ecosystems on our planet. They are a fundamental tool for modern biology and ecology.

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15.2: A Quick Lesson in Classification

For centuries, taxonomists relied on rank-based classification for describing the diversity of organisms. The development of cladistics spurred a new nomenclature and a reshuffling of evolutionary relationships. These reshufflings—some of which are controversial—have resulted in a Game of Thrones–type battle between various groups of taxonomists. (Let's just hope it ends better than the series did.) Both approaches have merit: traditional classification is easier to remember, but cladistics is more accurate. We briefly review both here.

The traditional Linnaean rank-based system relies on placement of organisms into different **taxa**, the different levels in the hierarchical system. The most common taxa—in order from the most specific to the most general—are species, genus, family, order, class, phylum, kingdom, and domain. Modified groupings also exist (e.g., subphyla, superfamily, infraorder), but we'll stick with the standard eight taxa here. You can recall the order of ranks with this helpful mnemonic: "Didn't Know Popeyes Chicken Offered Free Gizzard Strips." There are vegan alternatives, too, if you prefer. (See mnemonic-device.com 2022.) As one example, the largest animal to have ever lived on Earth—yes, bigger than any dinosaur found so far—goes by the common name blue whale—a filter-feeding baleen whale named for the blue hue of its skin when underwater. Its scientific name, *Balaenoptera musculus*, makes it part of the genus *Balaenoptera*, a genus with seven other species, including minke, Bryde's, fin, and sei whales. At the family level, these eight join the lone humpback whale species (*Megaptera novaeangliae*) in the *Balaenopteridae* (e.g., Fordyce and Perrin 2023).

At lower levels it gets trickier. And here's where classification using cladistics influences rank-based classification. When I learned whale taxonomy, baleen whales (suborder Mysticetes) joined toothed whales (suborder Odontocetes) in the order Cetacea. New fossil finds and molecular evidence joined the baleen and toothed whales with—wait for it—cows, camels, hippopotamuses, and deer, among others (e.g., Poor 2023). The combined group, known as the order Cetartiodactyla or Artiodactyla (depending on the taxonimists), now includes the Cetacea, Mysticeti, and Odontoceti but their ranks remain unclear (e.g., Fordyce and Perrin 2023). Dolphins and porpoises join this group, along with all other even-toed ungulates. These groupings are more accurate, but quite the tongue twisters.

To the layperson, this may seem like pencil straightening. But the discovery that whales and hippos have a common ancestor is truly remarkable and almost makes sense, given how hippos swim. The Royal Ontario Museum calls them "unlikely cousins" (Hirt 2017). Fortunately, at higher levels, blue whale classification is a bit more stable. They are members of the class Mammalia (hey, that's our class!), the phylum Chordata (our class!), the kingdom Animalia (our kingdom!), and the domain Eukarya (yep, ours). Hopefully, this brief example illustrates the level of detail inherent in the classification of organisms and, more important, the understanding that it brings to the natural world.

Be that as it may, the hierarchical rank-based system proves very useful for making sense of the world before your eyes. A trip to the rocky intertidal zone reveals a cornucopia of life-forms and ecological roles. Green, red, and brown seaweeds—the phyla (the plural of phylum) **Chlorophyta**, **Rhodophyta**, and **Phaeophyta**, respectively—form bands of color arranged by tide height. Tidepools reveal organisms that look like flowers—the sea anemones—the most abundant of which is commonly called the aggregating anemone, or *Anthopleura elegantissima*. If you snorkel out a ways (or visit a marine aquarium), you might see their gelatinous relatives, the jellies (not jellyfish because they're not a fish). Sea anemones and corals make up the stinging phylum, the **Cnidaria** (pronounced nye-DARE-ee-uh).

A superficially similar gelatinous form—the comb jellies, or phylum **Ctenophora**—may be the oldest animals on Earth, a position they currently compete for with sponges, the phylum **Porifera** (see Neilsen 2019; Li et al. 2021; Redmond and McLysaght 2021). If you look closely, you may see a few purple patches with tiny, chimney-like openings spread across the underside of a ledge. These are the purple encrusting sponge, *Haliclona*—a genus with many representatives around the world. They belong to the demosponges (class Demospongiae), the most diverse class (some 7,000 species) among the more than 9,000 species of sponges (Morrow and Cárdenas 2015; WoRMS Editoral Board 2023). Occasionally, a segmented bristle worm, a **polychaete**, will crawl across the rockscape. Members of the phylum **Annelida**—the same phylum as earthworms—polychaetes inhabit nearly every ocean environment, from free-swimming forms in surface waters to benthic forms on abyssal plains, hydrothermal vents, and oceanic trenches.

You're also sure to see a mollusk, phylum **Mollusca**, arguably the most successful phylum in the world ocean. Mollusks brought us seashells, one of nature's most beautiful forms. The phylum also includes the octopus, one of the most intelligent **invertebrates**—animals lacking a backbone. The phylum also includes animals we eat, namely, clams, mussels, and squid. The **byssal threads** by which mussels attach themselves to rocks, are among the strongest materials on Earth (e.g., Bell and Gosline 1996).

Of course, the phylum **Arthropoda**, the jointed appendage animals, which include the insects, are the most successful terrestrial phylum. Nevertheless, they are well represented in the ocean as species of crabs, shrimps, lobsters, barnacles, krill, sea spiders, and the flea-like copepods, possibly the most numerous animals in the ocean. Their movements are hypnotic, like tiny dancers beneath the sea.

And while there are many, many more varieties of incredible marine life-forms that I could talk about for days, I'll leave you with one of the most iconic forms, the sea star (again, not a fish). Their five arms, spiny skeleton, and legions of water-powered tube feet illustrate the major characteristics of the phylum **Echinodermata**, to which they belong. Along with the prickly sea urchins (purple and red ones in Southern California), the soft-bodied sea cucumbers (whose internal muscles are a delicacy in some parts of the world), the wavy-armed brittle stars (often found beneath rocks), and the less familiar crinoids (whose arms resemble the headpieces seen in Las Vegas shows), the echinoderms represent the largest ocean-only phylum and the most abundant phylum on the abyssal seafloor. Plastic sea stars make wonderful toppers on a Christmas tree. (Just don't use the real thing; they belong in the ocean . . . alive.)

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15.3: Two or Three Domains?

At the very highest levels of life on Earth, we find three major cell lines, the domains. The domain **Archaea** includes unique single-celled organisms found throughout the ocean and also in extreme environments (e.g., hot pools, high-salinity ponds). **Bacteria**, the most diverse domain of life, comprise another unique type of single-celled organism found virtually everywhere on Earth (e.g., Coleman et al. 2021). The third domain, the **Eukarya**, includes single-celled and multicellular organisms with yet another unique type of cell. This is our domain.

Applications of genetic sequencing in the late 1970s set the stage for establishing the three-domain system in use today. American microbiologist Carl Woese (1928–2012)—hailed as "one of the most significant biologists of the 20th century" (Illinois IGB 2013)—had a hunch that gene sequences could be used to learn something about the evolution and origins of life on Earth (Luehrsen 2014). What he figured out and accomplished—not without controversy—shattered long-held ideas in biology (Nair 2012). In a paper published in 1977, Woese and then-postdoctoral microbiologist George Fox (*b*. 1945) presented RNA-sequence evidence for a third "domain" of life, the Archaea. Prior to publication of this paper, biologists believed that bacteria and eukaryotes were the only cell lines on Earth. Though met with skepticism, their discovery of the domain Archaea has come to be acknowledged as "one of the most influential in microbiology and arguably, all of biology" (Nair 2012).

Subsequent work over the ensuing decades provided support for three domains. Archaea, Bacteria, and Eukarya each occupied a major branch of a three-branched phylogenetic tree of life. Significantly, the tree of life and its three major branches validated the **theory of common descent**, the idea that all life on Earth shared a universal ancestor, the last universal common ancestor, or LUCA (e.g., Fox et al. 1980; Doolittle 1999; Weiss et al. 2016; Crapitto et al. 2022). As Darwin put it, "All the organic beings which have ever lived on this earth have descended from some one primordial form" (Darwin 1860). The tree of life depicts this common ancestry and the branching that has occurred since life originated some 3.9 billion years ago.

Until recently, the Archaea, Bacteria, and Eukarya were considered distinct domains on a three-domain tree of life. But an ever-widening body of evidence supports the existence of only two domains—the Archaea and the Bacteria—on a two-domain tree of life (e.g., Rayman et al. 2015; Williams et al. 2020; Doolittle 2020). The Eukarya belong to a branch of the Archaea and either arose within that group (e.g., Williams et al. 2020) or evolved via **endosymbiosis** (endo meaning "within"; symbiosis meaning "living together"), a "merging" of two organisms (e.g., López-García and Moreira 2020). Some trees depict the Eukarya as an offshoot of the Archaea branch (e.g., Castelle and Banfield 2018), while others depict the Eukarya as a third branch formed between the Archaea and Bacteria branches (e.g., Skejo and Franjevic 2020).

All of these concepts and definitions serve to bring into focus the evolutionary lineages of life on Earth. But the history of life on Earth is only one part of the story, for life and Earth evolved together, as we shall now see.

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15.4: A Brief History of Life on Earth

American evolutionary biologist Stephen J. Gould (1941–2002) believed that the history of life on Earth is the history of microbes on Earth, that they "always have been the dominant forms of life on Earth" (Gould 1996). Using the lens of **geologic time**, the intervals of time since Earth's formation, we can sketch some of the major milestones that support Gould's idea. On the basis of key events in Earth's geologic history, geologists define four major divisions of geologic time, the **eons**:

- Hadean eon, 4.56–4 billion years before present (BP)
- Archaean eon, 4–2.5 billion years before present (BP)
- Proterozoic eon, 2.5–0.541 billion before present (BP)
- Phanerozoic eon, 541 million years ago to present

Except for the Hadean (and possibly even then), life has been a part of Earth's history. So far as we know with certainty, Earth is the only planet in the Universe that harbors life.

Our sketch here is necessarily brief and incomplete. While we focus on a few major events in the coevolution of life and the Earth system, we're leaving out big chunks of time and omitting major events. Our visit will be more like the three-minute Disneyland Indiana Jones Adventure version versus a 12-hour viewing of all four movies.

The Hadean (4.56–4 billion years BP)

The **Hadean** eon represents a time of great geological and chemical changes on Earth and includes the origin of the atmosphere, continents, and world ocean, and the startup of plate tectonics (e.g., Brown et al. 2020). Though modern people associate Hades with a "fiery hellscape," the ancient Greek version of Hades was "the god of a synonymous, mist-shrouded, riverine underworld" (Harrison 2020). Harrison notes the irony of an emerging scientific view of the Hadean as a time seemingly more favorable for early life than previously thought. This view of a benign Hadean supports the possibility of an earlier date for **abiogenesis**, the formation of living material from non-living material—that is, the formation of life. Previously, scientists thought that intense asteroid and comet impacts, a period called the **Late Heavy Bombardment**, prevented life from gaining a foothold. But there's an emerging view that the Late Heavy Bombardment never happened or happened earlier (Mann 2018; Mojzsis et al. 2019; Cartwright et al. 2022). Genomic evidence using calibrated molecular clocks support a possible origin for life as early as 3.9 billion years ago (Betts et al. 2018). From these first organisms—whatever form they may have taken—all life on Earth evolved.

The Archean (4–2.5 billion yrs BP)

By the time of the **Archean** (from the Greek arkhaios, or "ancient"), hints of our modern Earth began to take shape. An ocean covered nearly the entire planet (e.g., Nutman et al. 1997; Johnson and Wing 2020). Plate tectonics sputtered to a start (e.g., Palin et al. 2020; Roerdink et al. 2022). And life gained a foothold on Earth (e.g., Schopf 2006; Lepot 2020).

Evidence for life by at least 3.5 billion years ago comes in three ways: (1) studies of **microfossils**, the fossilized remains of microbes, in Archaean rocks; (2) studies of chemical "fingerprints" of life in rocks; and (3) studies of rock formations (i.e., sedimentary structures). We won't dive into the details here, but a number of studies in recent years support the conclusion that microfossils have biological versus geological or chemical origins (Wacey et al. 2011; Schirrmeister et al. 2015; Delarue et al. 2020). In 2019 geologists working in the Pilbara region of Western Australia found what appeared to be the remains of microbial mats in drill cores of 3.5-billion-year-old **stromatolites**, layered rock structures created in shallow waters out of fine sediments trapped by filamentous cyanobacteria (Tice et al. 2011; Baumgartner et al. 2019). While modern microbially produced stromatolites can be found in places like Shark Bay in Western Australia, ancient stromatolites can have nonbiological origins as well (e.g., Allwood et al. 2018; McMahon and Jordan 2022). Nevertheless, Baumgartner et al. (2019) report, "our findings provide exceptional evidence for the biogenicity of some of Earth's oldest stromatolites."

Archean life exerted its influence on Earth's atmosphere as well. Atmospheric oxygen was absent (or present in only trace amounts), but methane originating from the activities of methanogens (discussed in Chapter 10) was likely present at concentrations 100 to 10,000 times present atmospheric levels (e.g., Catling and Zahne 2020). The presence of methane (and possibly carbon dioxide) would have had a warming effect on the Archean Earth, but given that the Sun was about 20 to 25 percent fainter than modern levels, Earth remained quite cool. The presence of liquid water (and likely an ocean) since at least 4.4 billion years ago (Mojzsis et al. 2001; McGunnigle et al. 2022) requires some means to keep Earth above freezing. Greenhouse gases are

thought to be one means, but other hypotheses, such as a lowered albedo or Moon-driven tidal heating of Earth's interior, have also been proposed (Rosing et al. 2010; Charnay et al. 2020; Heller et al. 2021).

These geologic and geochemical data, when combined with genetic data (discussed below), establish in the Archean two domains of life—the Archaea (of course) and the Bacteria. Estimates of their diversity in modern times range from a few million (e.g., Louca et al. 2019) to as many as a trillion different kinds (Lennon and Loucey 2020).

The presence of archaea and bacteria in the Archean suggests that a multitude of metabolic pathways already existed in ancient times (e.g., Keller et al. 2014; Knoll et al. 2016; Havig et al. 2017). As Knoll et al. (2016) put it, "Halfway through Earth history, the microbial underpinnings of modern marine ecosystems began to take shape." These metabolic pathways establish the existence of Earth's **biogeochemical cycles**—the assembling and disassembling of molecules in a continuous recycling of Earth's matter—including cycles of carbon, sulfur, nitrogen, iron, and phosphorus (Knoll et al. 2016). For this, bacteria and archaea have come to be known as nature's little recyclers, turning once-living matter back into a form that can be reused by other organisms.

One other group of organisms merits our attention in this eon. **Marine viruses**, non-cellular entities with a protein shell that encapsulates genetic information (e.g., Raven et al. 2020), likely existed at this time and may have coevolved with archaea and bacteria (e.g. Harris and Hill 2021). Though some question whether they are alive, there seems to be consensus that viruses have played an important role in the evolution of life (e.g., Forterre 2005; Mughal et al. 2020; Nasir et al. 2020). It's also likely that they played a role in the establishment of Earth's biogeochemical cycles, a role they play to this day (e.g., Knoll et al. 2016; Zimmerman et al. 2020; Gazitúa et al. 2020; Zhang et al. 2022).

The Proterozoic (2.5–0.541 billion yrs BP)

When we enter the **Proterozoic**—the eon of early life (named before we knew about Archaean life)—we find abundant evidence of single-celled bacteria and archaea thriving in an atmosphere and ocean largely devoid of oxygen. Plate tectonics as we know it was in full swing, and some time between 1.9 and 1.5 billion years ago, the first true supercontinent, Columbia, formed. Hundreds of millions of years later—about 1 billion years ago—the pieces of continental crust reassembled into another supercontinent, Rodinia (e.g., Rogers and Santosh 2002; Palin et al. 2020).

The start of the Proterozoic marked a "decisive time" in Earth's geochemical history and the history of life (Javaux and Lepot 2018). The ocean and atmosphere gained oxygen—in fits and spurts, but gains, nonetheless. A new form of life arose, one that eventually gave rise to humans. Multicellular organisms evolved, but by the end of the eon, many of them had gone extinct. Nevertheless, the transition from this eon to the next brought a blossoming of new life-forms. And throughout all this, Earth experienced its first glaciations, including some that covered most of Earth's surface—a phenomenon called **Snowball Earth** (e.g., Kirschivink 1992; Hoffman et al. 1998; Hoffman et al. 2017; Mitchell et al. 2021).

The Proterozoic begins with a rise in atmospheric oxygen, an event so significant it has been called the **Great Oxidation Event**. Oxygen may have been present locally in shallow seas or lakes by the late Archaean, perhaps as early as 3.1 billion years ago (Jabłońska and Tawfik 2021). Knoll (2016) calls this "whiffs of oxygen." Formally, they're known as **Archean Oxidation Events** (Ostrander et al. 2021). But a clear shift exists in the chemistry of rocks and sediments during a period from 2.45 to 2 billion years ago that can only be explained by the presence of oxygen. Scientists generally accept that atmospheric oxygen concentrations from 1 to perhaps as much as 40 percent of present atmospheric levels were possible at this time (e.g., Holland 2006; Gumsley et al. 2017; Warke et al. 2020; Ostrander et al. 2022).

Of course, the next big question is what caused the Great Oxidation Event. Because cyanobacteria are the only group of bacteria capable of carrying out oxygenic photosynthesis—photosynthesis that yields free oxygen as a byproduct—scientists believe that cyanobacteria generated the Great Oxidation Event. Genomic and molecular studies have suggested that key components of the metabolic machinery needed for oxygen-producing photosynthesis were present in the Archean (e.g., Sanchez-Baracaldo et al., 2022), if not at the dawn of life (Oliver et al. 2021). And new research points to ancestral origins of cyanobacteria as far back as 3.4 billion years ago (e.g., Fournier et al. 2021). But the Archean environment limited their proliferation. Scientists hypothesize that around 2.4 billion years ago, the tectonic, geochemical, and ecological conditions on Earth began to favor cyanobacteria, permitting their expansion and diversification. As they spread across the planet, the concentrations of atmospheric oxygen rose (e.g., Olejarz et al. 2021; Fournier et al. 2021).

The rise in atmospheric oxygen forced a reshuffling of strategies for making a living on Earth. **Obligate anaerobes**, organisms for which oxygen is deadly, were forced to find refuge in anoxic deep ocean basins and muds—places where we find them to this day. Other species were forced to adapt to radically different chemistry of the air, ocean, and rocks brought about by the presence of oxygen. Metabolic pathways for **aerobic respiration**, the breakdown of organic matter in the presence of oxygen, began to diversify and expand in the bacteria and archaea. Suffice it to say that the Great Oxidation Event altered Earth in ways that we are just beginning to appreciate and understand (e.g., Knoll et al. 2016; Javaux and Lepot 2018; Cole et al. 2020). By expanding the kinds of habitats and chemistries available on Earth, the oxygenated atmosphere set the stage for the evolution, diversification, and proliferation of new forms of life. It's not correct to say that the Great Oxidation Event caused the evolution of new life-forms; evolution doesn't work that way. But the Great Oxidation Event did create a very different environment in which the evolution of life appeared to accelerate.

Among the life-forms that evolved during the Proterozoic was a cell lineage that led to humans, the **eukaryotes**. Based on genetic and fossil evidence, scientists place their evolution at around 1.8 billion years ago (e.g., Betts et al. 2018). Eukaryotic life-forms include the **protists**—a diverse collection of diverse and numerically abundant single-celled and multicellular species with a eukaryotic cell type—and other multicellular organisms, from seaweeds to sponges to whales. All Eukarya feature cells with a **nucleus**, the cell structure in which most of a cell's genetic material is housed. They also host **mitochondria**, structures that supply energy to eukaryotic cells (e.g., Roger et al. 2017). Biologists refer to the nucleus, mitochondria, and other cell structures as **organelles**—subcellular, specialized structures present in eukaryotes (and possibly Archaea and Bacteria). Though a defining feature of eukaryotes, we are learning that this distinction may not be so clear-cut.

Traditionally, Archaea and Bacteria represent what biologists call **prokaryotes**—cells lacking a visible nucleus and other organelles. This designation differentiates them from the eukaryotes. But as biologists probe deeper into the cell structure of archaea and bacteria, it appears that their cells are more organized than previously thought. We now know that archaea and bacteria cells exhibit complex structures analogous to eukaryotic ones (e.g., Jogler 2014; Mahajan et al. 2020; Khanna and Villa 2022)—what some researchers refer to as **archaeal organelles** or **bacterial organelles**, respectively (e.g., Greening and Lithgow 2020). There is also increasing agreement among scientists that the Eukarya arose through endosymbiosis, as mentioned above.

Scientists continue to debate the details of the sequence of events that gave rise to the Eukarya—a process called **eukaryogenesis**. Recent discoveries point to a lineage of archaea whose **genes**—the segments of genetic material that code for proteins and serve other cellular functions—share many similarities with eukaryotic genes (e.g., Zaremba-Niedzwiedzka et al. 2017; Liu et al. 2021; Da Cunha et al. 2022). As noted above, this close affinity between archaea and eukaryotes suggests that eukaryotes are a branch of the archaea and not an independent domain. Whether two domains or three, one thing is clear: Archaea, Bacteria, and Eukarya represent different types of cells (e.g., Woese 1994; Koonin 2010; but see also Di Guilo 2018). They employ different strategies for surviving and reproducing in the modern world. And all play a significant role in the modern ocean.

Finally, we arrive at the rise of organisms with more than one cell. **Colonial organisms**—those with hundreds to thousands of identical cells each of which may produce a whole new organism—may have been present in the form of microbial mats as far back as the Archaean. But true **multicellular organisms**, organisms with many different specialized cells which carry out specific functions and which cannot independently create a whole organism, likely did not evolve until the mid-Proterozoic. Multicellular red eukaryotic algae have been reported from as far back as 1.6 billion years ago (Bengtson et al. 2017). By at least 1 billion years ago, multicellular eukaryotic green algae can be found (Tang et al. 2020). But their contributions to oceanic food webs were likely limited by mostly inhospitable conditions (e.g., Brocks et al. 2017; Reinhard et al. 2020).

Nevertheless, multicellular organisms received a boost toward the end of the Proterozoic. Beginning about 800 million years ago, atmospheric oxygen concentrations began to rise again—albeit to only a few percent of modern levels—sufficient to oxygenate at least some deep ocean basins by 570 million years ago (Wood et al. 2019). This event, known as the **Neoproterozoic Oxygenation Event** (e.g., Knoll and Nowak 2017), set the stage for diversification of multicellular life-forms at the very end of the Proterozoic, from 635 to 541 million years ago—a finer-scale subdivision of geologic time known as the **Ediacaran Period** (Sperling et al. 2015). Here the first true animals appeared—what biologists called **metazoans**, multicellular animals with differentiated cells (i.e., cells, tissues, and organs with different functions). While the timeline of the first metazoans remains uncertain, the best estimates place their arrival at around 571 million years ago (Pu et al. 2016; Darroch et al. 2018). Most important, the evolution of all modern animals began with a common metazoan ancestor. You, me, Nemo, and SpongeBob descended from the same ancestor more than 500 million years ago.

Of considerable importance to modern life and its evolution from ancient life was establishment of two major body plans during the Ediacaran. **Radial symmetry** refers to a shape arranged around a central axis, like a cake or pie. Cnidarians—sea anemones, corals, and jellies—exhibit radial symmetry. **Bilateral symmetry** refers to a shape that can be divided into two halves. A worm, a crab, a clam, a fish, a whale, and a human illustrate bilateral symmetry. Organisms that exhibit bilateral symmetry belong to the **Bilateria**, a group with bilateral symmetry that includes all animals except sponges, comb jellies, and cnidarians. Sea stars, sea urchins, and other echinoderms—which appear radially symmetrical as adults—develop from a bilaterally symmetrical larval stage, thus placing them within the Bilateria (Raven et al. 2020). Whereas radial symmetry permits a top and a bottom, bilateral symmetry allows for a head and a tail end, a right and a left half, and an upper and a lower side. Bilateral symmetry provides advantages for motion, development of senses, and evolution of nervous, organ, and reproductive systems (Raven et al. 2020).

Nevertheless, the Ediacaran was apparently a time of great experimentation. The **Ediacara biota**—the fossil assemblages that appeared from 571 to 541 million years ago—represent the oldest macroscopic marine communities preserved in rocks. Most were soft-bodied—small and squishy, as some researchers put it—so their fallen bodies left fossilized impressions rather than hard remains (e.g., Tarhan et al. 2016). The Ediacara biota range in size from tiny animals smaller than your fingernails to seaweeds as tall as you are (e.g., Pandey and Sharma 2016; Wendel 2017; Bykova et al. 2020). They also exhibit a range of forms—thread, tube, worm, fan, frond, candelabra, oval with ridges—a veritable Etsy jewelry store of shapes (e.g., Hoffman et al. 2010; Droser et al. 2017). Found in over 40 localities around the world, the highly diverse Ediacara biota provide tantalizing insights into life in the ancient ocean.

We also know that the Ediacara biota were strictly benthic; that is, they inhabited the seafloor. There they likely grazed upon, plowed across, dug into, burrowed into, and tunneled under carpets of photosynthetic and sediment-dwelling bacteria known as **microbial mats** (e.g., Buatois et al. 2018; Evans et al. 2019; Bobrovskiy et al. 2022). The plow marks, potholes, trails, scratches, scribbles, spirals, burrows, and tunnels of these activities appear as **trace fossils**—the fossilized marks of animal activities (e.g., Buatois et al. 2018; Evans et al. 2019; Bobrovskiy et al. 2022). Trace fossils lend support to a wide variety of feeding modes and styles, affectionately referred to as mat encrusters, mat scratchers, mat stickers, and undermat miners (Seilacher 1999; Seilacher et al. 2003; Xiao and Laflamme 2009; Darroch et al. 2023).

A kind of organic glue secreted by bacteria and algae trapped sediment particles and created one of the most distinctive features of the Ediacaran world: microbially induced sedimentary structures, or **matgrounds**—surface crusts formed as a result of interactions between microbes and sediments (e.g., Seilacher 1999; Gehling 1999; Buatois et al. 2014). Matgrounds date back to the Archaean eon (e.g., Noffke et al. 2013), but they appear widespread and diverse in the Ediacaran (e.g., Droser et al. 2017). Several common patterns appear in matgrounds, including some that resemble the bumpy texture of an elephant's skin (Gehling et al. 2009). Matground fossils preserve entire communities of organisms, revealing a complex ecology appreciated only recently (e.g., Gehling et al. 2009; Evans et al. 2019; Darroch et al. 2023). It also reveals a kind of ancient tranquility—what has been called the Garden of Ediacara—a time when algae grew, grazers grazed, and few, if any, predators roamed the neighborhood (McMenamin 1986). That would all quickly change. New evidence suggests that the Ediacaran ended with the first major extinction of life in Earth's history (e.g., Darroch et al. 2015; Evans et al. 2022). More would follow in the first period of the next eon of geologic time, the Phanerozoic's Cambrian.

The Phanerozoic (541 million yrs ago to the present)

We now enter more familiar territory. Many of the life-forms of this eon were the ancestors of organisms we find in modern times. Plate tectonics brought us the supercontinent **Pangea**, which formed and then broke apart over an interval from 320 to 195 million years ago (e.g., de Lamotte et al. 2015). The puzzle-like fit of modern continents offers a lingering reminder of Pangea's breakup. While the continents were moving about, Earth's climate swayed between hothouse and icehouse states (e.g., Scotese et al. 2021). The **Tethys Ocean**—which covered 60 percent of our planet during Pangea—experienced dramatic swings in temperature, too. Though tough to pin down, researchers now believe that seawater temperatures during this eon ranged from 10°C to 30°C (e.g, Veizer and Prokoph 2015; Vérard and Veizer 2019). Some interpretations put paleotemperatures above 40°C (e.g., Sun et al. 2012; Grossman and Joachimski 2022). Perhaps most startling (and alarming for modern times) were the five **mass extinctions**—rapid and global decreases in the abundance and diversity of organisms—at various times during this eon (e.g., Bond and Grasby 2017). Truly, you can say it was the best of times and the worst of times.

The **Phanerozoic**—the eon of "visible life"—begins 541 million years ago with the appearance of trace fossils formed by the horizontal burrowing of a worm-like animal named *Treptichnus pedum*, which, roughly translated from Greek, means "can't walk straight." Trep (as we'll call it) exhibits a complex branching type of burrowing never before seen—the first hints of an **infauna**, organisms living within a substrate—as opposed to ones on top of it, an **epifauna** (e.g., Buatois 2017). This small step for burrowing kind places Trep at the beginning of a major expansion in the ecological complexity of life in the ocean (e.g., Xiao and Laflamme 2009; Schiffbauer et al. 2016; Linnemann et al. 2018; Cribb et al. 2019; Mángano and Buatois 2020; Buatois et al. 2020). Because Trep's fossil burrows can be found worldwide, it also makes a very convenient geologic marker for the start of the first geologic period of the Phanerozoic, the **Cambrian** (541–485.4 million years ago; e.g., Foster 2014). While interpretations of the ensuing millions of years have changed (e.g., Valentine 2002; Xiao and LaFlamme 2009; Linnemann et al. 2018; Wood et al. 2019; Bowyer et al. 2022), the Cambrian unleashed an astonishing diversity of new life-forms, what has come to be known as the **Cambrian radiation**, the rapid increase in animal diversity in the Cambrian (e.g., Marshall 2006; Beasecker et al. 2020). A radiation, in this sense, refers to **adaptive radiation**, "the evolution of ecological diversity within a rapidly multiplying lineage" (e.g., Schluter 2000).

Some scientists and the popular media still refer to this period as the Cambrian explosion, but that name has drawn criticism for failing to include a great deal of evolution that occurred before and after the Cambrian. The term "Cambrian explosion" historically refers to the very rapid appearance of animals in the fossil record starting at about 541 million years ago. The originator of the idea, American Earth scientist Preston Cloud (1912–1991), used the term "eruptive evolution" to describe the evolutionary diversification of animals in the period. He wasn't too fond of the term "explosive," noting that the process took millions of years and "probably did not make a loud noise" (Cloud 1948).

We now know that the diversification of animals—their radiation from a common ancestor—began in the late Ediacaran. While abundant and diverse hard-bodied animals mark the fossil record of the Cambrian, they represent one chapter in the evolutionary history of life (e.g., Lyons et al. 2018). As Schiffbauer et al. (2016) put it, "The earliest stages of animal diversification were neither Cambrian nor explosive . . . removed from their morphological and ecological diversification by a long fuse." Indeed, while nearly all major groups (i.e., phyla) of modern animals appear in the fossil record of the Cambrian, the next geologic period, the **Ordovician** (485.4–443.8 million years ago), expanded on that template.

The **Great Ordovician Biodiversity Events**, multiple radiations from the Early to Middle Ordovician (497.05–467.33 million years ago), brought its own "explosive" diversification of life-forms, including planktic (i.e., drifting) and nektic (swimming) forms—the drifters and swimmers, respectively. By the middle of this period, the triad of lifestyles that characterize modern ocean ecosystems would be in place (e.g., Servais et al. 2016; Servais and Harper 2018; Servais et al. 2021). Taken together, the diversification of life from the late Ediacaran to the Middle Ordovician encompasses more than 102 million years, a period that witnessed "the construction of Phanerozoic food webs from their Ediacaran precursors" (e.g., Marshall 2006).

One of the most recognizable features of the Phanerozoic is the appearance of organisms with easily preserved **skeletons**. Though human skeletons are one example, a skeleton is more generally defined as any framework that provides support, shape, or protection to an organism. All organisms—including archaea, bacteria, and single-celled eukaryotes—have skeletons that enable them to hold a shape (e.g., Jones et al. 2001; Ettema et al. 2011; Knoll and Kotrc 2015). The appearance of skeletons in the late Ediacaran to early Cambrian has been called "one of the most momentous events in the history of life" (Vermeij 1989).

The process by which organisms incorporate minerals into their body structures is called **biomineralization**. Most skeletons contain a mixture of minerals and organic materials, but some—such as those of insects—are constructed primarily from proteins (Raven et al. 2020). Marine organisms rely primarily on three different minerals for their skeletons: calcium carbonate, silica, and calcium phosphate. Most modern marine organisms have carbonate skeletons (Kouchinsky et al. 2011; Murdock 2020).

The variety of skeletons mirrors the variety of organisms, though they tend to be similar within a given phylum. A skeleton may appear on the outside of an animal—an **exoskeleton**—or it may be housed inside an animal—an **endoskeleton** (Ruppert et al. 2004). Crustaceans like crabs and lobsters possess a rigid, segmented exoskeleton that serves for protection and aids in locomotion and hunting. Of course, bony fishes and marine mammals feature the bony endoskeletons characteristic of most vertebrates. Some skeletons aren't obvious. The bodies of sponges contain needles of calcium carbonate or silica—known as **spicules**—embedded in a fibrous network of protein called **spongin** (Mason et al. 2020). It's what makes sponges spongy. Cylindrically shaped animals—such as sea anemones, worms, and sea cucumbers—use a **hydrostatic skeleton**, one whose shape is maintained by water pressure, like a flexible garden hose that expands when filled with water. When arthropods undergo **molting**—when the animal sheds its

exoskeleton to grow a larger one—their newly formed soft skeleton acts as a hydrostatic skeleton until it hardens. That makes hydrostatic skeletons the most widely used skeletal form on Earth (Kier 2012).

Despite more than 185 years of study (e.g., Geyer and Landing 2016), the causes of the Cambrian radiation remain uncertain (e.g., Zhuravlev and Wood 2020). While it's tempting to point to a single factor as the driving force behind the diversification of life—dissolved oxygen remains the most popular candidate—in fact, any of a number of abiotic and biotic factors may have contributed to the transformation of life-forms from the late Ediacaran to the Ordovician (e.g., Wood et al. 2019). Increases in oxygenation of the ocean—in time- and space-varying episodes, depending on the location—likely expanded organisms' ability to expend energy in search of food and shelter (e.g., Dahl et al. 2014; Sperling and Stockey 2018; Cole et al. 2022). Changes in seawater chemistry may have altered the biochemistry of organisms' outer shells and allowed experimentation with new body plans (e.g., Peters and Gaines 2012; Wood et al. 2019). Other factors, such as temperature, salinity, nutrient availability, and ocean acidity/alkalinity, certainly exerted their influence, at least on local scales. These abiotic factors may be viewed as setting the stage for a cast of actors: the scene and its set pieces are in place, but the curtain has yet to be drawn, and the play has yet to be improvised.

The appearance of burrowing organisms—even prior to Trep—had the effect of fragmenting and breaking apart the Ediacaran matground. Paleontologists refer to these kinds of activities as **ecosystem engineering**, the restructuring of a habitat through the activities of organisms. A study of trace fossils from Namibia, South Africa, revealed extensive ecosystem engineering underway by the late Ediacaran (e.g., Cribb et al. 2019). Using a kind of geological CT scan to get a three-dimensional look, another group of researchers found extensive and complex tunnels in early Cambrian rocks from Siberia (Marusin and Kuper 2020). These studies provide evidence for **bioturbation**—the disturbance and mixing of sediments by organisms—at the Ediacaran-Cambrian transition. By the middle of the Cambrian, these activities would replace matgrounds with **mixgrounds**, a deep slurry of "soft" seafloor sediments (Dornbos et al. 2005; Buatois et al. 2014; Buatois et al. 2018). This transformation of the seafloor has been called the **agronomic revolution** (e.g., Seilacher 1999; Bottjer et al. 2000). It's the ocean equivalent of plowing on land. Like plowing, the bioturbation of seafloor sediments increased their water content and oxygen concentration, turning a mostly two-dimensional habitat into a three-dimensional one (e.g., Zhang et al. 2017; Mángano and Buatois 2020). The physical transformation of the seafloor also established an exchange of energy, matter, and dissolved nutrients between the benthos and overlying water column, an ecological interaction referred to as **benthic–pelagic coupling**. In coastal and estuarine environments—where surface waters mix downward and come into contact with the seafloor—benthic-pelagic coupling contributes to some of the highest rates of productivity in the world ocean (e.g., Griffiths et al. 2017).

The expansion of habitats brought a new stage for improvisation and innovation (e.g., Payne et al. 2020). By strengthening their skeletons, organisms were able to move into and defend new territories, a kind of Cambrian gold rush. For immobile organisms, competition for space meant staking out your territory—erecting barriers or developing antagonistic behaviors—to avoid being pushed out. Competition for food meant exploiting food sources higher in the water column or deeper in the sediments. Competition fueled evolution of bodies and behaviors that made you smarter, stronger, or faster than your competitor. Still, some actors went right for the throat—literally—as making a living by eating your neighbors became a thing. The Ediacaran-Cambrian transition saw the evolution of **carnivory**—the eating of one animal by another (e.g., Fox 2016). Unprotected soft-bodied organisms were probably helpless against predators. Underdeveloped sensory systems would have made detection of predators difficult. Limited mobility and defenses would have made the Ediacara biota as helpless as the inhabitants of Westeros against the Night King and his White Walkers (Benioff and Weiss 2011–2019). In other words, they didn't have a chance. On the other hand, if you saw *My Octopus Teacher* (Ehrlich and Reed 2020), you'll remember the octopus that covered itself with shells when confronted by a potentially deadly shark. So behaviors to thwart predators kept soft-bodied animals in the game.

These biotic factors may not have triggered the rapid diversification of organisms, but they soon became a major part of it. An **evolutionary arms race**—the diversification of anatomies, physiologies, and behaviors to better survive—led to many of the biological novelties that appeared in the Cambrian and beyond (e.g., Bengston 2002; Wood and Zhuravlev 2012; Payne et al. 2020; Murdock 2020). Reefs were formed. Tentacles, tube feet, and jet propulsion were invented. Drills, claws, teeth, and toxins came onto the scene. Fish moved into every nook and cranny and hightailed it across the depths. Large reptiles roamed the ocean for a while, then perished. Indeed, no less than five mass extinctions occurred between 440 and 65 million years ago. Climate change, ocean acidification, and changes in sea level, as well as meteorite impacts and massive volcanic eruptions wrote their own chapters in the history of life. Of course, life crept into terrestrial habitats as well. At least one branch of that life returned to the ocean, including the lineage that produced the largest animal to ever inhabit the planet—the blue whale. And lest we get swept up in the

Disney parade of visible life-forms, we should not forget for a moment that none of this would have been possible had not invisible microbes created the atmosphere and biogeochemical cycles which sustain this life.

These early events in the history of life provide a better perspective of life in the modern ocean and offer a convenient baseline from which to judge the effects of human activities on the Earth system.

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15.5: Life and Earth as One?

By way of offering a theme to these pages, I'd like to draw inspiration from an uncharacteristic and outspoken scientist, English scientist James Lovelock (1919–2022). In the 1970s, Lovelock wrote a very controversial book called *Gaia: A New Look at Life on Earth* (Lovelock 1979). The book offered a speculative extension of work he started with NASA in the 1960s, in which he proposed that if a planet's atmosphere was out of chemical equilibrium, then it probably harbored life. By his analysis, life was not present on Mars because its atmosphere appeared to be in a state of equilibrium (Lovelock 1965). His *Gaia* book took things a bit further—too far for some scientists at the time. Lovelock presented circumstantial evidence that life didn't just inhabit Earth, but that Earth itself was a living organism. He called this idea the **Gaia Hypothesis**. In later years—and admitting that this first work was "poetic"—Lovelock modified the Gaia Hypothesis to state that the evolution of life and Earth's environment occurred "as a single, tightly coupled process, with the self-regulation of climate and chemistry as an emergent property" (1989).

This coevolution of life and Earth's environment forms the basis of a relatively new field of study known as **geobiology**, the study of life's interactions with the Earth and their evolution over geologic time. Lovelock calls it geophysiology, but they are essentially the same thing. At the heart of geobiology are the ways in which life has shaped Earth and vice versa. Much of what we have talked about in this chapter falls under the heading of geobiology. In the introduction to their textbook *Fundamentals of Geobiology*, Knoll and coauthors (2012) credit Lovelock's Gaia Hypothesis for grabbing "the attention of a broad scientific community." While the "strong" version of Gaia—that life regulates Earth for its own survival—receives less scientific support, there is now support for and attention given to the significant role of organisms in regulating at least some aspects of the Earth system. Of course, having read this book this far, you already know that.

Lovelock's Gaia Hypothesis provided a focal point for Earth systems science—the study of the interactions of the spheres introduced in Chapter 1—and brought greater attention to interdisciplinary studies of the Earth system as a whole. Of course, there is no greater need for this approach than today, as we increasingly recognize the negative impacts of human activities on the biosphere. Lovelock was vocal about climate change, too, but that is a story for another chapter.

Hopefully, this sweeping and admittedly imperfect summary of the history of life and our planet has provided a thoughtful perspective for understanding the world ocean and the organisms that inhabit it. We are products of our history—descendants of a drama in progress, if you will—the story of life on Earth. Next time you're roaming around the neighborhood, camping in the woods, rock-climbing in the desert, or visiting the tidepools, take a moment to consider the life-forms that surround you. You're here because they're here. To borrow a quote from a famous American poet, "And that has made all the difference" (Frost 1923; first published 1916).

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15.6: Chapter References

Allwood, Abigail C., Minik T. Rosing, David T. Flannery, Joel A. Hurowitz, and Christophere M. Heirwegh. 2018. "Reassessing Evidence of Life in 3,700-Million-Year-Old Rocks of Greenland." *Nature* 563: 241–244. https://doi.org/10.1038/s41586-018-0610-4

Bajpai, Sunil, and Philip D. Ginerich. 1998. "A New Eocene Archaeocete (Mammalia, Cetacea) from India and the Time of Origin of Whales." *PNAS* 95(26): 15464–15486. https://doi.org/10.1073/pnas.95.26.15464

Baumgartner, Raphael J., Martin J. Van Kranendonk, David Wacey, Marco L. Fiorentini, Martin Saunders, Stefano Cruso, Anais Pages, Martin Homann, and Paul Guagliardo. 2019. "Nano−Porous Pyrite and Organic Matter in 3.5-Billion-Year-Old Stromatolites Record Primordial Life." *Geology* 47(11): 1039–1043. https://doi.org/10.1130/G46365.1

Beasecker, Jacob, Zach Chamberlin, Nicole Lane, Katie Reynolds, Jack Stack, Kailey Wahrer, Abigail Wilff, Jo Devilbiss, Corey Wahr, Dan Durbin, Hannah Garneau, and Danita Brandt. 2020. "It's Time to Defuse the Cambrian 'Explosion.'" *GSA Today* 30(12) 26–27. https://doi.org/10.1130/GSATG460GW.1

Bell, E., and J. Gosline. 1996. "Mechanical Design of Mussel Byssus: Material Yield Enhances Attachment Strength." *Journal of Experimental Biology* 199(4): 1005–1017. https://doi.org/10.1242/jeb.199.4.1005

Bengtson, Stefan. 2002. "Origins and Early Evolution of Predation." *Paleontological Society Papers* 8: pp 289–318. https://doi.org/10.1017/S1089332600001133

Bengtson, Stefan, Therese Sallstedt, Veneta Belivanova, and Martin Whitehouse. 2017. "Three-Dimensional Preservation of Cellular and Subcellular Structures Suggests 1.6 Billion-Year-Old Crown-Group Red Algae." *PLOS Biology* 15(3): e2000735. https://doi.org/10.1371/journal.pbio.2000735

Benioff, David, and D. B. Weiss. 2011–2019. *Game of Thrones*. HBO Entertainment. Television series.

Betts, Holly C., Mark N. Puttick, James W. Clark, Tom A. Williams, Philip C. J. Donoghue, and Davide Pisani. 2018. "Integrated Genomic and Fossil Evidence Illuminates Life's Early Evolution and Eukaryote Origin." *Nature Ecology and Evolution* 2: 1556–1562. https://doi.org/10.1038/s41559-018-0644-x

Bhullar, Bhart-Anjan S., Jesús Marugán-Lobón, Fernando Racimo, Gabe S. Bever, Timothy B. Rowe, Mark A. Norell, and Arhat Abzhanov. 2012. "Birds Have Paedomorphic Dinosaur Skulls." *Nature* 487: 223–226. https://doi.org/10.1038/nature11146

Bobrovskiy, Ilya, Alexey Nagovitsyn, Janet M. Hope, Ekaterina Luzhnaya, and Jochen J. Brocks. 2022. "Guts, Gut Contents, and Feeding Strategies of Ediacaran Animals." *Current Biology* 32(24): 5382–5389. https://doi.org/10.1016/j.cub.2022.10.051

Bond, David P. G., and Stephen E. Grasby. 2017. "On the Causes of Mass Extinctions." *Paleogeography, Paleoclimatology, and Paleoecology* 478: 3–29. https://doi.org/10.1016/j.palaeo.2016.11.005

Bottjer, David J., James W. Hagadorn, and Stephen Q. Dornbos. 2000. "The Cambrian Substrate Revolution." *GSA Today* 10: 1–6. https://www.researchgate.net/publication/229535050_The_Cambrian_Substrate_Revolution

Bowyer, Fred T., Andrey Yu Zhuravlev, Rachel Wood, Graham A. Shields, Ying Zhou, Andrew Curtis, Simon W. Poulton, Daniel J. Condon, Chuan Yang, and Maoyan Zhu. 2022. "Calibrating the Temporal and Spatial Dynamics of the Ediacaran–Cambrian Radiation of Animals." *Earth-Science Reviews* 225: 103913. https://doi.org/10.1016/j.earscirev.2021.103913

Brocks, Jochen J., Amber J. M. Jarrett, Eva Sirantoine, Christian Hallman, Yosuke Hoshino, and Tharika Liyanage. 2017. "The Rise of Algae in Cryogenian Oceans and the Emergence of Animals." *Nature* 548: 578–581. https://doi.org/10.1038/nature23457

Brown, Michael, Tim Johnson, and Nicholas J. Gardiner. 2020. "Plate Tectonics and the Archean Earth." *Annual Review of Earth and Planetary Sciences* 48: 291–320. https://doi.org/10.1146/annurev-earth-081619-052705

Brunk, Clifford F., and William F. Martin. 2019. "Archaeal Histone Contributions to the Origin of Eukaryotes." *Trends in Microbiology* 27(8): 703–714. https://doi.org/10.1016/j.tim.2019.04.002

Buatois, Luis A., John Almond, M. Gabriela Mángano, Söen Jensen, and Gerard J. B. Germs. 2018. "Sediment Disturbance by Ediacaran Bulldozers and the Roots of the Cambrian Explosion." *Scientific Reports* 8: 4514. https://doi.org/10.1038/s41598-018-

22859-9

Buatois, Luis A., M. Gabriela Mángano, Nicholas J. Minter, Kai Zhou, Max Wisshak, Mark A. Wilson, and Ricardo A. Olea. 2020. "Quantifying Ecospace Utilization and Ecosystem Engineering during the Early Phanerozoic—The Role of Bioturbation and Bioerosion." *Science Advances* 6(33): eabb0618. https://doi.org/10.1126/sciadv.abb0618

Buatois, Luis A., Guy N. Narbonne, M. Ganriela Mángano, Noelia B. Carmona, and Paul Myrow. 2014. "Ediacaran Matground Ecology Persisted into the Earliest Cambrian." *Nature Communications* 5: 3544. https://doi.org/10.1038/ncomms4544

Buatois, Luis A., Max Wisshak, Mark A. Wilson, and M. Gabriela Mángano. 2017. "Categories of Architectural Designs in Trace Fossils: A Measure of Ichnodisparity." *Earth-Science Reviews* 164: 102–181. https://doi.org/10.1016/j.earscirev.2016.08.009

Bykova, Natalia, Steven T. LoDuca, Qin Ye, Vasiliy Marusin, Dmitriy Grazhdankin, and Shuhai Xiao. 2020. "Seaweeds through Time: Morphological and Ecological Analysis of Proterozoic and Early Paleozoic Benthic Macroalgae." *Precambrian Research* 350: 105875. https://doi.org/10.1016/j.precamres.2020.105875

Cartwright, J. A., K. V. Hodges, and M. Wadhwa. 2022. "Evidence against a Late Heavy Bombardment Event on Vesta." *Earth and Planetary Science Letters* 590: 117576. https://doi.org/10.1016/j.epsl.2022.117576

Castelle, Cindy J., and Jillian F. Banfield. 2018. "Major New Microbial Groups Expand Diversity and Alter Our Understanding of the Tree of Life." *Cell* 172(6): 1181–1197. https://doi.org/10.1016/j.cell.2018.02.016

Catling, David C., and Kevin J. Zahnle. 2020. "The Archean Atmosphere." *Science Advances* 6(9): eaax1420. https://doi.org/10.1126/sciadv.aax1420

Charnay, Benjamin, Eric T. Wolf, Bernard Marty, and Françis Forget. 2020. "Is the Faint Young Sun Problem for Earth Solved?" *Space Science Reviews* 216: 90. https://doi.org/10.1007/s11214-020-00711-9

Clarke, Arthur. 1960. *The Challenge of the Sea*. New York: Holt Rinehart & Winston. https://archive.org/details/challengeofsea00arth

Cloud, Preston E., Jr. 1948. "Some Problems and Patterns of Evolution Exemplified by Fossil Invertebrates." *Evolution* 2(4): 322–350. https://doi.org/10.1111/j.1558-5646.1948.tb02750.x

Cole, Devon B., Daniel B. Mills, Douglas H. Erwin, Erik A. Sperling, Susannah M. Porter, Christopher T. Reinhard, and Noah J. Planavsky. 2020. "On the Co-Evolution of Surface Oxygen Levels and Animals." *Geobiology* 18(3): 260–281. https://doi.org/10.1111/gbi.12382

Cole, Devon B., Kazumi Ozaki, and Christopher Reinhard. 2022. "Atmospheric Oxygen Abundance, Marine Nutrient Availability, and Organic Carbon Fluxes to the Seafloor." *Global Biogeochemical Cycles* 36(1): e2021GB007052. https://doi.org/10.1029/2021GB007052

Coleman, Gareth A., Adrián A. Davín, Tara A. Mahendrarajah, Lénárd L. Szánthó, Anja Spang, Philip Hugenholtz, Gergely J. Szöllősi, and Tom A. Williams. 2021. "A Rooted Phylogeny Resolves Early Bacterial Evolution." *Science* 372(6542): eabe0511. https://doi.org/10.1126/science.abe0511

Crapitto, Andrew J., Amy Campbell, A. J. Harris, and Aaron D. Goldman. 2022. "A Consensus View of the Proteome of the Last Universal Common Ancestor." *Ecology and Evolution* 12(6): e8930. https://doi.org/10.1002/ece3.8930

Cribb, Alison, Charlotte G. Kenchington, Bryce Koester, Brandt M. Gibson, Thomas H. Boag, Rachel A. Racicot, Helke Mocke, Marc Laflamme, and Simon A. F. Darroch. 2019. "Increase in Metazoan Ecosystem Engineering Prior to the Ediacaran–Cambrian Boundary in the Nama Group, Namibia." *Royal Society Open Science* 6(9): 190548. https://doi.org/10.1098/rsos.190548

Da Cunha, Violette, Morgan Gaïa, and Patrick Forterre. 2022. "The Expanding Asgard Archaea and Their Elusive Relationships with Eukarya." *MLife* 1(1): 3–12. https://doi.org/10.1002/mlf2.12012

Dahl, Tais W., Richard A. Boyle, Donald E. Canfield, James N. Connelly, Benjamin C. Gill, Timothy M. Lenton, and Martin Bizzarro. 2014. "Uranium Isotopes Distinguish Two Geochemically Distinct Stages during the Later Cambrian SPICE Event." *Earth and Planetary Science Letters* 401(1): 313–326. https://doi.org/10.1016/j.epsl.2014.05.043

Darroch, Simon A. F., Susana Gutarra, Hale Masaki, Andrei Olaru, Brandt M. Gibson, Frances S. Dunn, Emily G. Mitchell, Rachel A. Racicot, Gregory Burzynski, and Imran A. Rahman. 2023. "The Rangeomorph *Pectinifrons abyssalis*: Hydrodynamic Function at the Dawn of Animal Life." *iScience* 26(2): 105989.

Darroch, Simon A. F., Emily F. Smith, Marc Laflamme, and Douglas H. Erwin. 2018. "Ediacaran Extinction and Cambrian Explosion." *Trends in Ecology and Evolution* 33(9): 653–663. https://doi.org/10.1016/j.tree.2018.06.003

Darroch, Simon A. F., Erik A. Sperling, Thomas H. Boag, Rachel A. Raciot, Sara J. Mason, Alex S. Morgan, Sarah Tweedt, Paul Myrow, David T. Johnson, Douglas H. Erwin, and Marc Laflamme. 2015. "Biotic Replacement and Mass Extinction of the Ediacara Biota." *Proceedings of the Royal Society B* 282(1814): 20151003. https://doi.org/10.1098/rspb.2015.1003

Darwin, Charles. 1860. *The Origin of Species*. London: John Murray. https://archive.org/details/in.ernet.dli.2015.222367

de Lamotte, Dominique Frizon, Brendan Fourdan, Sophie Leleu, François Leparmentier, and Philippe de Clarens. 2015. "Style of Rifting and the Stages of Pangea Breakup**."** *Tectonics* 34(5): 1009–1029. https://doi.org/10.1002/2014TC003760

Delarue, Frédéric, François Robert, Sylvie Derenne, Romain Tartèse, Clément Jauvion, Sylvain Bernard, Sylvain Pont, Adriana Gonzalez-Cano, Rémi Duhamel, and Kenichiro Sugitani. 2020. "Out of Rock: A New Look at the Morphological and Geochemical Preservation of Microfossils from the 3.46 Gyr-old Strelley Pool Formation." *Precambrian Research* 336: 105472. https://doi.org/10.1016/j.precamres.2019.105472

Di Giulio, Massimo. 2018. "On Earth, There Would be a Number of Fundamental Kinds of Primary Cells—Cellular Domains—Greater than or Equal to Four." *Journal of Theoretical Biology* 443: 10–17. https://doi.org/10.1016/j.jtbi.2018.01.025

Doolittle, W. Ford. 1999. "Phylogenetic Classification and the Universal Tree." *Science* 284(5423): 2124–2128. https://doi.org/10.1126/science.284.5423.2124

———. 2014. "How Natural a Kind Is 'Eukaryote?'" *Cold Spring Harbor Perspectives in Biology* 6(6): a015974. https://doi.org/10.1101%2Fcshperspect.a015974

———. 2020. "Evolution: Two Domains of Life or Three?" *Current Biology* 30(4): R177–R179. https://doi.org/10.1016/j.cub.2020.01.010

Dornbos, Stephen Q., David J. Bottjer, and Jun-Yuan Chen. 2005. "Paleoecology of Benthic Metazoans in the Early Cambrian Maotianshan Shale Biota and the Middle Cambrian Burgess Shale Biota: Evidence for the Cambrian Substrate Revolution." *Paleogeography, Paleoclimatology, and Paleoecology* 220(1–2): 47–67. https://doi.org/10.1016/j.palaeo.2003.11.016

Dr. Biology. 2017. "If Birds Evolved from Dinosaurs, Would That Make Them Reptiles Too?" Arizona State University—Ask a Biologist. May 12, 2017. https://askabiologist.asu.edu/questions/birds-dinosaurs-reptiles

Droser, Mary L., Lidya G. Tarhan, and James G. Gehling. 2017. "The Rise of Animals in a Changing Environment: Global Ecological Innovation in the Late Ediacaran." *Annual Review of Earth and Planetary Sciences* 45: 593–617. https://doi.org/10.1146/annurev-earth-063016-015645

Ehrlich, Pippa, and James Reed. 2020. *My Octopus Teacher*. Off the Fence and The Sea Change Project. Digital film. 85 minutes. https://www.imdb.com/title/tt12888462/

Ettema, Thijs J. G., Ann-Christin Lindås, and Rolf Bernander. 2011. "An Actin-Based Cytoskeleton in Archaea." *Molecular Microbiology* 80(4): 1052–1061. https://doi.org/10.1111/j.1365-2958.2011.07635.x

Evans, Scott D., James G. Gehling, and Mary L. Droser. 2019. "Slime Travelers: Early Evidence of Animal Mobility and Feeding in an Organic Mat World." *Geobiology* 17(5): 490–509. https://doi.org/10.1111/gbi.12351

Evans, Scott D., Chenyi Tu, Adriana Rizzo, Rachel L. Surprenant, Phillip C. Boan, Heather McCandless, Nathan Marshall, Shuhai Xiao, and Mary L. Droser. 2022. "Environmental Drivers of the First Major Animal Extinction across the Ediacaran White Sea-Nama Transition." *PNAS* 119(46): e2207475119. https://doi.org/10.1073/pnas.2207475119

Fordyce, E., and W. F. Perrin. 2023. "About the World Cetacea Database." The World Cetacea Database. Accessed February 3, 2023. https://www.marinespecies.org/cetacea/index.php

Forterre, Patrick. 2005. “The Two Ages of the RNA World, and the Transition to the DNA World: A Story of Viruses and Cells.” *Biochimie* 87(9–10): 793–803. https://doi.org/10.1016/j.biochi.2005.03.015

Foster, John. 2014. *Cambrian Ocean World: Ancient Sea Life of North America*. Bloomington: Indiana University Press. https://iupress.org/9780253011824/cambrian-ocean-world/

Fournier, G. P., K. R. Moore, L. T. Rangel, J. G. Payette, L. Momper, and T. Bosak. 2021. “The Archean Origin of Oxygenic Photosynthesis and Extant Cyanobacterial Lineages.” *Proceedings of the Royal Society B* 288(1959): 20210675. https://doi.org/10.1098/rspb.2021.0675

Fox, Douglas. 2016. “What Sparked the Cambrian Explosion?” *Nature* 530: 268–270. https://doi.org/10.1038/530268a

Fox, G. E., E. Stackebrandt, R. B. Hespell, J. Gibson, J. Maniloff, T. A. Dyer, R. S. Wolfe, W. W. Balch, R. S. Tanner, L. J. Magrum, L. B. Zablen, R. Blakemore, R. Gupta, L. Bonen, B. J. Lewis, D. A. Stahl, K. R. Luehrsen, K. N. Chen, and C. R. Woese. 1980. “The Phylogeny of Prokaryotes.” *Science* 209(4455): 457-463. https://doi.org/10.1126/science.6771870

Frost, Robert. 1923. “The Road Not Taken.” In *Selected Poems by Robert Frost*. New York: Henry Holt and Company. https://www.gutenberg.org/files/59824/59824-h/59824-h.htm

Gazitúa, M. Consuelo, Dean R. Vik, Simon Roux, Ann C. Gregory, Benjamin Bolduc, Brittany Widner, Margaret R. Mulholland, Steven J. Hallam, Osvaldo Ulloa, and Matthew B. Sullivan. 2020. “Potential Virus-Mediated Nitrogen Cycling in Oxygen-Depleted Oceanic Waters.” *ISME Journal* 15: 981–998. https://doi.org/10.1038/s41396-020-00825-6

Gehling, James G. 1999. “Microbial Mats in Terminal Proterozoic Siliciclastics; Ediacaran Death Masks.” *Palaios* 14(1): 40–57. https://doi.org/10.2307/3515360

Gehling, James G., and Mary L. Droser. 2009. “Textured Organic Surfaces Associated with the Ediacara Biota in South Australia.” *Earth-Science Reviews* 96(3): 196–206. https://doi.org/10.1016/j.earscirev.2009.03.002

Geyer, Gerd, and Ed Landing. 2017. “The Precambrian–Phanerozoic and Ediacaran–Cambrian Boundaries: A Historical Approach to a Dilemma.” In *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Special Publications 448. Edited by A. T. Brasier, D. McIlroy, and N. McLoughlin, 311–349. London: Geological Society. http://doi.org/10.1144/SP448.10

Gould, Stephen Jay. 1996. “Planet of the Bacteria.” *Washington Post*. November 13, 1996. https://www.washingtonpost.com/archive/1996/11/13/planet-of-the-bacteria/6fb60f1d-e6fe-471e-8a0f-4cfa9373772c/

Greening, Chris, and Trevor Lithgow. 2020. “Formation and Function of Bacterial Organelles.” *Nature Reviews Microbiology* 18: 677–689. https://doi.org/10.1038/s41579-020-0413-0

Griffiths, Jennifer R., Martina Kadin, Francisco J. A. Nascimento, Tobias Tamelander, Anna Törnroos, Stefano Bonaglia, Erik Bonsdorff, Volker Brüchert, Anna Gårdmark, Marie Järnström, Jonne Kotta, Martin Lindegren, Marie C. Nordström, Alf Norkko, Jens Olsson, Benjamin Weigel, Ramunas Žydelis, Thorsten Blenckner, Susa Niiranen, and Monika Winder. 2017. “The Importance of Benthic–Pelagic Coupling for Marine Ecosystem Functioning in a Changing World.” *Global Change Biology* 23(6): 2179–2196. https://doi.org/10.1111/gcb.13642

Grossman, Ethan L., and Michael M. Joachimski. 2022. “Ocean Temperatures Through the Phanerozoic Reassessed.” *Scientific Reports* 12: 8938. https://doi.org/10.1038/s41598-022-11493-1

Gumsley, Ashley P., Kevin R. Chamberlain, Wouter Bleeker, Ulf Söderland, Michiel O. de Kock, Emilie R. Larsson, and Andrey Bekker. 2017. “Timing and Tempo of the Great Oxidation Event.” *PNAS* 114(8): 1811–1816. https://doi.org/10.1073/pnas.1608824114

Harris, Hugh M. B., and Colin Hill. 2021. “A Place for Viruses on the Tree of Life.” *Frontiers in Microbiology* 11: 604048. https://doi.org/10.3389/fmicb.2020.604048

Harrison, T. Mark. 2020. *Hadean Earth*. Cham: Springer. https://doi.org/10.1007/978-3-030-46687-9

Havig, Jeff R., Trinity L. Hamilton, Aviv Bachan, and Lee R. Kump. 2017. “Sulfur and Carbon Isotopic Evidence for Metabolic Pathway Evolution and a Four-Stepped Earth System Progression across the Archean and Paleoproterozoic.” *Earth-Science Reviews* 174: 1–21. https://doi.org/10.1016/j.earscirev.2017.06.014

Heller, René, Jan-Peter Duda, Max Winkler, Joachim Reitner, and Laurent Gizon. 2021. "Habitability of the Early Earth: Liquid Water under a Faint Young Sun Facilitated by Strong Tidal Heating Due to a Closer Moon." *PalZ* 95: 563–575. https://doi.org/10.1007/s12542-021-00582-7

Hirt, Natasha. 2017. "Hippos and Whales: Unlikely Cousins." Royal Ontario Museum. August 24, 2017. https://www.rom.on.ca/en/blog/hippos-and-whales-unlikely-cousins

Hoffman, Hans J., and Eric W. Mountjoy. 2010. "Ediacaran Body and Trace Fossils in Miette Group (Windermere Supergroup) near Salient Mountain, British Columbia, Canada." *Canadian Journal of Earth Sciences* 47(10): 1305–1325. https://doi.org/10.1139/E10-070

Hoffman, Paul F., Dorian S. Abbot, Yosef Ashkenazy, Douglas I. Benn, Jochen J. Brocks, Phoebe A. Cohen, Grant M. Cox, Jessica R. Creveling, Yannick Donnadieu, Douglas H. Erwin, Ian J. Fairchild, David Ferreira, Jason C. Goodman, Galen P. Halverson, Malte F. Jansen, Guillaume Le Hir, Gordon D. Love, Francis A. MacDonald, Adam C. Maloof, Camille A. Partin, Gilles Ramstein, Brian J. Rose, Catherine V. Rose, Peter M. Sadler, Eli Tziperman, Aiko Voigt, and Stephen G. Warren. 2017. "Snowball Earth Climate Dynamics and Cryogenian Geology-Geobiology." *Science Advances* 3(11): e1600983. https://doi.org/10.1126/sciadv.1600983

Hoffman, Paul F., Alan J. Kaufman, Galen P. Halverson, and Daniel P. Schrag. 1998. "A Neoporterozpoic Snowball Earth." *Science* 281(5381): 1342–1346. https://doi.org/10.1126/science.281.5381.1342

Holland, Heinrich D. 2006. "The Oxygenation of the Atmosphere and Oceans." *Philosophical Transactions of the Royal Society B* 361(1470): 903–915. https://doi.org/10.1098/rstb.2006.1838

Hug, Laura A., Brett J. Baker, Karthik Anantharaman, Christopher T. Brown, Alexander J. Probst, Cindy J. Castelle, Cristina N. Butterfield, Alex W. Hernsdorf, Yuki Amano, Kotaro Ise, Yohey Suzuki, Natasha Dudek, David A. Relman, Kari M. Finstad, Ronald Amundson, Brian C. Thomas, and Jillian F. Banfield. 2016. "A New View of the Tree of Life." *Nature Microbiology* 1: 16048. https://doi.org/10.1038/nmicrobiol.2016.48

Illinois IGB. 2013. "Carl R. Woese: 1928–2012." Illinois Institute for Genomic Biology (IGB). January 15, 2013. https://www.igb.illinois.edu/article/carl-r-woese-1928-%E2%80%93-2012

Jabłońska, Jagoda, and Dan. S. Tawfik. 2021. "The Evolution of Oxygen-Utilizing Enzymes Suggests Early Biosphere Oxygenation." *Nature Ecology and Evolution* 5: 442–448. https://doi.org/10.1038/s41559-020-01386-9

Javaux, Emmanuelle J., and Kevin Lepot. 2018. "The Paleoproterozoic Fossil Record: Implications for the Evolution of the Biosphere during Earth's Middle-Age." *Earth-Science Reviews* 176:68–86. https://doi.org/10.1016/j.earscirev.2017.10.001

Jogler, Christian. 2014. "The Bacterial 'Mitochondrium.'" *Molecular Microbiology* 94(4): 751–755. https://doi.org/10.1111/mmi.12814

Johnson, Kevin W., and Boswell A. Wing. 2020. "Limited Archaean Continental Emergence Reflected in an Early Archaean ^{18}O-Enriched Ocean." *Nature Geoscience* 13: 243–248. https://doi.org/10.1038/s41561-020-0538-9

Jones, Laura J. F., Rut Carballido-López, and Jeffery Errington. 2001. "Control of Cell Shape in Bacteria: Helical, Actin-like Filaments in *Bacillus subtilis*." *Cell* 104(6): 913–922. https://doi.org/10.1016/S0092-8674(01)00287-2

Keller, Markus A., Alexandra V. Turchyn, and Markus Ralser. 2014. "Non-Enzymatic Glycolysis and Pentose Phosphate Pathway-Like Reactions in a Plausible Archean Ocean." *Molecular Systems Biology* 10: 725. https://doi.org/10.1002/msb.20145228

Khanna, Kanika, and Elizabeth Villa. 2022. "Revealing Bacterial Cell Biology Using Cryo-Electron Tomography." *Current Opinion in Structural Biology* 75: 102419. https://doi.org/10.1016/j.sbi.2022.102419

Kier, William M. 2012. "The Diversity of Hydrostatic Skeletons." *Journal of Experimental Biology* 215(8): 1247–1257. https://doi.org/10.1242/jeb.056549

Kirschvink, Joseph L. 1992. "A Paleogeographic Model for Vendian and Cambrian Time." In *The Proterozoic Biosphere: A Multidisciplinary Study*. Edited by J. William Schopf and Cornekis Klein, 567–582. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511601064.014

Knoll, Andrew H., Kristin D. Bergmann, and Justin V. Strauss. 2016. “Life: The First Two Billion Years.” *Philosophical Transactions of the Royal Society B* 371(1707): 2015049. https://doi.org/10.1098/rstb.2015.0493

Knoll, Andrew H., Donald E.Canfield, and Kurt O. Konhauser. 2012. “What Is Geobiology?” In *Fundamentals of Geobiology*. Edited by Andrew H. Knoll, Donald E.Canfield, and Kurt O. Konhauser, 1–4. Hoboken: Blackwell Publishing. https://doi.org/10.1002/9781118280874.ch1

Knoll, Andrew H., and Benjamin Kotrc. 2015. “Protistan Skeletons: A Geologic History of Evolution and Constraint.” In *Evolution of Lightweight Structures*. Edited by Christian Hamm, 1–16. Dordrecht: Springer. https://doi.org/10.1007/978-94-017-9398-8_1

Knoll, Andrew H., and Martin A. Nowak. 2017. “The Timetable of Evolution.” *Science Advances* 3(5): e1603076. https://doi.org/10.1126/sciadv.1603076

Koonin, Eugene V. 2010. “The Two Empires and Three Domains of Life in the Postgenomic Age.” *Nature Education* 3(9): 27. https://www.nature.com/scitable/topicpage/the-two-empires-and-three-domains-of-14432998/

Kouchinsky, Artem, Stefan Bengston, Bruce Runnegar, Christian Skovsted, Michael Steiner, and Michael Vendrasco. 2011. “Chronology of Early Cambrian Biomineralization.” *Geological Magazine* 149(2): 221–251. https://doi.org/10.1017/S0016756811000720

Lennon, Jay T., and Kenneth J. Locey. 2020. “More Support for Earth’s Massive Microbiome.” *Biology Direct* 15: 5. https://doi.org/10.1186/s13062-020-00261-8

Lepot, Kevin. 2020. “Signatures of Early Microbial Life from the Archean (4 to 2.5 Ga) Eon.” *Earth-Science Reviews* 209: 103296. https://doi.org/10.1016/j.earscirev.2020.103296

Li, Yuanning, Xing-Xing Shen, Benjamin Evans, Casey W. Dunn, and Antonis Rokas. 2021. “Rooting the Animal Tree of Life.” *Molecular Biology and Evolution* 38(10): 4322–4333. https://doi.org/10.1093/molbev/msab170

Linnemann, Ulf, Maria Ovtcharova, Urs Schaltegger, Andreas Gärtner, Michael Hautmann, Gerd Geyer, Patricia Vickers-Rich, Tom Rich, Birgit Plessen, Mandy Hofmann, Johannes Zieger, Rita Krause, Les Kriesfeld, and Jeff Smith. 2018. “New High-Resolution Age Data from the Ediacaran–Cambrian Boundary Indicate Rapid, Ecologically Driven Onset of the Cambrian Explosion.” *Terra Nova* 31(1): 49–58. https://doi.org/10.1111/ter.12368

Lipscomb, Diana. 1998. *Basics of Cladistic Analysis*. Washington, DC: George Washington University. https://www2.gwu.edu/~clade/faculty/lipscomb/Cladistics.pdf

Liu, Yang, Kira S. Makarova, Wen-Cong Huang, Yuri I. Wolf, Anastasia N. Nikolskaya, Xinxu Zhang, Mingwei Cai, Cui-Jing Zhang, Wei Xu, Zhuhua Luo, Lei Cheng, Eugene V. Koonin, and Meng Li. 2021. “Expanded Diversity of Asgard Archaea and Their Relationships with Eukaryotes.” *Nature* 593: 553–557. https://doi.org/10.1038/s41586-021-03494-3

López-García, Purificación, and David Moreira. 2020. “Cultured Asgard Archaea Shed Light on Eukaryogenesis.” *Cell* 181(2): 232–235. https://doi.org/10.1016/j.cell.2020.03.058

Louca, Stilianos, Florent Mazal, Michael Doebeli, and Laura Wegener Parfrey. 2019. “A Census-Based Estimate of Earth’s Bacterial and Archaeal Diversity.” *PLoS Biology* 17(2): e3000106. https://doi.org/10.1371/journal.pbio.3000106

Lovelock, James A. 1965. “A Physical Basis for Life Detection Experiments.” *Nature* 207: 568–570. https://doi.org/10.1038/207568a0 See also http://www.jameslovelock.org/a-physical-basis-for-life-detection-experiments/

———. 1979. *Gaia: A New Look at Life on Earth*. Oxford: Oxford University Press. https://global.oup.com/academic/product/gaia-9780198784883

———. 1989. “Geophysiology, the Science of Gaia.” *Reviews of Geophysics* 27(2): 215–222. https://doi.org/10.1029/RG027i002p00215 See also http://www.jameslovelock.org/geophysiology-the-science-of-gaia/

Luehrsen, Kenneth R. 2014. “Remembering Carl Woese.” *RNA Biology* 11(3): 217–219. https://doi.org/10.4161/rna.27800

Lyons, Timothy W., Mary L. Droser, Kimberly V. Lau, and Sussanah M. Porter. 2018. “Early Earth and the Rise of Complex Life.” *Emerging Topics in Life Sciences* 2(2): 121–124. https://doi.org/10.1042/ETLS20180093

Mahajan, Mayank, Benjamin Yee, Emil Hägglund, Lionel Guy, John A. Fuerst, and Siv G. E. Andersson. 2020. "Paralogization and New Protein Architectures in Planctomycetes Bacteria with Complex Cell Structures." *Molecular Biology and Evolution* 37(4): 1020–1040. https://doi.org/10.1093/molbev/msz287

Mángano, M. Gabriela, and Luis A. Buatois. 2020. "The Rise and Early Evolution of Animals: Where Do We Stand from a Trace-Fossil Perspective?" *Interface Focus* 10(4): 20190103. https://doi.org/10.1098/rsfs.2019.0103

Mann, Adam. 2018. "Bashing Holes in the Tale of Earth's Troubled Youth." *Nature* 553: 393–395. https://doi.org/10.1038/d41586-018-01074-6

Marshall, Charles R. 2006. "Explaining the Cambrian 'Explosion' of Animals." *Annual Review of Earth and Planetary Sciences* 34: 355–384. https://doi.org/10.1146/annurev.earth.33.031504.103001

Marusin, Vasiliy, and Konstantin E. Kuper. 2020. "Complex Tunnel Systems of Early Fortunian Macroscopic Endobenthos in the Ediacaran–Cambrian Transitional Strata of the Olenek Uplift (NE Siberian Platform)." *Precambrian Research* 340: 105627. https://doi.org/10.1016/j.precamres.2020.105627

McGunnigle, J. P., E. J. Cano, Z. D. Sharp, K. Muehlenbachs, D. Cole, M. F. Hardman, T. Stachel, and D.G. Pearson. 2022. "Triple Oxygen Isotope Evidence for a Hot Archean Ocean." *Geology* 50(9): 991–995. https://doi.org/10.1130/G50230.1

McMahon, Sean, and Seán F. Jordan. 2022. "A Fundamental Limit to the Search for the Oldest Fossils." *Nature Ecology and Evolution* 6: 832–834. https://doi.org/10.1038/s41559-022-01777-0

McMenamin, Mark A. S. 1986. "The Garden of Ediacara." *Palaios* 1(2): 178–182. https://www.jstor.org/stable/3514512

Mitchell, Ross N., Thomas M. Gernon, Grant M. Cox, Adam R. Nordsvan, Uwe Kirscher, Chuang Xuan, Yebo Liu, Xu Liu, and Xiaofang He. 2021. "Orbital Forcing of Ice Sheets during Snowball Earth." *Nature Communications* 12: 4187. https://doi.org/10.1038/s41467-021-24439-4

Mnemonic Devices Memory Tools. 2023. "Domain, Kingdom, Phylum, Class, Order, Family, Genus, Species." Mnemonic Devices Memory Tools. Accessed February 3, 2023. https://www.mnemonic-device.com/biology/taxonomy/domain-kingdom-phylum-class-order-family-genus-species/

Mojzsis, S. J., T. M. Harrison, and R. T. Pidgeon. 2001. "Oxygen-Isotope Evidence from Ancient Zircons for Liquid Water at the Earth's Surface 4,300 Myr Ago." *Nature* 409: 178–181. https://doi.org/10.1038/35051557

MolluscaBase. 2023. "Introduction." MolluscaBase. Accessed February 3, 2023. https://www.molluscabase.org/

Morrow, Christine, and Paco Cárdenas. 2015. "Proposal for a Revised Classification of the Demospongiae (Porifera)." *Frontiers in Zoology* 12: 7. https://doi.org/10.1186/s12983-015-0099-8

Mughal, Fizza, Arshan Nasir, amd Gustavo Caetano-Anollés. 2020. "The Origin and Evolution of Viruses Inferred from Fold Family Structure." *Archives of Virology* 165: 2177–2191. https://doi.org/10.1007/s00705-020-04724-1

Murdock, Duncan J. E. 2020. "The 'Biomineralization Toolkit' and the Origin of Animal Skeletons." *Biological Reviews* 95(5): 1372–1392. https://doi.org/10.1111/brv.12614

Nair, Prashant. 2012. "Woese and Fox: Life, Rearranged." *PNAS* 109(4): 1019–1021. https://doi.org/10.1073/pnas.1120749109

Narendran, T. C. 2000. "The Importance of Systematics." *Resonance* 5: 60–88. https://doi.org/10.1007/BF02833856

Nasir, Arshan, Ethan Romero-Severson, and Jean-Michel Claverie. 2020. "Investigating the Concept and Origin of Viruses." *Trends in Microbiology* 28(12): 959–967. https://doi.org/10.1016/j.tim.2020.08.003

Nielsen, Claus. 2019. "Early Animal Evolution: A Morphologist's View." *Royal Society of Science* 6(7): 190638 https://doi.org/10.1098/rsos.190638

Noffke, Nora, Daniel Christian, David Wacey, and Robert M. Hazen. 2013. "Microbially Induced Sedimentary Structures Recording an Ancient Ecosystem in the ca. 3.48 Billion-Year-Old Dresser Formation, Pilbara, Western Australia." *Astrobiology* 13(12): 1103–1124. https://doi.org/10.1089/ast.2013.1030

Nutman, Allen P., Stephen J. Mojzsis, and Clark R. R. Friend. 1997. "Recognition of ≥3850 Ma Water-Lain Sediments in West Greenland and Their Significance for the Early Archaean Earth." *Geochimica et Cosmochimica Acta* 61(12): 2475–2484.

https://doi.org/10.1016/S0016-7037(97)00097-5

Olejarz, Jason, Yoh Iwasa, Andrew H. Knoll, and Martin A. Nowak. 2021. "The Great Oxygenation Event as a Consequence of Ecological Dynamics Modulated by Planetary Change." N*ature Communications* 12: 3985. https://doi.org/10.1038/s41467-021-23286-7

Oliver, Thomas, Patricia Sánchez-Baracaldo, Anthony W. Larkum, A. William Rutherford, and Tanai Cardona. 2021. "Time-Resolved Comparative Molecular Evolution of Oxygenic Photosynthesis." *Biochimica et Biophysica Acta* 1862(6): 148400. https://doi.org/10.1016/j.bbabio.2021.148400

Ostrander, Chadlin M., Aleisha C. Johnson, and Ariel D. Anbar. 2021. "Earth's First Redox Revolution." *Annual Review of Earth and Planetary Sciences* 49: 337–366. https://doi.org/10.1146/annurev-earth-072020-055249

Ostrander, Chadlin M., Brian Kendall, Gwyneth W. Gordon, Sune G. Nielsen, Wang Zheng, and Ariel D. Anbar. 2022. "Shale Heavy Metal Isotope Records of Low Environmental O2 Between Two Archean Oxidation Events." *Frontiers in Earth Science* 10: 833609. https://doi.org/10.3389/feart.2022.833609

Palin, Richard M., M. Santosh, Wentao Cao, Shan-Shan Li, David Hernández-Uribe, and Andrew Parsons. 2020. "Secular Change and the Onset of Plate Tectonics on Earth." *Earth-Science Reviews* 207: 103172. https://doi.org/10.1016/j.earscirev.2020.103172

Pandey, S. K., and Mukund Sharma. 2016. "Enigmatic Ediacaran Megascopic Bedding Plane Structures on the Sonia Sandstone, Jodhpur Group, Marwar Supergroup, India: Seaweed or Problematica?" *Geological Journal* 52(5): 784–807. https://doi.org/10.1002/gj.2840

Paterson, John R. 2019. "The Trouble with Trilobites: Classification, Phylogeny, and the Cryptogenesis Problem." *Geological Magazine* 157(1): 35–46. https://doi.org/10.1017/S0016756819000426

Payne, Jonathan L., Aviv Bachan, Noel A. Heim, Pincelli M. Hull, and Matthew L. Knope. 2020. "The Evolution of Complex Life and the Stabilization of the Earth System." *Interface Focus* 10(4): 20190106. https://doi.org/10.1098/rsfs.2019.0106

Peters, Shanan, and Robert R. Gaines. 2012. "Formation of the 'Great Unconformity' as a Trigger for the Cambrian Explosion." *Nature* 484: 363–366. https://doi.org/10.1038/nature10969

Poor, Allison. 2023. "Cetartiodactyla: Cetaceans and Artiodactyls." Animal Diversity Web. Accessed February 3, 2023. https://animaldiversity.org/accounts/Cetartiodactyla/

Pu, Judy P., Samuel A. Bowring, Jahandar Ramezani, Paul Myrow, Timothy D. Raub, Ed Landing, Andrea Mills, Eben Hodgin, and Francis A. Macdonald. 2016. "Dodging Snowballs: Geochronology of the Gaskiers Glaciation and the First Appearance of the Ediacaran Biota." *Geology* 44(11): 955–958. https://doi.org/10.1130/G38284.1

Raven, Peter, George Johnson, Kenneth Mason, Jonathan Losos, and Tod Duncan. 2020. *Biology*, 12th ed. New York: McGraw Hill Higher Education. https://www.mheducation.com/highered/product/biology-raven-johnson/M9781260169614.html

Raymann, Kasie, Céline Brochier-Armanet, and Simonetta Gribaldo. 2015. "The Two-Domain Tree of Life Is Linked to a New Root for the Archaea." *PNAS* 112(21): 6670–6675. https://doi.org/10.1073/pnas.1420858112

Redmond, Anthony K., and Aoife McLysaght. 2021. "Evidence for Sponges as Sister to All Other Animals from Partitioned Phylogenomics with Mixture Models and Recoding." *Nature Communications* 12: 1783. https://doi.org/10.1038/s41467-021-22074-7

Reinhard, Christopher T., Noah J. Planavsky, Ben A. Ward, Gordon D. Love, Guillaume Le Hir, and Andy Ridgwell. 2020. "The Impact of Marine Nutrient Abundance on Early Eukaryotic Ecosystems." *Geobiology* 18(2): 139–151. https://doi.org/10.1111/gbi.12384

Ritterbush, K. A., R. Hoffmann, A. Lukeneder, and K. De Baets. 2014. "Pelagic Palaeoecology: The Importance of Recent Constraints on Ammonoid Palaeobiology and Life History." *Journal of Zoology* 292(4): 229–241. https://doi.org/10.1111/jzo.12118

Roerdink, Desiree L., Yuval Ronen, Harald Strauss, and Paul D. Mason. 2022. "Emergence of Felsic Crust and Subaerial Weathering Recorded in Palaeoarchaean Barite." *Nature Geoscience* 15: 227–232. https://doi.org/10.1038/s41561-022-00902-9

Roger, Andrew J., Sergio A. Muñoz-Gómez, and Ryoma Kamikawa. 2017. “The Origin and Diversification of Mitochondria.” *Current Biology* 27(21): R1177–R1192. https://doi.org/10.1016/j.cub.2017.09.015

Rogers, John J. W., and M. Santosh. 2002. “Configuration of Columbia, a Mesoproterozoic Supercontinent.” *Gondwana Research* 5(1): 5–22. https://doi.org/10.1016/S1342-937X(05)70883-2

Rosing, Minik T., Dennis K. Bird, Norman H. Sleep, and Christian J. Bjerrum. 2010. “No Climate Paradox under the Faint Early Sun.” *Nature* 464: 744–747. https://doi.org/10.1038/nature08955

Ruppert, Edward E., Richard S. Fox, and Robert D. Barnes. 2004. *Invertebrate Zoology: A Functional Evolutionary Approach*. 7th ed. Belmont: Brooks/Cole. https://archive.org/details/isbn_9780030259821

Sánchez-Baracaldo, Patricia, Giorgio Bianchini, Jamie D. Wilson, and Andrew H. Knoll. 2022. “Cyanobacteria and Biogeochemical Cycles through Earth History.” *Trends in Microbiology* 30(2): 143–157. https://doi.org/10.1016/j.tim.2021.05.008

Schiffbauer, James D., John Warren Huntley, Gretchen R. O’Neill, Simon A. F. Darroch, Marc Laflamme, and Yaoping Cai. 2016. “The Latest Ediacaran Wormworld Fauna: Setting the Ecological Stage for the Cambrian Explosion.” *GSA Today* 26(11): 4–11. https://doi.org/10.1130/GSATG265A.1

Schirrmeister, Bettina E., Muriel Gugger, and Philip C. J. Donoghue. 2015. “Cyanobacteria and the Great Oxidation Event: Evidence from Genes and Fossils.” *Paleontology* 58(5): 769–785. https://doi.org/10.1111/pala.12178

Schluter, Dolph. 2000. *The Ecology of Adaptive Radiation*. Oxford: Oxford University Press. https://global.oup.com/academic/product/the-ecology-of-adaptive-radiation-9780198505228

Schopf, William. 2006. “Fossil Evidence of Archaean Life.” *Philosophical Transactions of the Royal Society of London B* 361(1470): 869–885. https://doi.org/10.1098/rstb.2006.1834

Scotese, Christopher R., Haijun Song, Benjamin J. W. Mills, and Douwe G. van der Meer. 2021. “Phanerozoic Paleotemperatures: The Earth’s Changing Climate during the Last 540 Million Years.” *Earth-Science Reviews* 215: 103503. https://doi.org/10.1016/j.earscirev.2021.103503

Seilacher, Adolf. 1999. “Biomat-Related Lifestyles in the Precambrian.” *Palaios* 14(1) 86–93. https://doi.org/10.2307/3515363

Seilacher, Adolf, Dmitri Grazhdankin, and Anton Legouta. 2003. “Ediacaran Biota: The Dawn of Animal Life in the Shadow of Giant Protists.” *Paleontological Research* 7(1): 43–54. https://doi.org/10.2517/prpsj.7.43

Servais, Thomas, Borja Cascales-Miñana, and David A. T. Harper. 2021. “The Great Ordovician Biodiversification Event (GOBE) Is Not a Single Event**.”** *Paleontological Research* 25(4): 315–328. https://doi.org/10.2517/2021PR001

Servais, Thomas, and David A. T. Harper. 2018. “The Great Ordovician Biodiversification Event (GOBE): Definition, Concept, and Duration.” *Lethaia* 51(2): 151–164. https://doi.org/10.1111/let.12259

Servais, Thomas, Vincent Perrier, Taniel Danelian, Christian Klug, Ronald Martin, Axel Munnecke, Hendrik Nowak, Alexander Nützel, Thijs R.A. Vandenbroucke, Mark Williams, and Christian M. Ø. Rasmussen. 2016. “The Onset of the ‘Ordovician Plankton Revolution’ in the Late Cambrian.” *Paleogeography, Paleoclimatology, and Paleoecology* 458: 12–28. https://doi.org/10.1016/j.palaeo.2015.11.003

Shark Bay World Heritage. 2023. “Hamelin Pool.” Shark Bay World Heritage Area. Accessed February 28, 2023. https://www.sharkbay.org/place/hamelin-pool/

Singer, Emily. 2015. “How Dinosaurs Shrank and Became Birds.” *Quanta Magazine*. June 2, 2015. https://www.quantamagazine.org/how-birds-evolved-from-dinosaurs-20150602

Skejo, Josip, and Damjan Franjević. 2020. “Eukaryotes Are a Holophyletic Group of Polyphyletic Origin.” *Frontiers in Microbiology* 11: 1380. https://doi.org/10.3389/fmicb.2020.01380

Sperling, Erik A., and Richard G. Stockey. 2018. “The Temporal and Environmental Context of Early Animal Evolution: Considering All the Ingredients of an ‘Explosion.’” *Integrative and Comparative Biology* 58(4): 605–622. https://doi.org/10.1093/icb/icy088

Sperling, Erik A., Charles J. Wolock, Alex S. Morgan, Benjamin C. Gill, Marcus Kunzmann, Galen P. Halverson, Francis A. Macdonald, Andrew H. Knoll, and David T. Johnston. 2015. “Statistical Analysis of Iron Geochemical Data Suggests Limited Late Proterozoic Oxygenation.” *Nature* 523: 451–454. https://doi.org/10.1038/nature14589

Sun, Yadong, Michael M. Joachimski, Paul B. Wignall, Chunbo Yan, Yanlong Chen, Haishui Jiang, Lina Wang, and Xulong Lai. 2012. “Lethally Hot Temperatures During the Early Triassic Greenhouse.” *Science* 338(6105): 366–370. https://doi.org/10.1126/science.1224126

Tang, Qing, Ke Pang, Xunlai Yuan, and Shuhai Xiao. 2020. “A One-Billion-Year-Old Multicellular Chlorophyte.” *Nature Ecology and Evolution* 4: 543–549. https://doi.org/10.1038/s41559-020-1122-9

Tarhan, Lidya G., Ashleigh v. S. Hood, Mary L. Droser, James G. Gehling, and Derek E. G. Briggs. 2016. “Exceptional Preservation of Soft-Bodied Ediacara Biota Promoted by Silica-Rich Oceans.” *Geology* 44(11): 951–954. https://doi.org/10.1130/G38542.1

Thewissen, J .G. M., Lisa Noelle Cooper, Mark T. Clementz, Sunil Bajpai, and B. N. Tiwari. 2007. “Whales Originated from Aquatic Artiodactyls in the Eocene Epoch of India.” *Nature* 450: 1190–1194. https://doi.org/10.1038/nature06343

Tice, Michael M., Daniel C. O. Thornton, Michael C. Pope, Thomas D. Olszewski, and Jian Gong. 2011. “Archean Microbial Mat Communities.” *Annual Review of Earth and Planetary Sciences* 39: 297–319. https://doi.org/10.1146/annurev-earth-040809-152356

Understanding Evolution. “Phylogenetic Systematics (Evolutionary Trees).” University of California Museum of Paleontology Understanding Evolution. Accessed February 3, 2023. https://evolution.berkeley.edu/phylogenetic-systematics/reading-trees-a-quick-review/

Valentine, James W. 2002. “Prelude to the Cambrian Explosion.” *Annual Review of Earth and Planetary Sciences* 30: 285–306. https://doi.org/10.1146/annurev.earth.30.082901.092917

Veizer, Jan, and Andreas Prokoph. 2015. “Temperatures and Oxygen Isotopic Composition of Phanerozoic Oceans.” *Earth-Science Reviews* 146: 92–104. https://doi.org/10.1016/j.earscirev.2015.03.008

Vérard, Christian, and Ján Vezier. 2019. “On Plate Tectonics and Ocean Temperatures.” *Geology* 47(9): 881–885. https://doi.org/10.1130/G46376.1

Vermeij, Geerat J. 1989. “The Origin of Skeletons.” *Palaios* 4(6): 585–589. https://www.jstor.org/stable/3514748

Wacey, David, Matt R. Kilburn, Martin Saunders, John Cliff, and Martin D. Braiser. 2011. “Microfossils of Sulphur-Metabolizing Cells in 3.4-Billion-Year-Old Rocks of Western Australia.” *Nature Geoscience* 4: 698–702. https://doi.org/10.1038/ngeo1238

Wanninger, Andreas, and Tim Wollesen. 2018. “The Evolution of Molluscs.” *Biological Reviews* 94(1): 102–115. https://doi.org/10.1111/brv.12439

Warke, Matthew R., Tommaso Di Rocco, Aubrey L. Zerkle, Aivo Lepland, Anthony R. Prave, Adam P. Martin, Yuichiro Ueno, Daniel J. Condon, and Mark W. Claire. 2020. “The Great Oxidation Event Preceded a Paleoproterozoic ‘Snowball Earth.’” *PNAS* 117(24): 13314–13320. https://doi.org/10.1073/pnas.2003090117

Weiss, Madeline C., Filipa L. Sousa, Natalia Mrnjavac, Sinje Neukirchen, Mayo Roettger, Shijulal Nelson-Sathi, and William F. Martin. 2016. “The Physiology and Habitat of the Last Universal Common Ancestor.” *Nature Microbiology* 1: 16116. https://doi.org/10.1038/nmicrobiol.2016.116

Wendel, JoAnna. 2017. “Hunting Rare Fossils of the Ediacaran.” EOS. November 13, 2017. https://doi.org/10.1029/2017EO086601

Wilcox, Christie. 2019. “What’s in a Name? Taxonomy Problems Vex Biologists.” *Quanta Magazine*. June 24, 2019. https://www.quantamagazine.org/phyla-and-other-flawed-taxonomic-categories-vex-biologists-20190624/

Williams, Tom A., Cymon J. Cox, Peter G. Foster, Gergely J. Szöllősi, and T. Martin Embley. 2020. “Phylogenomics Provides Robust Support for a Two-Domain Tree of Life.” *Nature Ecology and Evolution* 4: 138–147. https://doi.org/10.1038/s41559-019-1040-x

Wintrich, Tanja, René Jonas, Hans-Joachim Wilke, Lars Schmitz, and P. Martin Sander. 2019. "Neck Mobility in the Jurassic Plesiosaur *Cryptoclidus eurymerus*: Finite Element Analysis as a New Approach to Understanding the Cervical Skeleton in Fossil Vertebrates." *PeerJ* 7: e7658. https://doi.org/10.7717/peerj.7658

Woese, C. R. 1994. "There Must Be a Prokaryote Somewhere: Microbiology's Search for Itself." *Microbiological Reviews* 58(1): 1–9. https://doi.org/10.1128/mr.58.1.1-9.1994

Woese, Carl R., and George Fox. 1977. "Phylogenetic Structure of the Prokaryotic Domain: The Primary Kingdoms." *PNAS* 74(11): 5088–5090. https://doi.org/10.1073/pnas.74.11.5088

Woese, C. R., O. Kandler, and M. L. Wheelis. 1990. "Towards a Natural System of Organisms: Proposal for the Domains Archaea, Bacteria, and Eucarya." *PNAS* 87(12): 4576–4579. https://doi.org/10.1073/pnas.87.12.4576

Wood, Rachel, and Andrey Yu. Zhuravlev. 2012. "Escalation and Ecological Selectively of Mineralogy in the Cambrian Radiation of Skeletons." *Earth-Science Reviews* 115(4): 249–261. https://doi.org/10.1016/j.earscirev.2012.10.002

Wood, Rachel, Alexander G. Liu, Frederick Bowyer, Philip R. Wilby, Frances S. Dunn, Charlotte G. Kenchington, Jennifer F. Hoyal Cuthill, Emily G. Mitchell, and Amelia Penny. 2019. "Integrated Records of Environmental Change and Evolution Challenge the Cambrian Explosion." *Nature Ecology and Evolution* 3: 528–538. https://doi.org/10.1038/s41559-019-0821-6

WoRMS Editorial Board. 2023. "Statistics." World Register of Marine Species. Accessed February 3, 2023. https://www.marinespecies.org/aphia.php?p=stats

Xiao, Shuhai, and Marc Laflamme. 2009. "On the Eve of Animal Radiation: Phylogeny, Ecology, and Evolution of the Ediacara Biota." *Trends in Ecology and Evolution* 24(1): 31–40. https://doi.org/10.1016/j.tree.2008.07.015

Yilmaz, Pelin, Pablo Yarza, Josephine Z. Rapp, and Frank O. Glöckner. 2016. "Expanding the World of Marine Bacterial and Archaeal Clades." *Frontiers in Microbiology* 6: 1524. https://doi.org/10.3389/fmicb.2015.01524

Zaremba-Niedzwiedzka, Katarzyna, Eva F. Caceres, Jimmy H. Saw, Disa Bäckström, Lina Juzokaite, Emmelien Vancaester, Kiley W. Seitz, Karthik Anantharaman, Piotr Starnawski, Kasper U. Kjeldsen, Matthew B. Stott, Takuro Nunoura, Jillian F. Banfield, Andreas Schramm, Brett J. Baker, Anja Spang, and Thijs J. G. Ettema. 2017. "Asgard Archaea Illuminate the Origin of Eukaryotic Cellular Complexity." *Nature* 541: 353–358. https://doi.org/10.1038/nature21031

Zhang, Li-Jun, Yong-An Qi, Luis A. Buatois, M. Gabriela Mángano, Yao Meng, and Da Li. 2017. "The Impact of Deep-Tier Burrow Systems in Sediment Mixing and Ecosystem Engineering in Early Cambrian Carbonate Settings." *Scientific Reports* 7: 45773. https://doi.org/10.1038/srep45773

Zhang, Qi-Ya, Fei Ke, Lang Gui, and Zhe Zhao. 2022. "Recent Insights into Aquatic Viruses: Emerging and Reemerging Pathogens, Molecular Features, Biological Effects, and Novel Investigative Approaches." *Water Biology and Security* 1(4): 100062. https://doi.org/10.1016/j.watbs.2022.100062

Zhuravlev, Andrey Yu, and Rachel Wood. 2020. "Dynamic and Synchronous Changes in Metazoan Body Size during the Cambrian Explosion." *Scientific Reports* 10: 6784. https://doi.org/10.1038/s41598-020-63774-2

Zimmerman, Amy E., Cristina Howard-Varona, David M. Needham, Seth G. John, Alexandra Z. Worden, Matthew B. Sullivan, Jacob R. Waldbauer, and Maureen L. Coleman. 2020. "Metabolic and Biogeochemical Consequences of Viral Infection in Aquatic Ecosystems." *Nature Reviews Microbiology* 18: 21–34. https://doi.org/10.1038/s41579-019-0270-x

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CHAPTER OVERVIEW

16: Ocean Depth Zones

We live in remarkable times. Humans inhabit space aboard an orbiting space station. Robots dot the surface of Mars. Space probes travel to the far reaches of our solar system and beyond. Just about every part of the surface of our planet can be accessed in person or virtually in real time. Yet despite these feats of technology and human endurance, one region remains tantalizingly out of reach, at least in any sense of "Yeah, we go there."

The deep sea—the expanse of ocean deeper than 200 meters (660 ft)—continues to challenge our efforts to explore and understand it. Sure, more than two dozen people now have been ferried aboard a submersible to the deepest location in the world ocean. And robots and landers plumb these depths with increasing frequency. But our knowledge of these regions is woefully incomplete (e.g., Cui and Wu 2018). Nearly every new expedition uncovers something never before seen.

Of course, discovering the unknown is part of the excitement of deep sea research. Where organisms spend all or part of their lives proves critical for their conservation and management. As the documentary *The Living Sea* (MacGillivray 1995) puts it, "We can't protect what we don't understand." To ensure our sustainable use of ocean resources, we need to understand how organisms use different ocean environments and how our activities may affect them.

Our journey will take us from the surface to the seafloor and back again. We distinguish here between those organisms that inhabit the water column—known as the pelagos or **pelagic organisms**—and those that live on or near the seafloor—the benthos or **benthic organisms**. This distinction has led to two separate classification systems—one for the pelagic organisms and another for benthic organisms. For the most part, both classifications are based on depth. Take a deep breath. It's a long trip to the bottom.

16.1: Defining an Organism's Habitat
16.2: Marine Biogeography
16.3: Oceanic Environments
16.4: Pelagic Depth Zones
16.5: Benthic Depth Zones
16.6: Ocean Depth Zoning Out
16.7: Chapter References

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16.1: Defining an Organism's Habitat

Like teenagers, mobile organisms—the **nekton**—tend to congregate in locations best suited to their lifestyle and temperament. They have their preferred place to chill, their favorite fast food spot, their ideal spot to spend time with their special someone. Indeed, the whole advantage of being mobile is the ability to go where you want. Isn't this why teens can't wait to learn how to drive? The places where an organism spends time to feed, rest, hide, find mates, and reproduce define its **habitat** (e.g., Hall et al. 1997; Fraschetti et al. 2008; Bamford and Calver 2014; Boero et al. 2019).

There's a tendency in general textbooks to equate habitat with "the environment where an animal lives" (Castro and Huber 2019). But this definition contributes to an impression that habitat and environment are synonymous (e.g., Fraschetti et al. 2008; Costello 2009; Bamford and Calver 2014). In fact, an organism's various activities may occur in different **environments**, the geological, chemical, physical, and biological conditions at a given time and place. In many cases, organisms inhabit a range of environments during their lives, and their habitat includes all these multiple environments. Thus, I define habitat as the range of environments that support the survival and reproduction of a species on a permanent or temporary basis (e.g., Lack 1933; Morris 2005; Bamford and Calver 2014). This definition especially applies to marine organisms.

Consider benthic species that produce planktic larvae. The larvae live in the water column for an extended period of time. A deep-sea benthic larva that travels to the surface will cross a range of environments twice, once on the way up and once on the way down. Salmon offer another example. They're born in freshwater, migrate to saltwater to feed until adulthood, and then return to freshwater to spawn. Their habitat includes the rivers, estuaries, and oceanic regions where they spend at least part of their life cycle.

We also have to be careful to avoid equating habitats with specific geographic locations. Free-swimming organisms follow a specific set of geological, chemical, physical, and biological conditions wherever they occur. Changes in ocean climate—natural and human-caused—lead to changes in ocean conditions across multiple timescales. As a result of such changes, organisms may shift their location. For example, during periods of El Niño, when warmer-than-average water temperatures occur along the California coast, we often find tropical species—red crabs, mahi mahi, swordfish, and marlin—inhabiting our temperate shores (e.g., Lluch-Belda et al. 2005; Cimino et al. 2021; Broughton et al. 2022). Ocean heat waves can cause similar displacements of organisms and disruptions of regional food webs (e.g., Cavole et al. 2016 ; Arimitsu et al. 2021).

This distinction between habitat and environment proves critically important for the protection of species whose life cycles include multiple environments. Efforts to restore commercially important fish populations, for example, must recognize the importance of the different habitats that affect their birth, growth, survival, and successful reproduction (e.g., Lowerre-Barbieri et al. 2019). Such efforts have necessitated conversations between people not typically accustomed to talking to each other: commercial and recreational fishermen, loggers, tribal councils, water and hydroelectric managers, and city, state, and federal government officials (e.g., Heikkila and Gerlak 2005; Cote et al. 2021). A complete understanding of an organism's habitat necessarily takes into account the range of environments required by that organism to survive and reproduce.

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16.2: Marine Biogeography

The study of the relationship between the distribution of organisms and their environment belongs to a field of science known as **biogeography**. Marine biogeography—concerned with the distribution of marine organisms in the water column and on and below the seafloor—represents one branch of this field. Biogeography serves as a complementary field to **ecology**, the study of interactions between a co-occurring community of organisms and their environment. If there's any distinction between the two, it's that biogeographers tend to examine broader spatial and temporal scales (regional to global over geologic timescales) and make greater use of tools that generate large data sets. Ecologists focus on smaller spatial and temporal scales (local to regional, days to decades) and rely more on experimental methods (Jenkins and Ricklefs 2011). But in recent decades the distinctions between these two fields have blurred. Biogeography and ecology share a common interest in understanding the geological, chemical, physical, and biological factors that govern the distribution, ecology, and evolution of organisms (e.g., Jenkins and Ricklefs 2011; Heads 2015; Bianchi 2021).

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16.3: Oceanic Environments

The broadest classification of the ocean follows Haeckel (1893) and draws a boundary between waters overlying the continental shelves—the **coastal waters**, or neritic waters—and those above the ocean basins—the **oceanic waters**. In 1957 Scripps marine biologist Joel Hedgpeth (1911–2006) proposed a system for pelagic and benthic realms (Hedgpeth 1957). He sought to establish a consistent terminology to describe "the environment and its life." Notably he designated the upper lighted waters of the ocean as the **photic zone** and the dark waters as the **aphotic zone**. These zones were further subdivided into several other zones. With few modifications, Hedgpeth's system remains in use today. These environments—both in the water column and along the seafloor—have come to be known as **ocean depth zones** (also ocean life zones). Though idealized, they offer a remarkable framework for understanding the evolution and adaptations of marine organisms. They're a classic example of the way in which geological, chemical, and physical processes shape ocean life.

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16.4: Pelagic Depth Zones

Pelagic depth zones consist of horizontally arranged layers within the water column from the surface to the seafloor. Though often reported with fixed-depth ranges, their widths may vary. As Gage and Tyler (1991) put it, "this depth zone terminology cannot be rigidly applied, and vertical zonation of fauna . . . seems determined much more by a complex of sometimes interacting ecological factors than by simple physical variables associated with the depth gradient." Nevertheless, pelagic depth zones provide a simple and convenient means to categorize oceanic environments and the major groups of organisms dwelling within them.

The Sea Surface Microlayer Zone

Though not commonly presented as an ocean depth zone, the **sea surface microlayer zone** represents as distinct an environment as any (e.g., Wangersky 1976; Hardy 1982; Wurl et al. 2017). As Macintyre says, "Perhaps nowhere else do microscopic physiochemical and hydrodynamic processes exert so profound an influence over macroscopic geochemical and geophysical phenomena" (Macintyre 1974). It's been described as "that microscopic portion of the surface ocean which is in contact with the atmosphere and which may have physical, chemical, or biological properties that are measurably different from those of adjacent subsurface waters" (Hunter 1997). By definition, the sea surface microlayer occupies the top millimeter (1,000 µm) of the water column (e.g., GESAMP 1995).

This "vital skin" (e.g., Engel et al. 2017) gains its properties from the highly enriched, gel-like matrix of biogenic macromolecules that cover its surface. Despite its modest dimensions, the sea surface microlayer exhibits two sublayers, defined by Hardy and Word (1986) and Hardy (1997) and adopted by the UN's Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP; 1995): (1) the **nanolayer**, the thin organic coating at the very surface of the ocean, from 0 to 1 micrometer in depth; and (2) the **microlayer**, inhabited by a unique assemblage of microbes and various abiogenic and biogenic particles, found from 1 to 1,000 micrometers in depth. The nanolayer interacts primarily with Earth's atmosphere, while the microlayer connects with the water column below.

In recent years the sea surface microlayer has received attention for its role in cloud formation (e.g., Hendrickson et al. 2021), air–sea exchange of heat, water, and gases (e.g., Ribas-Ribas et al. 2018), and ocean biogeochemistry (e.g., Wurl et al. 2017; Ebling and Landing 2017; Mustaffa et al. 2018; Enders et al. 2023). Suppression of turbulence by the gelatinous surface film reduces the rate at which energy and matter are transferred across the air–sea interface. Gladyshev (2005) calls it a "bottleneck" for the exchange of heat and matter between the ocean and the atmosphere. In addition, the unique microbial populations of the sea surface microlayer (e.g., Sieburth 1983; Zäncker et al. 2021) and its importance as a nursery for diverse marine larvae, including larval fish (e.g., Whitney et al. 2021), establish this environment as a unique and critical zone at the very surface of the ocean.

The Epipelagic Zone (Surface Zone)

The lighted waters of the world ocean—those surface waters illuminated by the Sun directly beneath the sea surface microlayer—constitute the **epipelagic zone** (epi = "on top of"). This domain, though only some 4.5 percent of the ocean by volume (e.g., Bucklin et al. 2010), hosts those species of large animals best known and loved by the general public—the **charismatic megafauna**. Here you will find squids, whale sharks, great white sharks, sea turtles, sea otters, sea lions, dolphins, blue whales, humpback whales, and even polar bears. The animals that inhabit the epipelagic zone are most familiar to us because they live near the surface or are held captive in zoos and aquariums where we can see them. Some we recognize as guests on our dinner plates—members of the epipelagic nekton constitute the most commercially important species in the ocean (Moyle and Cech 2004).

The epipelagic zone—also known as the **euphotic zone**—represents the region of the water column sufficient to support the growth of plants (e.g., Warming 1909; Pearsall 1917; Gilson 1937; Sverdrup et al. 1942; Chandler and Weeks 1945; Ryther 1956; Banse 2004; NOAA 2023). However, because not all wavelengths of sunlight can be used by plants, oceanographers define a quantity known as **photosynthetically available radiation** (PAR), sunlight between the wavelengths of 400 and 700 nanometers (nm). Based on PAR, the boundaries of the euphotic zone range from PAR at (or just below) the ocean surface (Z_0^{PAR} or $Z_{0^-}^{PAR}$) to the depth where the underwater light intensity reaches about 1 percent of its surface value ($Z_{1\%}^{PAR}$; e.g., Mignot et al. 2014; Wu et al. 2021).

While the epipelagic zone and euphotic zone are often considered synonymous, most textbooks (and websites) define the epipelagic zone as the upper 200 meters (660 ft) of the ocean. This definition doesn't work for the euphotic zone. Flucutations in

the concentrations of phytoplankton, suspended particles (living and nonliving), and dissolved organic matter affect the depth of light penetration into the ocean. As well, recent observations suggest a need to refine the definition of the euphotic zone (e.g., Banse 2004), possibly using the 0.1 percent light level (Marra et al. 2014; Buesseler et al. 2020). That's beyond our discussion here, but these studies acknowledge a need to consider the "spatially and seasonally varying depth of light penetration" (Buesseler et al. 2020). Even Hedgpeth (1957) acknowledged the need "to indicate the depths in a flexible manner." Thus, if we follow the science, we expect the depth range of the epipelagic zone to vary with location (e.g., coastal versus oceanic, high versus low latitude), time of year (e.g., the spring bloom), and even over longer timescales. And indeed, that's just what we see.

If we use observations of euphotic zone depths as an estimate for the depth of the epipelagic zone, we find a fiftyfold range, from less than 5 meters (17 ft) in river-influenced coastal waters (e.g., Arnone et al. 2018) to near 250 meters (820 ft) in the clearest subtropical oceanic waters (e.g., Xing et al. 2020). Buesseler et al. (2020) reported euphotic zone depths from 30 to 60 meters (98—197 ft) in polar and coastal locations and 140 to 175 meters (459—574 ft) in subtropical gyres. Annual time-series observations of the submarine light field using Biochemical Argo floats (Chapter 4) clearly demonstrate seasonal variations in the depth of the euphotic zone (measured as isolumes), perhaps by as much as 50 meters (164 ft) in some regions of the ocean (e.g., Mignot et al. 2014).

All of this suggests that we treat the epipelagic zone as a dynamic region of the upper ocean that varies over spatial and temporal scales. An epipelagic zone model varying over time and space serves as a dynamic physical driver for changes in the abundance, distribution, and behavior of drifting and mobile organisms. It brings the epipelagic zone to life—physically, chemically, and biologically—in a way that static, fixed-depth definitions and diagrams do not convey.

Light also plays a role in the behavior and ecology of organisms, especially nekton. Unlike terrestrial animals who can seek refuge in bushes and trees, epipelagic organisms must devise their own means to avoid being seen or to scare away those who would eat them. Gelatinous animals and some larval fishes rely on transparent bodies to reduce their visibility in the water column. Fish on the menu of top predators form large schools meant to discourage predators from attacking (like raising your arms and making yourself big if you encounter a bear). In the wild, wild west of the epipelagic, animals must evolve different strategies—anatomical, physiological, or behavioral—to avoid being eaten.

Obviously, other physical, chemical, and geological factors operate in the epipelagic as well. As discussed in Chapter 13, seasonal changes in the depth of the mixed layer create physical structure in the upper ocean. Stratification of the water column divides the epipelagic zone into sublayers: the surface mixed layer, the thermocline layer, and the deeper water. Differences in temperature, salinity, and dissolved oxygen may develop. Ocean currents, upwelling, downwelling, and seafloor features that interact with currents (e.g., Cascão et al. 2019) can create mesoscale and submesoscale environments (e.g., McGillicuddy 2016; Penna and Gaube 2020). Such variations may favor some organisms and disfavor others. Swimming animals may seek out or avoid these environments. For example, some species of tuna prefer the warm (>68°F), well-oxygenated waters above the thermocline, while others appear quite comfortable in colder and deeper waters, at least for a time (e.g., Bernal et al. 2017). The epipelagic features a tapestry of complex and perhaps highly specialized environments that we are just beginning to appreciate and understand. All of these factors make the epipelagic zone the most dynamic and heterogeneous zone in the ocean.

The Mesopelagic Zone (Twilight Zone)

As we descend below depths of 200 meters (660 ft), we enter what oceanographers refer to as the **deep sea** (e.g., Rogers 2015). Collectively, most of the depth zones belong here.

The ocean depth zone immediately beneath the epipelagic—the **mesopelagic zone** (meso = "middle")—gains its nickname, the twilight zone, from its very dim and diffuse light, the kind of light you see in the sky just before sunrise or after sunset. Nevertheless, there are strong arguments to be made that this zone resembles the television show of the same name (the original or the modern series). A number of bizarre and enigmatic creatures roam these depths, almost supernatural in their appearance and behavior. The vampire squid, *Vampyroteuthis infernalis*—a relict cephalopod species, neither squid nor octopus—resembles a vampire with its purplish-black color and cloak-like webbing that it rolls up over its head when disturbed. But you won't find any blood on its lips. The vampire squid eats detritus. Need I say more?

Reported at a fixed-depth range from 200 to 1,000 meters (660—3,281 ft), the mesopelagic zone occupies an estimated 17 percent of the world ocean volume (e.g., Bucklin et al. 2010). Nevertheless, like the epipelagic zone, the boundaries of the mesopelagic zone vary with oceanographic conditions. According to Robinson et al. (2010), we can place "the top of the mesopelagic as the

base of the euphotic zone, where light is too low for photosynthesis, and the bottom of the mesopelagic as the depth where downwelling irradiance is insufficient for vision to be effective in capturing prey." Organisms, rather than physical or chemical factors, define the lower boundary of the mesopelagic zone.

During daylight hours, the mesopelagic is bathed in a diffuse glow of blue light (~490 nm). American marine biologist William Beebe (1877–1962) described this glow following his epic half-mile descent in a bathysphere in 1930:

Thousands upon thousands of human beings had reached the depth at which we were now suspended, and had passed on to lower levels. But all of these were dead. . . . We were the first living men to look out at the strange illumination. . . . It was of an indefinable translucent blue quite unlike anything I have ever seen in the upper world. . . . I think we both experienced a wholly new kind of mental reception of color impression. (1934, 109)

In the clearest waters, light may penetrate as deep as 1,100 meters (3,609 ft). In turbid coastal waters, light may not penetrate deeper than 100 meters (328 ft; Kaartvedt et al. 2019). A considerable body of evidence—much of it based on acoustic measurements—shows that mesopelagic animals move up and down in the water column in relation to varying intensities of light (e.g., Staby and Aksnes 2011; Røstad et al. 2016; Aksnes et al. 2017; Bosswell et al. 2020; Langbehn et al. 2021). They may even respond in a matter of hours to changes in weather—a passing storm—that reduce the intensity of the submarine light field (e.g., Kaartvedt et al. 2017). Remarkably, moonlight and even starlight may be sufficient to induce movements of mesopelagic organisms. During a full moon, a mesopelagic zone may be present to depths of 600 meters (1,969 ft) in the clearest waters. Starlight on a clear, moonless night may be visible to depths of 280 meters (919 ft; Kaartvedt et al. 2019). If you have ever visited Joshua Tree National Park during a full Moon—or any similar location far from city lights—you've likely experienced the "brightness" of moonlight, sufficient to scramble safely across rocks or follow a path. It's an otherworldly experience.

Studies of the movements of nekton and other animals in response to light further suggest that organisms prefer a range of light intensities, a light comfort zone (e.g., Røstad et al. 2016), as first proposed for vertically migrating jellies (Dupont et al. 2009). This flexibility in preferred light intensities provides a balance between finding food and avoiding predation (e.g., Aksnes et al. 2017), what Langbehn et al. (2019) call "a game of hide and seek."

The mesopelagic also contains **oxygen minimum zones** (OMZs), regions of reduced or absent dissolved oxygen caused by microbial respiration of organic matter (e.g., Robinson 2019). As phytoplankton and fecal material sink from the euphotic zone, microbes busily break it down, consuming oxygen and liberating carbon dioxide as they do so (Chapter 10). OMZs result from the decomposition of this rich supply of organic matter (e.g., Wyrtki 1962) and other factors (e.g., Oschlies et al. 2018). Below the OMZs, the diminshed supply of organic matter reduces rates of respiration and permits higher dissolved oxygen concentrations. Colder and well-oxygenated deep ocean currents also contribute to higher dissolved oxygen concentrations below the OMZ. Organisms that can tolerate hypoxic and anoxic conditions can find shelter within an OMZ, especially if their predators are less tolerant of reduced oxygen conditions. Thus, the OMZ may act as a barrier to some species and segregate their distributions to the upper or lower mesopelagic (e.g., Maas et al. 2014; Wishner et al. 2018; Deutsch et al. 2020).

Other oceanographic processes may also modify organisms' distributions. Subsurface currents can affect the distribution of subsurface water masses. Off the California coast, strengthening of the California Undercurrent (Chapter 17) has brought warmer, saltier, and less-oxygenated water to the subsurface (and surface) in recent decades (e.g., Meinvielle and Johnson 2013; Bograd et al. 2015). This redistribution of water masses—possibly due to the Pacific Decadal Oscillation—has brought shifts in mesopelagic communities (e.g., Brodeur et al. 2003; Koslow et al. 2019). Climate change has also been suggested for shifting species' distributions (e.g., Xiu et al. 2018; Bograd et al. 2023).

Subsurface eddies can pinch off portions of mesoscale water masses and take their organisms for a ride. These eddies may carry their nekton passengers thousands of miles (e.g., Garfield et al. 2001; Zhang et al. 2017; Penna and Gaube 2020; Wang et al. 2023). On their journey, these mobile "oases" may attract other species and create a kind of subsurface eddy community (e.g., Godø et al. 2012; Arostegui et al. 2022).

In low- and midlatitude waters, the mesopelagic zone hosts the permanent thermocline at depths from 200 to 1,000 meters (660–3,281 ft). The permanent thermocline represents Central Waters and exhibits a wide range of temperatures (5°–24°C; 41°–75°F) and salinities (34.3–36.4), which may further partition where predators and their prey hang out (e.g., Emery and Meincke 1986; Talley et al. 2011).

We should also be aware of pressure. As you know, each 10 meters (33 ft) of depth adds another atmosphere of pressure to the water column (Chapter 3). For organisms in the mesopelagic, water pressure may be 20 to 100 times that experienced at the surface. Despite this seeming obstacle, organisms inhabit nearly all depths in the ocean and exhibit a wide range of adaptations that enable them to do so (e.g., Menzies 1974; MacDonald 1997; Yancey 2020). The hadal snailfish—a fish related to tide pool sculpins—has been observed at 8,178 meters (more than five miles) deep in the Mariana Trench, the deepest fish found to date in the world ocean (Gerringer et al. 2021). Great white sharks in the North Atlantic make daily excursions from the surface to depths of more than 1,100 meters (3,608 ft; e.g., Skomal 2017; Gaube et al. 2018). Satellite-tagged Cuvier's beaked whales have been logged at depths close to 3,000 meters (9,843 ft), representing a three-hundred-fold change in pressure (Schorr et al. 2014).

Finally, the mesopelagic zone represents a kind of new frontier for fisheries. As global demand for seafood and nutraceuticals rises, fishers are targeting deeper fish populations as an abundant and profitable source. Estimates of mesopelagic fish populations rival or exceed current catches (e.g., Proud et al. 2019), but so little is known about this region of the ocean and potential effects on epipelagic fisheries that scientists and resource managers urge caution (e.g., Hidalgo and Browman 2019). We have much to learn before we can responsibly and sustainably harvest this region of the ocean (e.g., St. John et al. 2016; Fjeld et al. 2023).

The Bathypelagic Zone (Midnight Zone)

Below 1,000 meters (3,281 ft), the **bathypelagic zone** (bathy = "deep"), also known as the midnight zone, represents the largest depth zone in the world ocean, comprising an estimated 59 percent of its volume (e.g., Bucklin et al. 2010). Despite this, we probably know less about the bathypelagic zone than any other region of the ocean. That's because technology for exploring the water column at great depths has been limited. Even the abyssal seafloor is easier to sample. But interest in the deep sea for its role in climate change (specifically its ability or lack of ability to store carbon), its importance in ocean biodiversity (especially microbial diversity), and its susceptibility to seafloor mining (and how plumes of sediments may impact its species) have brought renewed attention to these waters. The need to study, understand, and even manage all organisms within the deep ocean has probably never been greater (e.g., Robison 2009; Roemmich et al. 2019; Danovaro et al. 2020; Amon et al. 2022; Bravo et al. 2023).

Despite this urgency, many people, including some scientists, consider the bathypelagic to be a dark, homogeneous, relatively uninteresting place. Other than its oft-publicized, wicked-looking predatory fishes (e.g., Simon 2020), it excites little public attention. In 1964 Canadian-born fisheries biologist Clarence P. Idyll (1916–2007)—author of *Abyss: The Deep Sea and the Creatures That Live in It*—described the bathypelagic in his classic book as follows:

The deep sea is pitch black, without the least glimmer of the sun's rays to give it cheer; it is cold, only a little above freezing; it is under enormous pressure, with power to crush to a shapeless mass any body not constructed to combat it; it is salty and laden with nutrient minerals, but these are useless since the energy of the light is missing; it is virtually still, with only the most languid currents moving. Yet this unlikely living space is inhabited by a huge variety of fishes and squids and other curious animals that are lucky enough not to realize that their home seems so unlivable. (1964, 49)

Life always finds a way to take what seems like an uninhabitable place and make it home. Archaea and other microbes appear to thrive in the bathypelagic. And so do dragonfish, anglerfish, and giant squid. It's a bit like *The Addams Family* (e.g., Koslow 2007), but it is a vibrant, thriving, and important community of organisms, nonetheless.

Scientists report the boundaries as fixed depths, albeit variable ones, from 1,000 to 3,000 (3,281–9,843 ft), 4,000 (13,123 ft), or 5,000 meters (16,404 ft), depending on the reference (e.g., Priede 2017; Bucklin et al. 2010; and Nagata et al. 2010, respectively). The upper boundary of the bathypelagic, of course, varies with the depth of light penetration from 100 to 1,100 meters (328–3,609 ft), as we saw above. Bruun (1956) sets the lower boundary at the depth of the 4°C isotherm (39.2°F), but this is probably too shallow given that in the Pacific, Indian, and parts of the Atlantic Ocean, this isotherm generally can be found at 1,000 meters (3,281 ft)—the lower limit of the mesopelagic zone (Talley et al. 2011).

Nagata et al. (2010), reviewing microbial processes in the bathypelagic zone, extend the lower boundary of the bathypelagic zone to 5,000 meters (16,404 ft). And Priede (2017) dispenses with any lower boundary at all, proposing that we use the term bathypelagic for all depths below 1,000 meters (3,281 ft) except the hadopelagic, the water column contained within the oceanic trenches (deeper than 6,000 meters; 19,685 ft). However, as we improve our technology for making measurements of temperature, salinity, dissolved oxygen, and other properties at depths from 2,000 meters (6,562 ft) to the seafloor, we'll get a clearer picture of

this environment and likely find ecologically relevant boundaries (e.g., Jamieson et al. 2010; Kawaguchi et al. 2018; Liu et al. 2020). For now, we shall have to be content that any well-defined lower boundary has yet to be established.

Perhaps the one defining feature of the bathypelagic is that sunlight cannot penetrate these depths. To that extent, characterization of this zone as "the dark ocean" (e.g., Arístegui et al. 2009) or the "midnight zone" (e.g., Hardt and Safina 2010) seems appropriate except for one small fact: organisms produce light here, living light, otherwise known as **bioluminescence**. Found at all depths and visible throughout the water column at night, bioluminescence becomes more visible (and useful) as the submarine light field diminishes and disappears.

In the bathypelagic zone, bioluminescence prevails as the sole light source. Discrete points of light are emitted from the specialized light organs of animals, their **photophores**. Used to attract prey, ward off predators, blend in, or communicate with potential reproductive partners, bioluminescence has become something of an art form in the otherwise "pitch black" waters of the bathypelagic (e.g., Haddock et al. 2010; Martini and Haddock 2017). Though natural levels of bioluminescence may be quite low at these depths—as few as one or two flashes per hour (e.g., Buskey and Swift 1990)—in the presence of hydrodynamic disturbances, such as a predator, flashes may increase substantially (e.g., Vacquié-Garcia et al. 2012). Given the extraordinary visual systems of deep sea fishes, bioluminescence likely plays an important role in their survival and reproduction (de Busserolles et al. 2020). So while the presence of light in the zones above creates an environmental gradient that drives the ecology of organisms, the absence of light—along with bioluminescence—does the same in the bathypelagic (e.g., Cohen et al. 2020; Davis et al. 2020).

Some of the organisms that live in the bathypelagic zone seek prey in the zone above—the mesopelagic. But many simply wait for unsuspecting prey to cross their path. Given its distance from the epipelagic zone, the bathypelagic zone relies entirely on food produced elsewhere. For that reason, it is generally characterized as "food-poor," or sparse in terms of food supply. However, this view may be changing. While oceanographers once thought that most particulate organic matter is recycled in the mesopelagic, recognition of the importance of slowly sinking particles and fast-sinking aggregates (e.g., phytodetritus and the carcasses of gelatinous organisms) has led to reassessment of the role of the "dark ocean" in ocean food webs and biogeochemical cycles. New appreciation for physical and biological mechanisms that deliver significant quantities of food-rich particles—what are called "particle injection pumps"—promise to "reshape" our view of deep-sea food webs and the role of the deep ocean in carbon and other biogeochemical cycles (e.g., Arístegui et al. 2009; Danovaro et al. 2014; Boyd et al. 2019; Buesseler et al. 2020; Baltar et al. 2021; Herndl et al. 2023; Lappan et al. 2023).

Indeed, if we follow the microbes, as it were, we discover an environment that is more heterogeneous than previously appreciated (e.g., Hewson et al. 2006; Nagata et al. 2010). Microbial "hotspots"—patches of elevated microbial activity in response to an uneven distribution of particulate or dissolved organic matter—may be more common than once thought (e.g., Azam et al. 1994; Bochdansky et al. 2017; Rahav et al. 2019). Patches of actively growing microbes offer a local food source for gelatinous, filter-feeding predators. These predators, in turn, appear on the menu of smaller predators that feed larger predators, and so on up the food web (e.g., Chi et al. 2020). Thus, environmental heterogeneity in the bathypelagic, especially as it affects the abundance and distribution of secondary producers (i.e., microbes), can have a significant effect on the transfer of energy and matter into pelagic food webs (e.g., Boyd et al. 2019; Iversen 2023).

Of all the zones in the ocean, the bathypelagic is perhaps the most isolated, at least ecologically. The supply of matter and energy here relies on internal oceanic sources, unlike upper ocean depth zones, which regularly interact with the atmosphere. In any case, it's certainly not the "unlivable" zone envisioned by Idyll because life is clever and remarkably tenacious.

The Abyssopelagic Zone (Mystery Zone)

The **abyssopelagic zone** (abysso = "bottomless") encompasses some 19 percent of the ocean volume at depths from 4,000 to 7,000 meters (13,123–22,966 ft; e.g., Bucklin et al. 2010). More commonly, the depth range is set from 3,000 to 6,000 meters (9,843 ft–19,685 ft; e.g., Herring 2002; Priede 2017). Not everyone recognizes the abyssopelagic as a distinct zone. Herring (2002) includes it with the bathypelagic (starting at 1,000 m, or 3,281 ft). Everything deeper he refers to as hadopelagic (see below). Sutton (2013) similarly includes the abyssopelagic with the bathypelagic and sets the lower boundary at 100 meters (328 ft) above the seafloor. A few studies cite peaks in fish abundance at depths greater than 2,500 meters (8,202 ft) as evidence of a distinct environment (e.g., Sutton 2013; Sutton and Milligan 2019). And studies of microbes hint at discrete communities at abyssopelagic depths (e.g., Walsh et al. 2016). In truth, a lack of studies at these depths makes it challenging to affirm or reject the existence of an ecologically distinct abyssopelagic zone (e.g., Costello and Breyer 2017). Including this zone as part of the bathypelagic seems the most

parsimonious interpretation of existing data. Still, like Pluto's status as a planet (e.g., Carter 2021), the abyssopelagic could be reinstated if convincing arguments can be made.

The Hadopelagic Zone (Trench Zone)

Should you ever be told to spend some time in the underworld ("Go to the devil!"), you may take less offense if you consider that the ocean region named after the Greek god of the underworld, Hades, can be quite peaceful. Removed from the hustle and bustle of life on the abyssal plains and out of the main freeway of the strongest abyssal currents, the **hadopelagic zones**—the regions of the water column bounded by oceanic trenches—represent the deepest and most remote parts of the ocean. Defined as depths greater than 6,000 meters (19,685 ft; e.g., Jamieson 2015—the authority we'll accept here), greater than 6,500 meters (21,325 ft; e.g., UNESCO 2009), or greater than 7,000 meters (22,966 ft; e.g., Bucklin et al. 2010), the hadal zone represents a tiny fraction of the volume of the world ocean. Nevertheless, the hadal depth range, from its shallowest at 6,000 meters (19,685 ft) to its deepest at 10,925 meters (35,843 ft, the depth of the Challenger Deep), includes 45 percent of the total depth range of the ocean.

The hadopelagic represents several independent zones, mostly unconnected to each other. Using 6,000 meters (19,685 ft) as a cutoff depth, Jamieson (2015) identified 46 distinct hadal environments. These occur mostly in trenches, but waters deeper than 6,000 meters (19,685 ft) can also be found in deep basins, fracture zones, and transform faults (Jamieson and Stewart 2021). The deepest, of course, is the Mariana Trench, but trenches vary considerably in their depth, volume, morphology, and degree of isolation (e.g., Stewart and Jamieson 2018). Even the Mariana Trench can be subdivided into five distinct regions. At its northern end, a "bridge" of seafloor shallower than 6,000 meters (19,685 ft) divides it from the Volcano Trench, whose depths exceed 8,500 meters (27,887 ft; Jamieson and Stewart 2021). This complex seafloor morphology has led oceanographers to view hadal zones as isolated "islands" where species evolve independently with little exchange between adjacent regions and trenches (e.g., Stewart and Jamieson 2018). The evolution of different species of finches on the various Galapagos Islands—observed by Charles Darwin and acknowledged in modern times as evidence for speciation by evolution—serves as an example of what may occur in trenches.

Seawater temperatures in the hadopelagic resemble those of abyssal waters in the bathypelagic, with a range of 1° to 4°C (33.8°–39.2°F). But extreme pressure presents the biggest challenge to life here. Using the pressure equation introduced in Chapter 3, we calculate a pressure 600 to 1,100 times greater than sea level. Snailfish are the deepest species (e.g., Gerringer et al. 2021), but no fish have ever been observed at depths deeper than 8,400 meters (27,559 ft; e.g., Yancey et al. 2014). Decapod crustaceans (e.g., shrimp) can only make it to 7,700 meters (25,262 ft). Benthic lander video of an octopus swimming at 6,957 meters (22,825 ft) is the deepest observation of a cephalopod (Jamieson and Vecchione 2020). On the other hand, deep sea amphipods—relatives of the beach hoppers you often see around kelp and other beached seaweeds—have been collected with a hadal lander at the very bottom of the Challenger Deep in the Mariana Trench at 10,929 meters (within the margin of error of the deepest official depth; e.g., Lan et al. 2016). Foraminifera—mostly the unshelled variety—also thrive at these depths (e.g., Zeppilli et al. 2018).

The Benthopelagic Zone (Near-Bottom Zone)

The **benthopelagic zone** represents the portion of the water column within 100 meters (328 ft) of the seafloor. Thus, its lower boundary varies with the bathymetry of the seafloor from 0 to 10,925 meters (35,843 ft). Though typically considered a part of the benthic environment, the benthopelagic, as its name implies, proves an important part of the water column as well. It represents a kind of transition zone for exchanges between the water column and the seafloor (e.g., Marshall and Merrett 1977 ; Wishner 1980; Sutton and Milligan 2019). Diverse and abundant organisms—planktic and nektic—can be found in the benthopelagic, supported by pulses of phytodetritus that arrive on the seafloor or larger bounties, like the carcasses of fishes or whales (e.g., Mauchline and Gordon 1991).

Organisms at these depths may travel higher in the water column and prey on pelagic species (e.g., Mauchline and Gordon 1991) or be preyed upon by pelagic species hunting in the deep (e.g., Drazen et al. 2008). Importantly, the connections between benthic and pelagic food webs have implications for the fate of carbon in the deep sea. Organic matter consumed by benthic species may do an about-face when consumed by a pelagic predator that returns to the upper water column.

Though the upper boundary of this zone is defined as 100 meters (328 ft) above the bottom, this boundary likely fluctuates depending on geological and physical conditions. Seafloor features, such as seamounts and oceanic ridges, interact with abyssal currents and generate turbulence in the overlying water column. This effect is most pronounced where seafloor bathymetry varies abruptly—characterized as "rough topography"—versus the relatively smooth topography of abyssal plains (e.g., Orellana-Rovirosa and Richards 2017). With sufficient current speeds, the bottom-enhanced turbulence may reach all the way to the surface

(e.g., Polzin et al. 1997). On average, this effect is most pronounced within 200 to 300 meters (656–984 ft) of the bottom (e.g., Waterhouse et al. 2014). Recent theoretical work and general circulation models confirm that bottom-enhanced mixing may be sufficient to drive abyssal circulation (e.g., Callies et al. 2018; Drake et al. 2020). Thus, we find a possible pathway for particles and properties to return from the seafloor to the surface where they originated. In any case, a better understanding of the benthopelagic and all deep-sea zones will be needed to assess their connectivity and their role in food webs, biogeochemical cycles, and ocean conservation (e.g., Sutton 2013).

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16.5: Benthic Depth Zones

We finally arrive at the seafloor environment and the **benthic depth zones**. Should you be wondering if you will ever make it back to the surface, rest assured that our ascent to the surface will be much quicker than our descent into the abyss. Many of the properties of the benthic zones—pressure, temperature, and salinity—are quite similar to those of the pelagic ones. But some properties do vary, so we'll need to stop at these depths and take a look around. A big theme in the benthic depth zones is the heterogeneity of the seafloor on spatial and temporal scales. Ripples, scarps, and dunes—features you might see on a sandy beach—appear on the seafloor as well. Disturbances such as turbidity currents or seasonal pulses of food generate temporal variability. This heterogeneity contributes to greater diversity in the benthos than might otherwise be expected based on physical properties alone (e.g., Sanders 1968). The seafloor also boasts rich mineral deposits (Chapter 7). A major driver of modern deep-sea exploration—especially on the seafloor—concerns a desire to assess the economic potential of deep-sea mining. Before such mining, however, it's essential to document and understand the biodiversity of the deep sea and assess its potential for pharmaceutical and other human uses (in addition, of course, to its ecological importance for sustaining the ocean). We begin where we left off—in the oceanic trenches.

The Hadal Benthic Zone (Hadobenthic Zone)

The **hadal benthic zone** (or hadobenthic zone) comprises the seafloor deeper than 6,000 to 6,500 meters (19,685–21,325 ft; UNESCO 2009; Jamieson 2015). Though mostly contained within oceanic trenches, hadal environments can be found in deep basins, fracture zones, and transform faults, too. The largest in terms of area—the Izu-Bonin trench that extends north from the Mariana Trench to coastal Japan—covers some 100,000 square kilometers (38,610 mi^2), an area roughly the size of Iceland (Jamieson 2015). As in the hadopelagic, seawater temperatures are cold except where hydrothermal vents are present. And, of course, extreme water pressure exists everywhere.

An interesting feature of trench hadal environments is their asymmetry. Oceanic trenches form where two plates collide. The denser underthrust plate slides beneath the less dense overthrust plate, and a trench forms. But because the motion is not smooth—the plates tend to lock up—the overthrust plate may arch upward, elevating the seafloor. Thus, the overthrust side of a trench tends to be steeper, while the underthrust side slopes more gradually. This asymmetry produces a rockier terrain and more frequent sediment slides on the overthrust side. The underthrust side more resembles an abyssal plain with thick sediments and soft features. These differences may give rise to quite different communities of organisms within the same trench (e.g., Jamieson et al. 2010).

Food supply, predictably, might be considered low given the distance of hadal environments from productive surface waters. But hadal zones are not the biological deserts they were once thought to be. Cold seeps have been found in hadal environments supporting a diverse community of chemosynthetic organisms and their associates (e.g., Rathburn et al. 2009; Suess 2014; 2020; Nanajkar et al. 2022). And the V shape of trenches acts as a funnel for sinking particles and debris, concentrating organic materials along the trench axis, the bottom of the V. These sites of enhanced deposition—called **depocenters** (short for depositional centers)—rival coastal areas in their concentrations of organic matter and microbial activity (e.g., Danovaro et al. 2003; Glud et al. 2021). Earthquakes may suspend continental shelf and slope sediments, which can then be carried by currents into nearby trenches (e.g., Itou et al. 2000; Oguri et al. 2013; Oguri et al. 2022).

Unfortunately, any suspended material that sinks may accumulate in hadal zones. High concentrations of microplastics—weighted down by their microbial passengers—have been found in deep ocean and trench sediments (e.g., Woodall et al. 2014; Jamieson et al. 2019). Whether trenches represent "the ocean's ultimate trashcan" (e.g., Peng et al. 2020) remains to be seen. As Jamieson et al. (2010) admit, "Trenches are poorly sampled and our knowledge of the ecological structure and functioning of this environment remains rudimentary." We have much to learn.

The Abyssal Benthic Zone (Abyssobenthic Zone)

The **abyssal benthic zone** (or abyssobenthic zone) occurs at depths from 3,000 to 6,500 meters (9,843–21,325 ft). It covers nearly 74 percent of the entire seafloor—267 million square kilometers (103 million square miles; e.g., Menard and Smith 1966), the greatest percentage of any benthic zone. That's slightly more than half of Earth's surface! Abyssal hills and abyssal plains dominate this region. At least some portion of the base of many oceanic ridges also occurs at these depths (e.g., Harris 2014). Thus, if you had to generalize about the abyssal zone—and Earth's surface, for that matter—you would not be wrong to say that most of it looks like Chino Hills, without the ranch homes and excellent Mexican restaurants. (Mi Ranchito is my favorite.) In fact, food here, as

you might expect, arrives as a slow rain of organic matter interrupted by pulses of phytodetritus and carrion falls. It's a bit colder than Chino Hills too. Abyssal zone temperatures average about 39°F (4°C), whereas average temperatures in Chino Hills vary from 68° to 77°F (20°–25°C) seasonally (World Weather and Climate Information 2023).

Until recently, the abyssal zone was characterized as flat and featureless expanses of sediments—mostly sands, silts, and clays (e.g., Smith et al. 2008). But as we continue to explore these depths using sound and deep-sea robots equipped with cameras, a different picture of the abyss has emerged. Movements of the seafloor along transform faults and their associated fracture zones expose chunks of oceanic crust in what has been called "abyssal rock patches" (Riehl et al. 2020). Imagery taken using camera-equipped epibenthic sleds and high-resolution bathymetry obtained using multibeam sonar reveal a patchwork of exposed "hard rock" intermixed with various forms of sediments, manganese nodules, and polymetallic crusts. The geologic heterogeneity of the abyssal seafloor offers a broad range of microenvironments for organisms, solid substrate for attachment, and caves and crevices for hiding (Riehl et al. 2020). These rock exposures interact with abyssal currents like rocks in a river, creating eddies of faster water that suspend and transport sediments or slower water that permits sediments to settle and accumulate (Chapter 6). Accumulations of sediments increase the likelihood of turbidity flows and sediment slumps—especially during earthquakes—adding environmental disturbance to the list of possible traits to which organisms may adapt.

Greater environmental heterogeneity promotes greater organismal diversity (e.g., Barry and Dayton 1991; Snelgrove and Smith 2002; Sigwart et al. 2023). The paradigm of the abyssal seafloor as a relatively homogenous and sparsely populated environment no longer holds true (e.g., Snelgrove 1999; Ramirez-Llorda et al. 2010; Ramirez-Llorda 2020). As Leray and Machida (2020) express it, "The deep seafloor is teeming with life, most of which remains poorly known to science." A recent study on the seafloor of the Clarion Clipperton Zone between Mexico and Hawaii underscores their remark. Of the 5,578 species of animals found there, more than 90 percent may be new to science (Rabone et al. 2023).

These organisms hold potential for natural products and marine drugs. They also provide clues about the origins, evolution, and ecology of life in one of the most extreme environments on Earth. And we're still learning about the role of the deep sea in biogeochemical cycles, carbon storage, and marine food webs (e.g., Glover and Smith 2003; Stratmann et al. 2021). New tools for observing the deep sea are starting to provide new insights into this vast wilderness. As we look to the abyssal seafloor for extraction of mineral and other resources (e.g., Hein et al. 2020; Hyman et al. 2022), oceanographers urge caution. "Humans are in danger of modifying one of the largest, most intriguing, ecosystems long before its natural state is fully understood" (e.g., Glover and Smith 2003).

The Bathyal Benthic Zone (Bathybenthic Zone)

The **bathyal benthic zone** (or bathybenthic zone) has been described as "where shallow meets the deep" (Levin and Dayton 2009). Indeed, extending from the shelf break, at about 200 meters (656 ft), to the bottom of the continental rise, at 3,500 meters (11,483 ft), the bathyal benthic represents a zone of transition from shallow- to deep-water environments. Though mostly associated with continental margins (Chapter 7), a significant percentage of bathyal depths can be found along the flanks and tops of seamounts and oceanic ridges (UNESCO 2009). Combined, bathyal depths cover 17.8 percent of the seafloor (Zezina 1997). The zone is often divided into an upper bathyal (200–800 meters; 656–2,625 ft) and a lower bathyal (800–3,500 meters; 2,625–11,483 ft), but given the enormous diversity of environments it encompasses, such depth-based boundaries may be more hopeful than useful.

The bathyal zone exhibits wide variability in pressure (20–300 atmospheres), temperature (<0°–10°C), and dissolved oxygen (<1–7 milliliters per liter ; e.g., UNESCO 2009). These factors vary with depth and location. Bathyal zones beneath swift-moving western boundary currents experience greater turbulent energy than their eastern boundary counterparts. Polar bathyal environments differ from tropical ones.

Like we found with the abyssal benthic zone, scientific characterization of the bathyal benthic zone has changed upon further scrutiny. Robotic and acoustic technologies have revealed an environment far more interesting than the "monotonous mud slopes" it was once thought to be (Levin and Sibuet 2012). The bathyal zone offers a rich collection of flat-topped guyots, rugged seamounts, steep submarine canyons, plunging vertical walls, massive rocky outcrops, cold seeps, and soft sediments shaped into ripples, mounds, or depressions (e.g., Gage and Tyler 1992; de la Torriente et al. 2018; Sutton and Milligan 2019; Leitner et al. 2021). These diverse features offer environments for habitation and ecological specialization (e.g., Sanders 1968; Menot et al. 2010; Levin and Sibuet 2012; Paulus 2021).

Biological structures also contribute to the environmental heterogeneity: deep-sea glass sponges (so named for their siliceous skeletons), deep-sea corals, tube-building worms, and various kinds of bivalves—deep water oysters, clams, and mussels. The structures of these "ecosystem engineers" modify the physical and geological environment and contribute to establishment of a mosaic of microenvironments (e.g., Jones et al. 1994; Levin et al. 2001; Wright and Jones 2006; Cordes et al. 2009; Levin and Sibuet 2012; McClain et al. 2020). Whereas the unexpected high biodiversity of bathyal environments was once difficult to explain, it's now becoming clear that environmental heterogeneity (e.g., substrate, sediment size, biological engineeering), food supply (e.g., food pulses, chemosynthetic food factories, nutrient depocenters, food falls), and environmental disturbances (e.g., turbidity flows, water mass shifts, oxygen minimum zones) help to structure these diverse ecosystems (e.g., Rex and Etter 2010; McClain et al 2020; Furness et al. 2021; Bryant and McClain 2022). The degree to which each or all of these factors maintain deep-sea biodiversity remains to be seen.

As humans increasingly look to the deep sea for energy, minerals, food, biotechnology, and other goods, the need to understand deep-sea ecosystems is greater than ever. As Levin and Sibuet (2012) put it:

This high regional biodiversity is fundamental to the production of valuable fisheries, energy, and mineral resources, and performs critical ecological services (nutrient cycling, carbon sequestration, nursery and habitat support). . . . Serious actions are required to preserve the functions and services provided by the deep-sea settings we are just now getting to know.

The Sublittoral Zone (Coastal Benthic Zone)

Covering nearly 9 percent of the seafloor (e.g., Harris et al. 2014), the **sublittoral zone**, the region below the littoral zone (from the Latin litoralis, or "shore"), extends from the zero tide height (i.e., 0 meters) to the shelf break—about 200 meters (656 ft), in theory. Of all the terms in the oceanographic literature, "sublittoral" and "littoral" are my least favorites. In my opinion, the term "littoral zone" lacks context and meaning for most American readers. In addition, it sounds too much like "literal" and is frequently spelled as such. Where we encounter "littoral zone" we could (and often do) substitute "intertidal zone." But, as noted by Hedgpeth (1957), many regions of the world lack discernible tides, making the term less satisfactory on a global basis. We would substitute "subtidal" for "sublittoral" if this term didn't already restrict its meaning to nearshore waters immediately below the zero tide height.

Efforts to improve the terminology (e.g., Dauvin et al. 2008) urge adoption of the region below the littoral zone as the **infralittoral zone**, exposed only by the lowest tides and often occupied by seaweeds, and the **circalittoral zone**, whose lower boundary extends to the 1 percent light level (i.e., the euphotic zone depth). Of course, we already know the 1 percent light level depends greatly on water clarity, which can be highly variable. Such a definition would place the lower boundary of the circalittoral at quite shallow depths. The term **elittoral zone** has been proposed, in this case, to account for depths deeper than the circalittoral but shallower than the bathyal. Other alternatives (e.g., Pérès 1982) include phytal (suitable for photosynthesis) and aphytal (not suitable for photosynthesis), but these have been vigorously contested (e.g., Golikov 1985). If you're expecting a satisfactory outcome here, you won't find one. Different terms remain in use in different parts of the world, often because the environments are quite different. While it may be desirable to establish a common terminology, the sublittoral zone—for historical and practical reasons—may defy such a simple classification (e.g., Costello 2009). The etymology aside, we'll stick with the term sublittoral and let 0–200 meters (656 ft) define its boundaries.

That said, we immediately encounter exceptions. Continental shelves, to which this zone mostly applies, vary widely in width (from less than a mile to hundreds of miles); their geology may be quite different (from rocky to muddy); they may be incised by deep submarine canyons (e.g., Monterey Bay Submarine Canyon); and they may be subject to extensive modification by terrestrial processes, especially in the vicinity of major rivers, such as the Amazon (e.g., Lavagnino et al. 2020). As one example of a regional approach to defining sublittoral, Valentine et al. (2005) extend the lower boundary to 400 meters (154 ft) to include the very wide continental shelves of the Gulf of Mexico and even deeper—up to 800 meters (309 ft)—in the vicinity of submarine canyons.

The sublittoral also differs in its physical, chemical, and biological properties (e.g., Brown et al. 2011). Waves, tides, currents, solar radiation, temperatures, salinities, terrestrial inputs, and biological productivity are among the many possible players in the sublittoral environment. The degree to which these properties influence the distribution of benthic organisms in a given region depends on oceanographic and terrestrial processes. The highly dynamic coastal benthic zone—as I prefer to call it—awaits further study and characterization. Given its importance to human enterprises, the need for young scientists to study this zone couldn't be greater.

The Littoral Zone (Intertidal Zone)

Humans have long been fascinated by life at the ocean's edge. The shore offered the world's first unlimited buffet with food that "littorally" could not be fresher. Evidence of shell middens—piles of discarded and presumably eaten shellfish—on the shores of Africa date back some 120,000 years (e.g., Niespolo et al. 2021). A wide variety of material resources and even energy were available in the remains of organisms, including whales (e.g., Erlandson et al. 2015; Kishigami 2021).

Scientific observations of the distribution of marine organisms along the shore span nearly two centuries (e.g., Forbes 1840; Verrill 1874; Sumner 1910; Colman 1933; Doty 1946; Stephenson and Stephenson 1949; Ebling et al. 1960; Dayton 1971; Connell 1972; Lubchenco 1980; Gaines and Roughgarden 1985; Paine 1994; Robles and Desharnais 2002; Menge et al. 2003; Bird et al. 2013; Weitzman et al. 2021). Naturalist Edward Forbes (1815–1854), born on the Isle of Man (in the Irish Sea), defined the littoral zone as "the tract that lies between the high and low water marks" (Forbes 1840). Indeed, the littoral zone encompasses the region of the shoreline regularly submerged—what's known as **submersion**—or exposed to air—that is, **emersion**. Because it occupies such a narrow strip of seafloor along the sea's edge, it's been callled the ocean's "bathtub ring" (Menge and Branch 2001).

Organisms living here straddle oceanic and terrestrial environments, the "sea-land gradient" (Raffaelli and Hawkins 1999). Both oceanic and terrestrial conditions establish the environments available for habitation by organisms. Raffaelli and Hawkins (1999) stress that tides represent only one of the many environmental factors that influence the distribution of organisms along the shore. Waves (high- versus low-energy), geologic substrate (sedimentary or rocky), and salinity (from brackish to highly saline) also play roles. Because many factors are at play, they prefer the term "littoral" (i.e., the shore) to "intertidal" (between the tides) but acknowledge that "intertidal is in such common usage that it would now be difficult to replace."

From the earliest days of research in the littoral zone, marine biologists sought to explain the visible and persistent patterns in the distribution of organisms. Even a casual visitor can discern the distinct regions of color and texture that often appear at different "heights" above the water's edge. These regions represent the phenomenon of **intertidal zonation**, the grouping of organisms into horizontal bands along vertical gradients in elevation along a shoreline. Note that height refers to the vertical distance above or below the zero tide height (i.e., mean sea level). In some cases, the zones and their community of organisms are distinct. In others they appear as a gradient of species, with some more abundant at different heights (e.g., Helmuth 2015).

The observation of discrete bands of organisms within the littoral zone (and above and below it) has led to a set of terms to classify these subdivisions. As you might expect, the terms vary, but attempts have been made to standardize the terminology to make it applicable worldwide (e.g., Stephenson and Stephenson 1949; Lewis 1964). We'll follow subdivisions proposed by Raffaelli and Hawkins (1999)—largely based on the work of Stephenson and Stephenson (1949, 1972) and Lewis (1964), but also Ricketts and Calvin (1962). These latter authors worked along the Pacific Coast, so their zones apply better for US shores.

While the names differ, all authors agree on at least three subdivisions of the littoral zone: (1) **the splash zone** (Ricketts and Calvin 1962), also known as the supralittoral fringe (e.g., Stephenson and Stephenson 1972; Bertness 1999) and littoral fringe (Raffaelli and Hawkins 1999), characterized by organisms that require occasional wetting; (2) the **intertidal zone** (Ricketts and Calvin 1962), also referred to as the eulittoral zone (Raffaelli and Hawkins 1999; eu = "true" or "real"), the region of alternating submersion and emersion; and (3) the **subtidal zone** (Ricketts and Calvin 1962), infralittoral (Stephenson and Stephenson 1972), or sublittoral (Raffaelli and Hawkins 1999), the region rarely exposed to air. See what I mean about names?

Though generally in agreement with the above scheme, Ricketts and Calvin (1962) offer a slightly different approach for subdividing the intertidal zone. Their epic and aptly named book *Between Pacific Tides*, first published in 1939 and now in its fifth edition (1985), was heavily criticized by marine biologists prior to publication. Fortunately, it gained popularity and went on to sell more than 100,000 copies, a huge success for its publisher (Tamm 2004). Writing for "beachcombers" as well as "professors," Ricketts and Calvin divide the intertidal (their preferred term for the littoral) into four zones based on tide heights, which they numbered one through four. Their numbering system provides a convenient shorthand for notetaking in the field—not an easy task when you're ever watchful for crashing waves and slippery surfaces.

The uppermost Zone 1, the **upper intertidal**, centers around the high high tide (Chapter 20)—roughly at a tide height of 1.5–2 meters (5–7 ft) and higher, inclusive of the splash zone. Zones 2 and 3 represent the **middle intertidal**, occupying heights up to 1.5 meters (5 ft) above the zero tide height. This zone is further subdivided into an **upper middle** and **lower middle intertidal**, respectively, with the dividing line set at the height of the mean high low tide, roughly 0.5 to 1.5 meters (2.5–5 ft). The **lower intertidal**, Zone 4, extends from the zero tide height to the lowest minus tide. Raffaelli and Hawkins (1999) refer to Zone 4 as the

sublittoral fringe. Stephenson and Stephenson (1972) call this the infralittoral fringe (infra = "below"). Ricketts and Calvin's subtidal zone—the nearshore region below the intertidal—has been defined as the region in which seaweeds and seagrasses flourish (e.g., Dauvin et al. 2008). Others simply call this region the sublittoral (e.g., Dauvin et al. 2008). If you're a student in an oceanography or marine biology laboratory or field course on the North American West Coast, you're likely to encounter upper, upper middle, lower middle, and lower as the four subdivisions of the intertidal.

Broadly speaking, environmental factors explain the upper limit of most organisms' distributions on the shore (e.g., Dayton 1971). As noted above, wave energy, substrate heterogeneity, temperature, salinity, and other factors interact along with tides to modify where they can live. For example, wave-exposed regions develop a different assemblage of organisms than sheltered locations. The type of substrate—sand, gravel, cobble, boulder, or solid rock—determines sediment stability under different wave conditions. It's hard to stay attached if your home is rolling in the waves. Mixed substrates—including fractured or eroded stretches of rock—offer the potential for tide pools and nooks and crannies in which organisms can hang out to avoid adverse conditions. Temperature variations—especially during low tides—can bake or freeze organisms exposed to the air. Whether an organism survives depends on its physiology and the duration of exposure to such adverse conditions.

Salinity comes into play when tidal fluctuations bring saltier or fresher water to the intertidal. Precipitation can lower salinities, even to zero during prolonged storm events. On the other hand, evaporation in tide pools—especially those less frequently submerged—can cause salinity to increase.

Physical factors may vary over temporal scales as well—from days to decades. Thus, the assemblage of species at a given location may represent a montage of different events separated in time. For example, a random log that crashes onto a shore and clears a space will look quite different from the surrounding rock—especially in its initial stages—as new larvae and mobile organisms grab the space and make a home.

Biological factors—especially competition for food and space and predation—generally set the lower limits of species' distributions (e.g., Dayton 1971). A classic set of field experiments carried out in the rocky intertidal of Scotland by UC Santa Barbara ecologist Joseph Connell (1923–2020) demonstrated the ability of the larger and faster-growing common rock barnacle (*Semibalanus balanoides*) to displace and outcompete the smaller and slower-growing stellate barnacle (*Chthamalus stellatus)*. The larger barnacle simply "smothered, undercut, or crushed" the smaller one and prevented it from occupying its preferred habitat. When the larger barnacle was excluded (by removing newly settled larvae with a needle), the smaller barnacle did quite well (Connell 1961). These experiments set the stage for decades of experimental manipulations in the intertidal to study interactions among species. Of course, generalizations only take us so far. Biological factors may set the upper boundary for some organisms and physical factors the lower boundary. In ecology, there are always exceptions to "rules" (e.g., Bird et al. 2013; Underwood 2000; Hawkins et al. 2020).

Beaches and estuaries with sandy, silty, and muddy shores experience many of the same environmental challenges as rocky shores (e.g., Knox 2001; Kennish 2016). Waves, tides, and currents act on sediments and move them in relation to their energy and particle size (Chapter 6). In some environments, their zonation remains hidden beneath their sediments. In others, the presence of marine plants—seagrasses and cord grasses—structure the environment (e.g., Degraer et al. 1999; Knox 2001; Semeniuk and Brocx 2016). We don't have the space here to discuss soft-bottom environments, but know that they are every bit as fascinating. We'll reserve our discussion of soft bottoms to the chapters ahead on the organisms that live there.

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16.6: Ocean Depth Zoning Out

Aquatic scientists have long debated the terms and definitions used to classify regions of the seafloor (e.g., Forbes and Hanley 1853; Southern 1915; Ekman 1953; Hedgpeth 1957; Pérès 1982; Golikov 1985; Dauvin et al. 2008; Fraschetti et al. 2008; Costello 2009; Althaus et al. 2015; Costello et al. 2017). As pointed out by Trombley and Cottenie (2019), "The usage of ambiguous terminology can cause confusion or discord among members of the same field and fuel unproductive debates." On the other hand, they acknowledge that "ambiguity can speed up the acquisition of knowledge by allowing definitions to change as knowledge on the subject increases."

Now, I admit it may have been simpler (and occupied far fewer pages) to simply present the "textbook" scheme for classifying marine environments. But that approach ignores two very important principles of science (as we discussed way back in Chapter 2). First, science is an active, ongoing process that yields new data and new ideas subject to revision, review, and rejection; and second, science communication, especially to the public, demands a clear and transparent accounting of new data and ideas. Thus, while it may seem tedious and even a bit annoying to get the play-by-play as the science unfolds—like listening to a neighbor describe the installation of power outlets in the remodel of their home—in truth, nearly all science requires revision and freshening up. I feel strongly committed to promoting a view of science as a process and helping the public understand what scientists do and how they do it. It's important to know where those terms and facts come from—and their limits—so that you are better skilled at using science in your own life.

The regular "upheaval" of ideas in science was not lost on the California-born American writer John Steinbeck (1902–1968). A close friend of marine biologist Ed Ricketts (1897–1948), Steinbeck frequently incorporated marine science in his work, especially *Cannery Row* (1945) and *The Log from the Sea of Cortez* (1951). He also wrote a foreword for the Third Edition of *Between Pacific Tides* (Ricketts and Calvin 1962), mentioned above. Commenting on modern science, Steinbeck wrote:

> *And in many fields young, inquisitive are seeing new worlds. And from their seeing will emerge not only new patterns but new ethics, disciplines, and manners. The upheaval of the present world may stimulate restive minds to new speculations and evaluations. . . . The world is being broken down to be built up again.*

Steinbeck ends with a quote from the book:

> *There are good things to see in the tidepools and there are exciting and interesting thoughts to be generated from the seeing. Every new eye applied to the peep hole which looks out at the world may fish in some new beauty and see some new pattern, and the world of the human mind must be enriched by such fishing.*

New tools for observing the ocean, especially robots and drones, offer opportunities to sample across larger areas on scales not possible with traditional methods. With changes in the ocean happening at an unprecedented rate, our understanding of this environment may be more important than ever. We still have much to learn. Be enriched, ocean fisher. And carry your ocean message to others. We live because the sea lives!

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16.7: Chapter References

Aksnes, Dag, Anders Røstad, Stein Kaartvedt, Udane Martinez, Carlos M. Duarte, and Xabier Irigoien. 2017. “Light Penetration Structures the Deep Acoustic Scattering Layers in the Global Ocean.” *Science Advances* 3: e1602468. https://doi.org/10.1126/sciadv.1602468

Althuas, Franziska, Nicole Hill, Renata Ferrari, Luke Edwards, Rachel Przeslawski, Christine H. L. Schönberg, Rick Stuart-Smith, Neville Barrett, Graham Edgar, Jamie Colquhoun, Maggie Tran, Alan Jordan, Tony Rees, and Karen Gowlett-Holmes. 2015. “A Standardised Vocabulary for Identifying Benthic Biota and Substrata from Underwater Imagery: The CATAMI Classification Scheme.” *PLoS ONE* 10(10): e0141039. https://doi.org/10.1371/journal.pone.0141039

Amon, Diva J., Randi D. Rotjan, Brian R. C. Kennedy, Gerard Alleng, Rafael Anta, Eriatera Aram, Thera Edwards, Marcia Creary-Ford, Kristina M. Gjerde, Judith Gobin, Laura-Ashley Henderson, Alexis Hope, Raquel Khan Ali, Sebastian Lanser, Keith Lewis, Hannah Lochan, Scott MacLean, Nabuti Mwemwenikarawa, Brennan Phillips, Betarim Rimon, Stacey-Ann Sarjursingh, Tooreka Teemari, Aranteiti Tekiau, Alan Turchik, Henri Vallès, Kareati Waysang, and Katherine L. C. Bell. 2022. “My Deep Sea, My Backyard: A Pilot Study to Build Capacity for Global Deep-Ocean Exploration and Research.” *Philosophical Transactions of the Royal Society B* 377(1854): 20210121. https://doi.org/10.1098/rstb.2021.0121

Arimitsu, Mayumi L., John F. Piatt, Scott Hatch, Robert M. Suryan, Sonia Batten, Mary Anne Bishop, Rob W. Campbell, Heather Coletti, Dan Cushing, Kristen Gorman, Russell R. Hopcroft, Kathy J. Kuletz, Caitlin Marsteller, Caitlin McKinstry, David McGowan, John Moran, Scott Pegau, Anne Schaefer, Sarah Schoen, Jan Straley, and Vanessa R. von Biela. 2021. “Heatwave-Induced Synchrony within Forage Fish Portfolio Disrupts Energy Flow to Top Pelagic Predators.” *Global Change Biology* 27(9): 1859–1878. https://doi.org/10.1111/gcb.15556

Arístegui, Javier, Josep M. Gasol, Carlos M. Duarte, and Gerhard J. Hernld. 2009. “Microbial Oceanography of the Dark Ocean’s Pelagic Realm.” *Limnology and Oceanography* 54(5): 1501–1529. https://doi.org/10.4319/lo.2009.54.5.1501

Arnone, Robert, Brooke Jones, Sherwin Ladner, and Inia Soto. 2018. “Seasonal Trends of Biophysical Ocean Properties and Anomalies across the Mississippi Shelf.” *Proceedings Volume 10631, Ocean Sensing and Monitoring X*: 1063102. https://doi.org/10.1117/12.2309427

Arostegui, Martin C., Peter Gaube, Phoebe A. Woodworth-Jefcoats, Donald R. Kobayashi, and Camrin D. Braun. 2022. “Anticyclonic Eddies Aggregate Pelagic Predators in a Subtropical Gyre.” *Nature* 609: 535–540. https://doi.org/10.1038/s41586-022-05162-6

Azam, F., D. C. Smith, G. F. Steward, and Å. Hagström. 1994. “Bacteria-Organic Matter Coupling and Its Significance for Oceanic Carbon Cycling.” *Microbial Ecology* 28: 167–179. https://doi.org/10.1007/BF00166806

Baltar, Federico, Xosé A. Alvarez-Salgado, Javier Arístegui, Ronald Benner, Dennis A. Hansell, Gerhard J. Herndl, and Christian Lønborg. 2021. “What Is Refractory Organic Matter in the Ocean?” *Frontiers in Marine Science* 8: 642637. https://doi.org/10.3389/fmars.2021.642637

Bamford, Michael, and Michael Calver. 2014. “A Precise Definition of Habitat Is Needed for Effective Conservation and Communication.” *Australian Zoologist* 37(2): 245–247. https://doi.org/10.7882/AZ.2014.015

Banse, Karl. 2004. “Should We Continue to Use the 1% Light Depth Convention for Estimating the Compensation Depth of Phytoplankton for Another 70 Years?” *Limnology and Oceanography Bulletin* 13(3): 49–52. https://doi.org/10.1002/lob.200413349

Barry, James P., and Paul K. Dayton. 1991. “Physical Heterogeneity and the Organization of Marine Communities.” In *Ecological Heterogeneity*. Edited by Jurek Kolasa, and Steward T. A. Pickett, 270–320. New York: Springer. https://doi.org/10.1007/978-1-4612-3062-5_14

Beebe, William. 1934. *Half Mile Down*. New York: Harcourt, Brace, and Company. https://archive.org/details/halfmiledown00beeb

Bernal, Diego, Richard W. Brill, Kathryn A. Dickson, and Holly Shiels. 2017. “Sharing the Water Column: Physiological Mechanisms Underlying Species-Specific Habitat Use in Tuna.” *Reviews in Fish Biology and Fisheries* 27: 843–880. https://doi.org/10.1007/s11160-017-9497-7

Bertness, Mark D. 1999. *The Ecology of Atlantic Shorelines*. Sunderland: Sinauer Associates. https://www.google.com/books/edition/The_Ecology_of_Atlantic_Shorelines/9zVkQgAACAAJ

Bianchi, Thomas. 2021. "The Evolution of Biogeochemistry: Revisited." *Biogeochemistry* 154: 141–181. https://doi.org/10.1007/s10533-020-00708-0

Bird, Christopher E., Erik C. Franklin, Celia M. Smith, and Robert J. Toonen. 2013. "Between Tide and Wave Marks: A Unifying Model of Physical Zonation on Littoral Shores." *PeerJ* 1:e154. https://doi.org/10.7717/peerj.154

Bochdansky, Alexander B., Melissa A. Clouse, and Gerhard J. Herndl. 2017. "Eukaryotic Microbes, Principally Fungi and Labyrinthulomycetes, Dominate Biomass on Bathypelagic Marine Snow." *ISME Journal* 11: 362–373. https://doi.org/10.1038/ismej.2016.113

Boero, Ferdinando, Francesco De Leo, Simonette Fraschetti, and Gianmarco Ingrosso. 2019. "The Cells of Ecosystem Functioning: Towards a Holistic Vision of Marine Space." *Advances in Marine Biology* 82: 129–153. https://doi.org/10.1016/bs.amb.2019.03.001

Bograd, Steven J., Mercedes Pozo Buil, Emanuele Di Lorenzo, Carmen G. Castro, Isaac D. Schroeder, Ralf Goericke, Clarissa R. Anderson, Claudia Benitez-Nelson, and Frank A. Whitney. 2015. "Changes in Source Waters to the Southern California Bight." *Deep Sea Research Part II: Topical Studies in Oceanography* 112: 42–52. https://doi.org/10.1016/j.dsr2.2014.04.009

Bograd, Steven J., Michael G. Jacox, Elliott L. Hazen, Elisa Lovecchio, Ivonne Montes, Mercedes Pozo Buil, Lynne J. Shannon, William J. Sydeman, and Ryan R. Rykaczewski. 2023. "Climate Change Impacts on Eastern Boundary Upwelling Systems." *Annual Review of Marine Science* 15: 303–328. https://doi.org/10.1146/annurev-marine-032122-021945

Boswell, Kevin M., Marta D'Elia, Matthew W. Johnston, John A. Moran, Joseph D. Warren, R. J. David Wells, and Tracey T. Sutton. 2020. "Oceanographic Structure and Light Levels Drive Patterns of Sound Scattering Layers in a Low-Latitude Oceanic System." *Frontiers in Marine Science* 7: 51. https://doi.org/10.3389/fmars.2020.00051

Boyd, Philip, Hervé Claustre, Marina Levy, David A. Siegel, and Thomas Weber. 2019. "Multi-Faceted Particle Pumps Drive Carbon Sequestration in the Ocean." *Nature* 568: 327–335. https://doi.org/10.1038/s41586-019-1098-2

Bravo, M. Emilia, Miriam I. Brandt, Jesse M. A. van der Grient, Thomas G. Dahlgren, Patricia Esquete, Sabine Gollner, Daniel O. B. Jones, Lisa A. Levin, Craig R. McClain, Bhavani E. Narayanaswamy, Tracey Sutton, Lissette Victorero, and Erik E. Cordes. 2023. "Insights from the Management of Offshore Energy Resources: Toward an Ecosystem-Services Based Management Approach for Deep-Ocean Industries." *Frontiers in Marine Science* 9: 994632. https://doi.org/10.3389/fmars.2022.994632

Brodeur, Richard D., William G. Pearcey, and Stephen Ralston. 2003. "Abundance and Distribution Patterns of Nekton and Micronekton in the Northern California Current Transition Zone." *Journal of Oceanography* 59: 515–535. https://doi.org/10.1023/A:1025548801541

Broughton, Jack M., Brian F. Codding, J. Tyler Faith, Kathryn A. Mohlenhoff, Ruth Gruhn, Joan Brenner-Coltrain, and Isaac A. Hart. 2022. "El Niño Frequency Threshold Controls Coastal Biotic Communities." *Science* 377(6611): 1202–1205. https://doi.org/10.1126/science.abm1033

Brown, Craig J., Stephen J. Smith, Peter Lawton, and John T. Anderson. 2011. "Benthic Habitat Mapping: A Review of Progress Towards Improved Understanding of the Spatial Ecology of the Seafloor Using Acoustic Techniques." *Estuarine, Coastal and Shelf Science* 92(3): 502–520. https://doi.org/10.1016/j.ecss.2011.02.007

Bruun, Anton Fr. 1956. "The Abyssal Fauna: Its Ecology, Distribution, and Origin." *Nature* 177: 1105–1108. https://doi.org/10.1038/1771105a0

Bryant, S. River D., and Craig R. McClain. 2022. "Functional Space Expansion Driven by Transitions between Energetically Advantageous Traits in the Deep Sea." *Proceedings of the Royal Society B* 289(1987): 20221302. https://doi.org/10.1098/rspb.2022.1302

Bucklin, Ann, Shuhei Nishida, Sigrid Schnack-Schiel, Peter H. Wiebe, Dhugal Lindsay, Ryuji J. Machida, and Nancy J. Copley. 2010. "A Census of Zooplankton of the Global Ocean." In *Life in the World's Oceans: Diversity, Distribution, and Abundance*. Edited by Alasdair D. McIntyre, 247–265. Oxford: Blackwell Publishing. https://doi.org/10.1002/9781444325508.ch13

Buesseler, Ken O., Philip W. Boyd, Erin E. Black, and David A. Siegel. 2020. “Metrics that Matter for Assessing the Ocean Biological Carbon Pump.” *PNAS* 117(18): 9679–9687. https://doi.org/10.1073/pnas.1918114117

Buskey, Edward, and Elijah Swift. 1990. “An Encounter Model to Predict Natural Planktonic Bioluminescence.” *Limnology and Oceanography* 35(7): 1469–1485. https://doi.org/10.4319/lo.1990.35.7.1469

Callies, Jörn, and Raffaele Ferrari. 2018. “Dynamics of an Abyssal Circulation Driven by Bottom-Intensified Mixing on Slopes.” *Journal of Physical Oceanography* 48(6): 1257–1282. https://doi.org/10.1175/JPO-D-17-0125.1

Carter, Jamie. 2021. “Yes, Pluto Is a Planet Says NASA Scientist at the Site of Its Discovery 91 Years Ago This Week.” *Forbes*. February 15, 2021. https://www.forbes.com/sites/jamiecartereurope/2021/02/15/yes-pluto-is-a-planet-says-nasa-scientist-at-the-site-of-its-discovery-91-years-ago-this-week/

Cascão, Irma, Réka Domokos, Marc O. Lammers, Ricardo S. Santos, and Mónica A. Silva. 2019. “Seamount Effects on the Diel Vertical Migration and Spatial Structure of Micronekton.” *Progress in Oceanography* 175: 1–13. https://doi.org/10.1016/j.pocean.2019.03.008

Castro, Peter, and Michael Huber. 2019. *Marine Biology*. 11th ed. New York: McGraw Hill Higher Education. https://www.mheducation.com/highered/product/marine-biology-castro-huber/M9781259880032.html

Cavole, Letícia M., Alyssa M. Demko, Rachel E. Diner, Ashlyn Giddings, Irina Koester, Camille M. L. S. Pagniello, May-Linn Paulsen, Arturo Ramirez-Valdez, Sarah M. Schwenck, Nicole K. Yen, Michelle E. Zill, and Peter J. S. Franks. 2016. “Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future.” *Oceanography* 29(2): 273–285. https://doi.org/10.5670/oceanog.2016.32

Chandler, David C., and Owen B. Weeks. 1945. “Limnological Studies of Western Lake Erie: V. Relation of Limnological and Meteorological Conditions to the Production of Phytoplankton in 1942.” *Ecological Monographs* 15(4): 435–457. https://doi.org/10.2307/1948429

Chi, Xupeng, Jan Dierking, Henk-Jan Hoving, Florian Lüskow, Anneke Denda, Bernd Christiansen, Ulrich Sommer, Thomas Hansen, and Jamileh Javidpour. 2020. “Tackling the Jelly Web: Trophic Ecology of Gelatinous Zooplankton in Oceanic Food Webs of the Eastern Tropical Atlantic Assessed by Stable Isotope Analysis.” *Limnology and Oceanography* 66(2): 289–305. https://doi.org/10.1002/lno.11605

Cimino, Megan A., Michael G. Jacox, Steven J. Bograd, Stephanie Brodie, Gemma Carroll, Elliott L. Hazen, Bertha E. Lavaniegos, Mark M. Morales, Erin Satterthwaite, and Ryan R. Rykaczewski. 2021. “Anomalous Poleward Advection Facilitates Episodic Range Expansions of Pelagic Red Crabs in the Eastern North Pacific.” *Limnology and Oceanography* 66(8): 3176–3189. https://doi.org/10.1002/lno.11870

Cohen, Jonathan H., Jørgen Berge, Mark A. Moline, Geir Johnsen, and Artur P. Zolich. 2020. “Light in the Polar Night.” In *POLAR NIGHT Marine Ecology: Life and Light in the Dead of Night*. Advances in Polar Ecology, Volume 4. Edited by Jørgen Berge, Geir Johnsen, and Jonathan H. Cohen, 37–66. Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-33208-2_3

Colman, John. 1933. “The Nature of the Intertidal Zonation of Plants and Animals.” *Journal of the Marine Biological Association of the United Kingdom* 18(2): 435–476. https://doi.org/10.1017/S0025315400043794

Connell, Joseph H. 1961. “The Influence of Interspecific Competition and Other Factors on the Distribution of the Barnacle *Chthamalus stellatus*.” *Ecology* 42(4): 710–723. https://doi.org/10.2307/1933500

———. 1972. “Community Interactions on Marine Rocky Intertidal Shores.” *Annual Review of Ecology and Systematics* 3: 169–192. https://www.jstor.org/stable/2096846

Cordes, Erik E., Derk C. Berquist, and Charles R. Fisher. 2009. “Macro-Ecology of Gulf of Mexico Cold Seeps.” *Annual Review of Marine Science* 1: 143–168. https://doi.org/10.1146/annurev.marine.010908.163912

Costello, Mark J. 2009. “Distinguishing Marine Habitat Classification Concepts for Ecological Data Management.” *Marine Ecology Progress Series* 397: 253–268. https://doi.org/10.3354/meps08317

Costello, Mark J., and Sean Breyer. 2017. “Ocean Depths: The Mesopelagic and Implications for Global Warming.” *Current Biology* 27(1): R19–R41. https://doi.org/10.1016/j.cub.2016.11.042

Costello, Mark J., Peter Tsai, Pui Shan Wong, Alan Kwok Lun Cheung, Zeenatul Basher, and Chhaya Chaudhary. 2017. “Marine Biogeographic Realms and Species Endemicity.” *Nature Communications* 8: 1057. https://doi.org/10.1038/s41467-017-01121-2

Cote, David, Cassandra A. Konecny, Jennica Seiden, Tristan Hauser, Trond Kristiansen, and Ben J. Laurel. 2021. “Forecasted Shifts in Thermal Habitat for Cod Species in the Northwest Atlantic and Eastern Canadian Arctic.” *Frontiers in Marine Science* 8: 764072. https://doi.org/10.3389/fmars.2021.764072

Cui, Weicheng, and Xin Wu. 2018. “A Chinese Strategy to Construct a Comprehensive Investigation System for Hadal Trenches.” *Deep Sea Research Part II: Topical Studies in Oceanography* 155: 27–33. https://doi.org/10.1016/j.dsr2.2018.10.012

Danovaro, R., N. Della Croce, A. Dell’Anno, and A. Pusceddu. 2003. “A Depocenter of Organic Matter at 7800 m Depth in the SE Pacific Ocean.” *Deep Sea Research Part I: Oceanographic Research Papers* 50(12): 1411–1420. https://doi.org/10.1016/j.dsr.2003.07.001

Danovaro, Roberto, Emanuela Fanelli, Jacopo Aguzzi, David Billett, Laura Carugati, Cinzia Corinaldesi, Antonio Dell’Anno, Kristina Gjerde, Alan J. Jamieson, Salit Kark, Craig McClain, Lisa Levin, Noam Levin, Eva Ramirez-Llodra, Henry Ruhl, Craig R. Smith, Paul V. R. Snelgrove, Laurenz Thomsen, Cindy L. Van Dover, and Moriaki Yasuhara. 2020. “Ecological Variables for Developing a Global Deep-Ocean Monitoring and Conservation Strategy.” *Nature Ecology and Evolution* 4: 181–192. https://doi.org/10.1038/s41559-019-1091-z

Danovaro, Roberto, Paul V. R. Snelgrove, and Paul Tyler. 2014. “Challenging the Paradigms of Deep-Sea Ecology.” *Trends in Ecology and Evolution* 29(8): 465–475. https://doi.org/10.1016/j.tree.2014.06.002

Dauvin, Jean-Claude, Gerard Bellan, and Denise Bellan-Santini. 2008. “The Need for Clear and Comparable Terminology in Benthic Ecology. Part I. Ecological Concepts.” *Aquatic Conservation* 18(4): 432–445. https://doi.org/10.1002/aqc.865

Davis, Alexander L., Kate N. Thomas, Freya E. Goetz, Bruce H. Robison, Sönke Johnsen, and Karen J. Osborn. 2020. “Ultra-Black Camouflage in Deep-Sea Fishes.” *Current Biology* 30(17): 3470–3476. https://doi.org/10.1016/j.cub.2020.06.044

Dayton, Paul K. 1971. “Competition, Disturbance, and Community Organization: The Provision and Subsequent Utilization of Space in a Rocky Intertidal Community.” *Ecological Monographs* 41(4): 351–389. https://doi.org/10.2307/1948498

de Busserolles, Fanny, Lily Fogg, Fabio Cortesi, and Justin Marshall. 2020. “The Exceptional Diversity of Visual Adaptations in Deep-Sea Teleost Fishes.” *Seminars in Cell and Developmental Biology* 106: 20–30. https://doi.org/10.1016/j.semcdb.2020.05.027

Degraer, S., I. Mouton, L. De Neve, and M. Vincx. 1999. “Community Structure and Intertidal Zonation of the Macrobenthos on a Macrotidal, Ultra-Dissipative Sandy Beach: Summer-Winter Comparsion.” *Estuaries* 22: 742–752. https://doi.org/10.2307/1353107

de la Torriente, A., A. Serrano, L. M. Fernández-Salas, M. García, and R. Aguilar. 2018. “Identifying Epibenthic Habitats on the Seco de los Olivos Seamount: Species Assemblages and Environmental Characteristics.” *Deep Sea Research Part I: Oceanographic Research Papers* 135: 9–22. https://doi.org/10.1016/j.dsr.2018.03.015

Deutsch, Curtis, Justin L. Penn, and Brad Seibel. 2020. “Metabolic Trait Diversity Shapes Marine Biogeography.” *Nature* 585: 557–562. https://doi.org/10.1038/s41586-020-2721-y

Doty, Maxwell S. 1946. “Critical Tide Factors That Are Correlated with the Vertical Distribution of Marine Algae and Other Organisms along the Pacific Coast.” *Ecology* 27(4): 315–328. https://doi.org/10.2307/1933542

Drake, Henri F., Raffaele Ferrari, and Jörn Callies. 2020. “Abyssal Circulation Driven by Near-Boundary Mixing: Water Mass Transformations and Interior Stratification.” *Journal of Physical Oceanography* 50(8): 2203–2226. https://doi.org/10.1175/JPO-D-19-0313.1

Drazen, Jeffrey C., Brian N. Popp, C. Anela Choy, Tara Clemente, Lisa De Forest, and Kenneth L. Smith Jr. 2008. “Bypassing the Abyssal Benthic Food Web: Macrourid Diet in the Eastern North Pacific Inferred from Stomach Content and Stable Isotopes Analyses.” *Limnology and Oceanography* 53(6): 2644–2654. https://doi.org/10.4319/lo.2008.53.6.2644

Dupont, Nicolas, T. A. Klevjer, S. Kaartnedt, and D. L. Aksneasa. 2009. “Diel Vertical Migration of the Deep-Water Jellyfish *Periphylla periphylla* Simulated as Individual Responses to Absolute Light Intensity.” *Limnology and Oceanography* 54 95): 1765–1775. https://doi.org/10.4319/lo.2009.54.5.1765

Ebling, Alina M., and William M. Landing. 2017. “Trace Elements in the Sea Surface Microlayer: Rapid Responses to Changes in Aerosol Deposition.” *Elementa: Science of the Anthropocene* 5:42. https://doi.org/10.1525/elementa.237

Ebling, F. J., M. A. Sleigh, J. F. Sloane, and J. A. Kitching. 1960. “The Ecology of Lough Ine: VII. Distribution of Some Common Plants and Animals of the Littoral and Shallow Sublittoral Regions.” *Journal of Ecology* 48(1): 29–53. https://doi.org/10.2307/2257306

Ekman, Sven. 1953. *Zoogeography of the Sea*. London: Sidgwick and Jackson. https://archive.org/details/in.ernet.dli.2015.74439/mode/2up

Emery, W. J., and J. Meincke. 1986. “Global Water Masses—Summary and Review.” *Oceanologica acta* 9(4): 383–391. https://archimer.ifremer.fr/doc/00110/22090/

Enders, Abigail A., Scott M. Elliott, and Heather C. Allen. 2023. “Carbon on the Ocean Surface: Temporal and Geographical Investigation.” *ACS Earth and Space Chemistry* X:X. https://doi.org/10.1021/acsearthspacechem.2c00248

Engel, Anja, Hermann W. Bange, Michael Cunliffe, Susannah M. Burrows, Gernot Friedrichs, Luisa Galgani, Hartmut Mermann, Norbert Hertkorn, Martin Johnson, Peter S. Liss, Patricia K. Quinn, Markus Schartau, Alexander Soloviev, Christian Stolle, Robert C. Upstill-Goddard, Manuela van Pinxerton, and Birthe Zänker. 2017. “The Ocean’s Vital Skin: Toward an Integrated Understanding of the Sea Surface Microlayer.” *Frontiers in Marine Science* 4: 165. https://doi.org/10.3389/fmars.2017.00165

Erlandson, Jon M., Todd J. Braje, Kristina M. Gill, and Michael H. Graham. 2015. “Ecology of the Kelp Highway: Did Marine Resources Facilitate Human Dispersal from Northeast Asia to the Americas?” *Journal of Island and Coastal Archaeology* 10(3): 392–411. https://doi.org/10.1080/15564894.2014.1001923

Eronat, Elizabeth Grace Tunka. 2016. “Feeding Ecology and Trophic Level of *Chimaera monstrosa* Linnaeus, 1758 (Holocephali: Chimaeridae) in the Eastern Mediterranean.” *Zoology in the Middle East* 62(1): 51–57. https://doi.org/10.1080/09397140.2015.1132560

Fjeld, Kristian, Rachel Tiller, Eduwardo Grimaldo, Leif Grimsmo, and Inger-Beate Standal. 2023. “Mesopelagics—New Gold Rush or Castle in the Sky?” *Marine Policy* 147: 105359. https://doi.org/10.1016/j.marpol.2022.105359

Forbes, Edward. 1840. “On the Associations of Mollusca on the British Coasts, considered with reference to Pleistocene Geology.” In *The Edinburgh Academic Annual for MDCCCXL. Consisting of Contributions in Literature and Science*. By Alumni of the University of Edinburgh. Edinburgh: Adam and Charles Black. https://www.google.com/books/edition/The_Edinburgh_Academic_Annual_for_MDCCCX/iEpgAAAAcAAJ

Forbes, Edward, and Sylvanus Hanley. 1853. *A History of British Mollusca and Their Shells*. London: John Van Voorst. https://www.biodiversitylibrary.org/bibliography/16341

Fraschetti, Simonetta, Antonio Terlizzi, and Ferdinando Boero. 2008. “How Many Habitats Are There in the Sea (and Where)?” *Journal of Experimental Marine Biology and Ecology* 366(1–2): 109–115. https://doi.org/10.1016/j.jembe.2008.07.015

Furness, Euan N., Russell J. Garwood, Philip D. Mannion, and Mark D. Sutton. 2021. “Evolutionary Simulations Clarify and Reconcile Biodiversity-Disturbance Models.” *Proceedings of the Royal Society B* 288(1949): 20210240. https://doi.org/10.1098/rspb.2021.0240

Gage, John D., and Paul A. Tyler. 1991. *Deep-Sea Biology: A Natural History of Organisms at the Deep-Sea Floor*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139163637

Gaines, S., and J. Roughgarden. 1985. “Larval Settlement Rate: A Leading Determinant of Structure in an Ecological Community of the Marine Intertidal Zone.” *PNAS* 82(11): 3707–3711. https://doi.org/10.1073/pnas.82.11.3707

Garfield, Newell, Mathew E. Maltrud, Curtis A. Collins, Thomas A. Rago, and Robert G. Paquette. 2001. “Lagrangian Flow in the California Undercurrent, an Observation and Model Comparison.” *Journal of Marine Systems* 29(1–4): 201–220. https://doi.org/10.1016/S0924-7963(01)00017-3

Gaube, Peter, Camrin D. Braun, Gareth L. Lawson, Dennis J. McGillicuddy Jr., Alice Della Penna, Gregory B. Skomal, Chris Fischer, and Simon R. Thorrold. 2018. “Mesoscale Eddies Influence the Movements of Mature Female White Sharks in the Gulf Stream and Sargasso Sea.” *Scientific Reports* 8: 7363. https://doi.org/10.1038/s41598-018-25565-8

Gerringer, M. E., A. S. Dias, A. A. von Hagel, J. W. Orr, A. P. Summers, and S. Farina. 2021. “Habitat Influences Skeletal Morphology and Density in the Snailfishes (Family Liparidae).” *Frontiers in Zoology* 18: 16. https://doi.org/10.1186/s12983-021-00399-9

Gerringer, Mackenzie E., Tjomas D. Linley, and Jørgen G. Nielsen. 2021. “Revision of the Depth Record of Bony Fishes with Notes on Hadal Snailfishes (Liparidae, Scorpaeniformes) and Cusk Eels (Ophidiidae, Ophidiiformes).” *Marine Biology* 168: 167. https://doi.org/10.1007/s00227-021-03950-8

GESAMP. 1995. *The Sea-Surface Microlayer and Its Role in Global Change*. GESAMP Reports and Studies, No. 59. Geneva: World Meteorological Organization. http://www.gesamp.org/publications/the-sea-surface-microlayer-and-its-role-in-global-change

Gilson, H. Cary. 1937. “The Nitrogen Cycle.” In *The John Murray Expeditions 1933–34, Scientific Reports, Volume II: Meteorological, Chemical, and Physical Investigations*, 21–81. https://www.biodiversitylibrary.org/page/49520335

Gladyshev, Michail I. 1997. “Biophysics of the Surface Film of Aquatic Ecosystems.” In *The Sea Surface and Global Change*. Edited by Peter S. Liss and Robert A. Duce, 321–338. https://doi.org/10.1017/CBO9780511525025.011

Glover, Adrian G., and Craig R. Smith. 2003. “The Deep-Sea Floor Ecosystem: Current Status and Prospects of Anthropogenic Change by the Year 2025.” *Environmental Conservation* 30(3): 219–241. https://doi.org/10.1017/S0376892903000225

Glud, Ronnie N., Peter Berg, Bo Thamdrup, Morten Larsen, Heather A. Stewart, Alan J. Jamieson, Anni Glud, Kazumasa Oguri, Hamed Sanei, Ashley A. Rowden, and Frank Wenzhöfer. 2021. “Hadal Trenches Are Dynamic Hotspots for Early Diagenesis in the Deep Sea.” *Communications Earth and Environment* 2: 21. https://doi.org/10.1038/s43247-020-00087-2

Godø, Annette Samuelsen, Gavin J. Macaula, Ruben Patel, Solfrid Sætre Hjøllo, John Horne, Stein Kaartvedt, and Johnny A. Johannessen. 2012. “Mesoscale Eddies Are Oases for Higher Trophic Marine Life.” *PLoS ONE* 7(1): e30161. https://doi.org/10.1371/journal.pone.0030161

Golikov, A. N. 1985. “Zonations and Organismic Assemblages: Comments on the Comprehensive Review by Pérès (1982).” *Marine Ecology Progress Series* 23(2): 203–206. https://www.jstor.org/stable/24816815

Haddock, Stephen H. D., Mark A. Moline, and James F. Case. 2010. “Bioluminescence in the Sea.” *Annual Review of Marine Science* 2: 443–493. https://doi.org/10.1146/annurev-marine-120308-081028

Haeckel, Ernst. 1893. “Planktonic Studies: A Comparative Investigation of the Importance and Constitution of the Pelagic Fauna and Flora.” In *Report of the US Commissioner of Fish and Fisheries for 1889 to 1891*. Translated by George Field, 565–641. https://doi.org/10.5962/bhl.title.7615

Hall, Linnea S., Paul R. Krausman, and Michael L. Morrison. 1997. “The Habitat Concept and a Plea for Standard Terminology.” *Wildlife Society Bulletin* 25(1): 173–182. https://www.jstor.org/stable/3783301

Hardt, Marah J., and Carl Safina. 2010. “Threatening Ocean Life from the Inside Out.” *Scientific American* 303(2): 66–73. https://www.jstor.org/stable/26002133

Hardy, John T. 1982. “The Sea Surface Microlayer: Biology, Chemistry and Anthropogenic Enrichment.” *Progress in Oceanography* 11(4): 307–328. https://doi.org/10.1016/0079-6611(82)90001-5

———. 1997. “Biological Effects of Chemicals in the Sea-Surface Microlayer.” In *The Sea Surface and Global Change*. Edited by Peter S. Liss and Robert A. Duce, 287–320. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511525025.012

Hardy, John T., and Jack Word. 1986. “Contamination of the Water Surface in Puget Sound.” In *Puget Sound Notes*. Edited by Martha Burke, 3–6. Seattle: EPA Region 10. https://www.blueplanetpublishing.com/public-domain-references/

Harris, P. T., M. Macmillan-Lawler, J. Rupp, and E .K. Baker. 2014. “Geomorphology of the Oceans.” *Marine Geology* 352: 4–24. https://doi.org/10.1016/j.margeo.2014.01.011

Hawkins, Stephen J., Kathryn E. Pack, Kieran Hyder, Lisandro Benedetti-Cecchi, and Stuart R. Jenkins. 2020. "Rocky Shores as Tractable Test Systems for Experimental Ecology." *Journal of the Marine Biological Association of the United Kingdom* 100(7): 1017–1041. https://doi.org/10.1017/S0025315420001046

Heads, Michael. 2015. "The Relationship between Biogeography and Ecology: Envelopes, Models, Predictions." *Biological Journal of the Linnean Society* 115(2): 456–468. https://doi.org/10.1111/bij.12486

Hedgpeth, Joel W. 1957. "Classification of Marine Environments." In *Treatise on Marine Ecology and Paleoecology*. Edited by Joel W. Hedgpeth, 17–27. New York: The Geological Society of America. https://doi.org/10.1130/MEM67V1-p17

Heikkila, Tanya, and Andrea K. Gerlak. 2005. "The Formation of Large-Scale Collaborative Resource Management Institutions: Clarifying the Roles of Stakeholders, Science, and Institutions." *Policy Studies Journal* 33(4): 583–612. https://doi.org/10.1111/j.1541-0072.2005.00134.x

Hein, James R., Andrea Koschinsky, and Thomas Kuhn. 2020. "Deep-Ocean Polymetallic Nodules as a Resource for Critical Materials." *Nature Reviews Earth and Environment* 1: 158–169. https://doi.org/10.1038/s43017-020-0027-0

Helmuth, Brian. 2016. "Intertidal Zonation." In *Encyclopedia of Estuaries*. Edited by Michael Kennish, 361. Dordrecht: Springer. https://doi.org/10.1007/978-94-017-8801-4_293

Hendrickson, Brianna N., Sarah D. Brooks, Daniel C. O. Thornton, Richard H. Moore, Ewan Crosbie, Luke D. Ziemba, Craig A. Carlson, Nicholas Baetge, Jessica A. Mirrielees, and Alyssa N. Alsante. 2021. "Role of Sea Surface Microlayer Properties in Cloud Formation." *Frontiers in Marine Science* 18: 596225. https://doi.org/10.3389/fmars.2020.596225

Herndl, Gerhard, Barbara Bayer, Federico Baltar, and Thomas Reinthaler. 2023. "Prokaryotic Life in the Deep Ocean's Water Column." *Annual Review of Marine Science* 15: 461–483. https://doi.org/10.1146/annurev-marine-032122-115655

Herring, Peter. 2002. *The Biology of the Deep Ocean*. Oxford: Oxford University Press. https://global.oup.com/academic/product/the-biology-of-the-deep-ocean-9780198549550

Hewson, Ian, Joshua A. Steele, Douglas G. Capone, and Jed A. Fuhrman. 2006. "Remarkable Heterogeneity in Meso- and Bathypelagic Bacterioplankton Assemblage Composition." *Limnology and Oceanography* 51(3): 1274–1283. https://doi.org/10.4319/lo.2006.51.3.1274

Hidalgo, Manuel, and Howard Browman. 2019. "Developing the Knowledge Base Needed to Sustainably Manage Mesopelagic Resources." *ICES Journal of Marine Science* 76(3): 609–615. https://doi.org/10.1093/icesjms/fsz067

Hunter, Keith A. 1997. "Chemistry of the Sea-Surface Microlayer." In *The Sea Surface and Global Chang*. Edited by Peter S. Liss and Robert A. Duce, 1–34. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511525025.002

Hyman, Jayden, Rodney A. Stewart, Oz Sahin, Michael Clarke, and Malcolm R. Clark. 2022. "Visioning a Framework for Effective Environmental Management of Deep-Sea Polymetallic Nodule Mining: Drivers, Barriers, and Enablers**."** *Journal of Cleaner Production* 337: 130487. https://doi.org/10.1016/j.jclepro.2022.130487

Idyll, Clarence P. 1964. *Abyss: The Deep Sea and the Creatures That Live in It*. New York: Thomas Y. Crowell Company. https://archive.org/details/abyssdeepseacrea01idyl

Itou, M., I. Matsumura, and S. Noriki. 2000. "A Large Flux of Particulate Matter in the Deep Japan Trench Observed Just After the 1994 Sanriku-Oki Earthquake." *Deep Sea Research Part I: Oceanographic Research Papers* 47(10): 1987–1998. https://doi.org/10.1016/S0967-0637(00)00012-1

Iversen, Morten H. 2023. "Carbon Export in the Ocean: A Biologist's Perspective." *Annual Review of Marine Science* 15: 357–381. https://doi.org/10.1146/annurev-marine-032122-035153

Jamieson, Alan J. 2015. *The Hadal Zone: Life in the Deepest Oceans*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139061384

Jamieson, Alan J., L. S. R. Brooks, W. D. K. Reid, S. B. Piertney, B. E. Narayanaswamy, and T. D. Linley. 2019. "Microplastics and Synthetic Particles Ingested by Deep-Sea Amphipods in Six of the Deepest Marine Ecosystems on Earth." *Royal Society Open Science* 6(2): 180667. https://doi.org/10.1098/rsos.180667

Jamieson, Alan J., Toronobu Fujii, Daniel J. Mayor, Martin Solan, and Imants G. Priede. 2010. “Hadal Trenches: The Ecology of the Deepest Places on Earth.” *Trends in Ecology and Evolution* 25(3): 190–197. https://doi.org/10.1016/j.tree.2009.09.009

Jamieson, Alan J., and Heather A. Stewart. 2021. “Hadal Zones of the Northwest Pacific Ocean.” *Progress in Oceanography* 190: 102447. https://doi.org/10.1016/j.pocean.2020.102477

Jamieson, Alan J., Heather A. Stewart, Johanna N. J. Weston, Patrick Lahey, and Victor L. Vescovo. 2022. “Hadal Biodiversity, Habitats and Potential Chemosynthesis in the Java Trench, Eastern Indian Ocean.” *Frontiers in Marine Science* 9: 856992. https://doi.org/10.3389/fmars.2022.856992

Jamieson, Alan J., and Michael Vecchione. 2020. “First In Situ Observation of Cephalopoda at Hadal Depths (Octopoda: Opisthoteuthidae: *Grimpoteuthis* sp.).” *Marine Biology* 167: 82. https://doi.org/10.1007/s00227-020-03701-1

Jenkins, David G., and Robert E. Ricklefs. 2011. “Biogeography and Ecology: Two Views of One World.” *Philosophical Transactions of the Royal Society B* 366(1576): 2331–2335. https://doi.org/10.1098/rstb.2011.0064

Jones, Clive G., John H. Lawton, and Moshe Shachak. 1994. “Organisms as Ecosystem Engineers.” *Oikos* 69(3): 373–386. https://doi.org/10.2307/3545850

Kaartvedt, Stein, Tom J. Langbehn, and Dag L. Aksnes. 2019. “Enlightening the Ocean’s Twilight Zone.” *ICES Journal of Marine Science* 76(4): 803–812. https://doi.org/10.1093/icesjms/fsz010

Kaartvedt, Stein, Anders Røstad, and Dag Aksnes. 2017. “Changing Weather Causes Behavioral Responses in the Lower Mesopelagic.” *Marine Ecology Progress Series* 574: 259–263. https://doi.org/10.3354/meps12185

Kawagucci, Shinsuke, Akiko Makabe, Taketoshi Kodama, Yohei Matsui, Chisato Yoshikawa, Etsuro Ono, Masahide Wakita, Takuro Nunoura, Hiroshi Uchida, and Taichi Yokokawa. 2018. “Hadal Water Biogeochemistry over the Izu–Ogasawara Trench Observed with a Full-Depth CTD-CMS.” *Ocean Science* 14: 575–588. https://doi.org/10.5194/os-14-575-2018

Kennish, Michael J. 2016. “Littoral Zone.” In *Encyclopedia of Estuaries*. Edited by Michael Kennish, 385. Dordrecht: Springer. https://doi.org/10.1007/978-94-017-8801-4_238

Kishigami, Nobuhiro. 2021. “World Whaling and Recent Whaling Research Trends.” *Senri Ethnological Studies* 104: 1–30. http://doi.org/10.15021/00009653

Knox, George A. 2001. *The Ecology of Seashores*. Boca Raton: CRC Press. https://www.routledge.com/The-Ecology-of-Seashores/Knox/p/book/9780849300080

Koslow, J. Anthony, Pete Davison, Erica Ferrer, S. Patricia A. Jiménez Rosenberg, Gerardo Aceves-Medina, and William Watson. 2019. “The Evolving Response of Mesopelagic Fishes to Declining Midwater Oxygen Concentrations in the Southern and Central California Current.” *ICES Journal of Marine Science* 76(3): 626–638. https://doi.org/10.1093/icesjms/fsy154

Koslow, Tony. 2007. *The Silent Deep: The Discovery, Ecology, and Conservation of the Deep Sea*. Chicago: University of Chicago Press. https://www.google.com/books/edition/The_Silent_Deep/CJ8sAAAAYAAJ

Lack, David. 1933. “Habitat Selection in Birds. With Special Reference to the Effects of Afforestation on the Breckland Avifauna.” *Journal of Animal Ecology* 2(2): 239–262. https://doi.org/10.2307/961

Lan, Yi, Jin Sun, Douglas H. Bartlett, Greg W. Rouse, Harry G. Tabata, and Pei-Yuan Qian. 2016. “The Deepest Mitochondrial Genome Sequenced from Mariana Trench *Hirondellea gigas* (Amphipoda).” *Mitochndrial DNA Part B* 1(1): 802–803. https://doi.org/10.1080/23802359.2016.1214549

Langbehn, Tom J., Dag L. Aksnes, Stein Kaartvedt, Øyvind Fiksen, and Christian Jørgensen. 2019. “Light Comfort Zone in a Mesopelagic Fish Emerges from Adaptive Behaviour along a Latitudinal Gradient.” *Marine Ecology Progress Series* 623: 161–174. https://doi.org/10.3354/meps13024

Langbehn, Tom J., Dag L. Aksnes, Stein Kaartvedt, Øyvind Fiksen, Gabriella Ljungström, and Christian Jørgensen. 2021. “Poleward Distribution of Mesopelagic Fishes Is Constrained by Seasonality in Light.” *Global Ecology and Biogeography* 31(3): 546–561. https://doi.org/10.1111/geb.13446

Lappan, Rachael, Guy Shelley, Zahra F. Islam, Pok Man Leung, Scott Lockwood, Philipp A. Nauer, Thanavit Jirapanjawat, Gaofeng Ni, Ya-Jou Chen, Adam J. Kessler, Timothy J. Williams, Ricardo Cavicchioli, Federico Baltar, Perran L. M. Cook, Sergio E. Morales, and Chris Greening. 2023. "Molecular Hydrogen in Seawater Supports Growth of Diverse Marine Bacteria." *Nature Microbiology*. https://doi.org/10.1038/s41564-023-01322-0

Lavagnino, Ana Carolina, Alex Cardosa Bastos, Gilberto Menezes Amado Filho, Fernando Coreixas de Moraes, Lais Silva Araujo, and Rodrigo Leão de Moura. 2020. "Geomorphometric Seabed Classification and Potential Megahabitat Distribution in the Amazon Continental Margin." *Frontiers in Marine Science* 7: 190. https://doi.org/10.3389/fmars.2020.00190

Leitner, Astrid Brigitta, Tobias Friedrich, Christopher D. Kelley, Seth Travis, Dale Partridge, Brian Powell, and Jeffrey C. Drazen. 2021. "Biogeophysical Influence of Large-Scale Bathymetric Habitat Types on Mesophotic and Upper Bathyal Demersal Fish Assemblages: A Hawaiian Case Study." *Marine Ecology Progress Series* 659: 219–236. https://doi.org/10.3354/meps13581

Leray, Matthieu, and Ryuji J. Machida. 2020. "Seabed Mining Could Come at a High Price for a Unique Fauna." *Molecular Ecology* 29(23): 4506–4509. https://doi.org/10.1111/mec.15678

Levin, Lisa A., and Paul K. Dayton. 2009. "Ecological Theory and Continental Margins: Where Shallow Meets Deep." *Trends in Ecology and Evolution* 24(11): 606–617. https://doi.org/10.1016/j.tree.2009.04.012

Levin, Lisa A., Ron J. Etter, Michael A. Rex, Andrew J. Gooday, Craig R. Smith, Jesús Pineda, Carol T. Stuart, Robert R. Hessler, and David Pawson. 2001. "Environmental Influences on Regional Deep-Sea Species Diversity." *Annual Review of Ecology and Systematics* 32: 51–93. https://doi.org/10.1146/annurev.ecolsys.32.081501.114002

Levin, Lisa A., and Myriam Sibuet. 2012. "Understanding Continental Margin Biodiversity: A New Imperative." *Annual Review of Marine Science* 4: 79–112. https://doi.org/10.1146/annurev-marine-120709-142714

Lewis, John Robert. 1964. *The Ecology of Rocky Shores*. London: The English Universities Press. https://www.google.com/books/edition/The_Ecology_of_Rocky_Shores/GXIVAQAAIAAJ

Linley, Thomas D., Mackenzie E. Gerringer, Heather Ritchie, Johanna N. J. Weston, Amy Scott-Murray, Vincent Fernandez, Jhoann Canto-Hernández, Frank Wenzhöfer, Ronnie N. Glud, and Alan J. Jamieson. 2022. "Independent Radiation of Snailfishes into the Hadal Zone Confirmed by *Paraliparis selti* sp. nov. (Perciformes: Liparidae) from the Atacama Trench, SE Pacific." *Marine Biodiversity* 52: 56. https://doi.org/10.1007/s12526-022-01294-0

Liu, Xuehai, Yongzhi Liu, Wei Cao, and Chengjun Sun. 2020. "Water Characteristics of Abyssal and Hadal Zones in the Southern Yap Trench Observed with the Submersible *Jiaolong*." *Journal of Oceanology and Limnology* 38: 593–605. https://doi.org/10.1007/s00343-019-8368-6

Lluch-Belda, Daniel, Daniel B. Lluch-Cota, and Savador E. Lluch-Cota. 2005. "Changes in Marine Faunal Distributions and ENSO Events in the California Current." *Fisheries Oceanography* 14(6): 485–467. https://doi.org/10.1111/j.1365-2419.2005.00347.x

Lowerre-Barbieri, Susan K., Roland Kays, James T. Thorson, and Martin Wikelski. 2019. "The Ocean's Movescape: Fisheries Management in the Bio-Logging Decade (2018–2028)." *ICES Journal of Marine Science* 76(2): 477–488. https://doi.org/10.1093/icesjms/fsy211

Lubchenco, Jane. 1980. "Algal Zonation in the New England Rocky Intertidal Community: An Experimental Analysis." *Ecology* 61(2): 333–344. https://doi.org/10.2307/1935192

Maas, Amy E., Sarah L. Frazar, Dawn M. Outram, Brad A. Seibel, and Karen F. Wishner. 2014. "Fine-Scale Vertical Distribution of Macroplankton and Micronekton in the Eastern Tropical North Pacific in Association with an Oxygen Minimum Zone." *Journal of Plankton Research* 36(6): 1557–1575. https://doi.org/10.1093/plankt/fbu077

MacDonald, A. G. 1997. "Hydrostatic Pressure as an Environmental Factor in Life Processes." *Comparative Biochemistry and Physiology Part A: Physiology* 116(4): 291–297. https://doi.org/10.1016/S0300-9629(96)00354-4

MacGillivray, Greg, director. 1995. *The Living Sea*. Laguna Beach, CA: MacGillivray Freeman Films. Film. 40 minutes.

MacIntyre, Ferren. 1974. "The Top Millimeter of the Ocean." *Scientific American* 5: 67–77. https://www.jstor.org/stable/24950076

Marra, John F., Veronica P. Lance, Robert D. Vaillancourt, and Bruce R. Hargreaves. 2014. “Resolving the Ocean’s Euphotic Zone.” *Deep Sea Research Part I: Oceanographic Research Papers* 83: 45–50. https://doi.org/10.1016/j.dsr.2013.09.005

Martini, Séverine, and Stephen H. D. Haddock. 2017. “Quantification of Bioluminescence from the Surface to the Deep Sea Demonstrates Its Predominance as an Ecological Trait.” *Scientific Reports* 7: 45750. https://doi.org/10.1038/srep45750

Mauchline, John, and John D. M. Gordon. 1991. “Oceanic Pelagic Prey of Benthopelagic Fish in the Benthic Boundary Layer of a Marginal Oceanic Region.” *Marine Ecology Progress Series* 74(2/3): 109–115. https://www.jstor.org/stable/24825817

MBARI. 2023. “Psychedelic Jelly, *Crossota millsae*.” Monterey Bay Aquarium Research Institute (MBARI). Accessed March 5, 2023. https://www.mbari.org/animal/psychedelic-jelly/

McClain, Craig R., Thomas J. Webb, Clifton C. Nunnally, S. River Dixon, Seth Finnegan, and James A. Nelson. 2020. “Metabolic Niches and Biodiversity: A Test Case in the Deep Sea Benthos.” *Frontiers in Marine Science* 7: 216. https://doi.org/10.3389/fmars.2020.00216

McGillicuddy, Dennis J., Jr. 2016. “Mechanisms of Physical-Biological-Biogeochemical Interaction at the Oceanic Mesoscale.” *Annual Review of Marine Science* 8: 125–159. https://doi.org/10.1146/annurev-marine-010814-015606

Meinvielle, M., and Gregory C. Johnson. 2013. “Decadal Water-Property Trends in the California Undercurrent, with Implications for Ocean Acidification.” *Journal of Geophysical Research Oceans* 118(12): 6687–6703. https://doi.org/10.1002/2013JC009299

Menard, H. W., and Stuart M. Smith. 1966. “Hypsometry of Ocean Basin Provinces.” *Journal of Geophysical Research* 71(18): 4305–4325. https://doi.org/10.1029/JZ071i018p04305

Menge, Bruce A., and George M. Branch. 2001. “Rocky Intertidal Communities.” In *Marine Community Ecology*. Edited by Mark D. Bertness, Steven D. Gaines, and Mark E. Hay, 221–251. Sunderland: Sinauer Associates. https://www.google.com/books/edition/Marine_Community_Ecology/EEp4QgAACAAJ

Menge, B. A., J. Lubchenco, M. E. S. Bracken, F. Chan, M. M. Foley, T. L. Freidenburg, S. D. Gaines, G. Hudson, C. Krenz, H. Leslie, D. N. L. Menge, R. Russell, and M. S. Webster. 2003. “Coastal Oceanography Sets the Pace of Rocky Intertidal Community Dynamics.” *PNAS* 100(21): 12229–12234. https://doi.org/10.1073/pnas.1534875100

Menot, Lenaick, Myriam Sibuet, Robert S. Carney, Lisa A. Levin, Gilbert T. Rowe, David S. M. Billett, Gary Poore, Hiroshi Kitazato, Ann Vanreusel, Joëlle Galéron, Helena P. Lavrado, Javier Sellanes, Baban Ingole, and Elena Krylova. 2010. “New Perceptions of Continental Margin Biodiversity.” In *Life in the World’s Oceans: Diversity, Distribution, and Abundance*. Edited by Alasdair D. McIntyre, 79–101. Oxford: Blackwell Publishing. https://doi.org/10.1002/9781444325508.ch5

Menzies, Dr. Robert J., and M. Selvakumaran. 1974. “The Effects of Hydrostatic Pressure on Living Aquatic Organisms VI. Organic Complexity and Hydrostatic Pressure Sensitivity.” *Internationale Revue der gesamten Hydrobiologie und Hydrographie* 59(2): 207–212. https://doi.org/10.1002/iroh.19740590207

Mignot, Alexandre, Hervé Claustre, Julia Uitz, Antoine Poteau, Fabrizio D’ Ortenzio, and Xiaogang Xing. 2014. “Understanding the Seasonal Dynamics of Phytoplankton Biomass and the Deep Chlorophyll Maximum in Oligotrophic Environments: A Bio-Argo Float Investigation**.”** *Global Biogeochemical Cycles* 28(8): 856–876. https://doi.org/10.1002/2013GB004781

Morris, Douglas W. 2005. “Habitat-Dependent Foraging in a Classic Predator–Prey System: A Fable from Snowshoe Hares.” *Oikos* 109(2): 239–254. https://doi.org/10.1111/j.0030-1299.2005.13789.x

Moyle, Peter B., and Joseph J. Cech. 2004. *Fishes: An Introduction to Ichthyology*. 5th ed. Upper Saddle River: Prentice Hall. https://www.pearson.com/en-us/subject-catalog/p/fishes-an-introduction-to-ichthyology/P200000006918/9780131008472

Mustaffa, Nur Ili Hamizah, Thomas H. Badewien, Mariana Ribas-Ribas, and Oliver Wurl. 2018. “High-Resolution Observations on Enrichment Processes in the Sea-Surface Microlayer.” *Scientific Reports* 8: 13122. https://doi.org/10.1038/s41598-018-31465-8

Nagata, Toshi, Christian Tamburini, Javier Arístegui, Federico Baltar, Alexander B. Bochdansky, Serena Fonda-Umani, Hideki Fukuda, Alexandra Gogou, Dennis A. Hansell, Roberta L. Hansman, Gerhard J. Herndl, Christos Panagiotopoulos, Thomas Reinthaler, Rumi Sohrin, Pedro Verdugo, Namiha Yamada, Youhei Yamashita, Taichi Yokokawa, and Douglas H. Bartlett. 2010. “Emerging Concepts on Microbial Processes in the Bathypelagic Ocean—Ecology, Biogeochemistry, and Genomics.” *Deep Sea Research Part II: Topical Studies in Oceanography* 57(16): 1519–1536. https://doi.org/10.1016/j.dsr2.2010.02.019

Nanajkar, Mandar, Kalyan De, Aniket Desai, Sambhaji Mote, and Sabyasachi Sautya. 2022. “Ecology of Cold Seep Habitats.” In *Systems Biogeochemistry of Major Marine Biomes*. Edited by Aninda Mazumdar and Wriddhiman Ghosh, 263–283. Hoboken: Wiley. https://doi.org/10.1002/9781119554356.ch13

Niespolo, Elizabeth M., Warren D. Sharp, Graham Avery, and Todd E. Dawson. 2021. “Early, Intensive Marine Resource Exploitation by Middle Stone Age Humans at Ysterfontein 1 Rockshelter, South Africa.” *PNAS* 118(16): e2020042118. https://doi.org/10.1073/pnas.2020042118

NOAA. 2023. “How Far Does Light Travel in the Ocean?” NOAA Ocean Exploration. Accessed February 13, 2023. https://oceanexplorer.noaa.gov/facts/light-distributed.html

Oguri, Kazumasa, Kiichiro Kawamura, Arito Sakaguchi, Takashi Toyofuku, Takafumi Kasaya, Masafumi Murayama, Katsunori Fujikura, Ronnie N. Glud, and Hiroshi Kitazato. 2013. “Hadal Disturbance in the Japan Trench Induced by the 2011 Tohoku–Oki Earthquake.” *Scientific Reports* 3: 1915. https://doi.org/10.1038/srep01915

Oguri, Kazumasa, Pere Masqué, Matthias Zabel, Heather A. Stewart, Gillian MacKinnon, Ashley A. Rowden, Peter Berg, Frank Wenzhöfer, and Ronnie N. Glud. 2022. “Sediment Accumulation and Carbon Burial in Four Hadal Trench Systems.” *JGR Biogeosciences* 127(10): e2022JG006814. https://doi.org/10.1029/2022JG006814

Orellana-Rovirosa, Felipe, and Mark Richards. 2017. “Rough Versus Smooth Topography along Oceanic Hotspot Tracks: Observations and Scaling Analysis.” *Geophysical Research Letters* 44(9): 4074–4081. https://doi.org/10.1002/2016GL072008

Oschlies, Andreas, Peter Brandt, Lothar Stramma, and Sunke Schmidtko. 2018. “Drivers and Mechanisms of Ocean Deoxygenation.” *Nature Geoscience* 11: 467–473. https://doi.org/10.1038/s41561-018-0152-2

Paine, Robert T. 1974. “Intertidal Community Structure: Experimental Studies on the Relationship between a Dominant Competitor and Its Principal Predator.” *Oecologia* 15: 93–120. https://doi.org/10.1007/BF00345739

———. 1994. *Marine Rocky Shores and Community Ecology: An Experimentalist’s Perspective*. Oldendorf/Luhe: Inter-Research Science. https://www.int-res.com/?id=7888

Palomares, M. L. D., and D. Pauly. 2022. “*Poralia rufescens* Vanhöffen, 1902.” SeaLifeBase. Accessed February 28, 2023. https://www.sealifebase.ca/summary/Poralia-rufescens.html

Paterson, Shane E. 1998. “Group Occurrence of Great Barracuda (*Sphyraena barracuda*) in the Turks and Caicos Islands.” *Bulletin of Marine Science* 63(3): 633–638. https://www.ingentaconnect.com/content/umrsmas/bullmar/1998/00000063/00000003/art00018

Paulus, Eva. 2021. “Shedding Light on Deep-Sea Biodiversity—A Highly Vulnerable Habitat in the Face of Anthropogenic Change.” *Frontiers in Marine Science* 8: 667048. https://doi.org/10.3389/fmars.2021.667048

Pearsall, W. H. 1917. “The Aquatic and Marsh Vegetation of Esthwaite Water.” *Journal of Ecology* 5(3/4): 180–202. https://doi.org/10.2307/2255656

Peng, Guyu, Richard Bellerby, Feng Zhang, Xuerong Sun, and Daoji Li. 2020. “The Ocean’s Ultimate Trashcan: Hadal Trenches as Major Depositories for Plastic Pollution.” *Water Research* 168: 115121. https://doi.org/10.1016/j.watres.2019.115121

Penna, Alice Della, and Peter Gaube. 2020. “Mesoscale Eddies Structure Mesopelagic Communities.” *Frontiers in Marine Science* 7: 454. https://doi.org/10.3389/fmars.2020.00454

Pérès, J. M. 1982. “Zonations.” In *Marine Ecology, a Comprehensive, Integrated Treatise on Life in Oceans and Coastal Waters. Volume V: Ocean Management, Part 1*. Edited by O. Kinne, 9–45. New York: Wiley. https://www.google.com/books/edition/Marine_Ecology/GV0ewAEACAAJ

Polzin, K. L., J. M. Toole, J. R. Ledwell, and R. W. Schmitt. 1997. “Spatial Variability of Turbulent Mixing in the Abyssal Ocean.” *Science* 276(5309): 93–96. https://doi.org/10.1126/science.276.5309.93

Priede, Imants G. 2017. *Deep-Sea Fishes: Biology, Diversity, Ecology, and Fisheries*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781316018330

Proud, Roland, Nils Olav Handegard, Rudy J. Kloser, Martin J. Cox, and Andrew Brierley. 2019. “From Siphonophores to Deep Scattering Layers: Uncertainty Ranges for the Estimation of Global Mesopelagic Fish Biomass.” *ICES Journal of Marine Science* 76(3): 718–733. https://doi.org/10.1093/icesjms/fsy037

Rabone, Muriel, Joris. H. Wiethase, Erik Simon-Lledó, Aidan M. Emery, Daniel O. B. Jones, Thomas G. Dahlgren, Guadalupe Bribiesca-Contreras, Helen Wiklund, Tammy Horton, and Adrian Glover. 2023. “How Many Metazoan Species Live in the World’s Largest Mineral Exploration Region?” *Current Biology* 33: 1–14. https://doi.org/10.1016/j.cub.2023.04.052

Raffaelli, David, and Stephen Hawkins. 1999. *Intertidal Ecology*. Dordrecht: Springer. https://doi.org/10.1007/978-94-009-1489-6

Rahav, Eyal, Jacob Silverman, Ofrat Raveh, Or Hazan, Maxim Rubin-Blum, Christina Zeri, Alexandra Gogou, Martina Kralj, Alexandra Pavlidou, and Nurit Kress. 2019. “The Deep Water of Eastern Mediterranean Sea Is a Hotspot for Bacterial Activity.” *Deep Sea Research Part II: Topical Studies in Oceanography* 164: 135–143. https://doi.org/10.1016/j.dsr2.2019.03.004

Ramirez-Llodra, Eva. 2020. “Deep-Sea Ecosystems: Biodiversity and Anthropogenic Impacts.” In *The Law of the Seabed: Access, Uses, and Protection of Seabed Resources*. Edited by Catherine Banet, 36–60. Boston: Brill Nijhoff. https://doi.org/10.1163/9789004391567_004

Ramirez-Llodra, E., A. Brandt, R. Danovaro, B. De Mol, E. Escobar, C. R. German, L. A. Levin, P. Martinez Arbizu, L. Menot, P. Buhl-Mortensen, B. E. Narayanaswamy, C. R. Smith, D. P. Tittensor, P. A. Tyler, A. Vanreusel, and M. Vecchione. 2010. “Deep, Diverse, and Definitely Different: Unique Attributes of the World’s Largest Ecosystem.” *Biogeosciences* 7: 2851–2899. https://doi.org/10.5194/bg-7-2851-2010

Rathburn, A. E., L. A. Levin, M. Tryon, J. M. Gieskes, J. B. Martin, M. E. Pérez, F. J. Fodrie, C. Neira, G. J. Fryer, G. Mendoza, P. A. McMillan, J. Kluesner, J. Adamic, and W. Ziebis. 2009. “Geological and Biological Heterogeneity of the Aleutian Margin (1965–4822 m).” *Progress in Oceanography* 80(1–2): 22–50. https://doi.org/10.1016/j.pocean.2008.12.002

Rex, Michael A., and Ron J. Etter. 2010. *Deep-Sea Biodiversity*. Cambridge: Harvard University Press. https://www.hup.harvard.edu/catalog.php?isbn=9780674036079

Ribas-Ribas, Mariana, Frank Helleis, Janina Rahlff, and Oliver Wurl. 2018. “Air-Sea CO_2-Exchange in a Large Annular Wind-Wave Tank and the Effects of Surfactants.” *Frontiers in Marine Science* 5: 457. https://doi.org/10.3389/fmars.2018.00457

Ricketts, Edward F., and Jack Calvin. 1962. *Between Pacific Tides*. 3rd ed. Stanford: Stanford University Press. https://archive.org/details/betweenpacificti00rick

Ricketts, Edward F., Jack Calvin, and Joel W. Hedgpeth. 1985. *Between Pacific Tides*. 5th ed. Stanford: Stanford University Press. https://www.sup.org/books/title/?id=3019

Riehl, Torben, Anne-Cathrin Wölfl, Nico Augustin, Colin W. Devey, and Angelika Brandt. 2020. “Discovery of Widely Available Abyssal Rock Patches Reveals Overlooked Habitat Type and Prompts Rethinking Deep-Sea Biodiversity.” *PNAS* 117(27): 15450–15459. https://doi.org/10.1073/pnas.1920706117

Robinson, Carol. 2019. “Microbial Respiration, the Engine of Ocean Deoxygenation.” *Frontiers in Marine Science* 5: 533. https://doi.org/10.3389/fmars.2018.00533

Robinson, Carol, Deborah K. Steinberg, Thomas R. Anderson, Javier Arístegui, Craig A. Carlson, Jessica R. Frost, Jean-François Ghiglione, Santiago Hernández-León, George A. Jackson, Rolf Koppelmann, Bernard Quéguiner, Olivier Ragueneau, Fereidoun Rassoulzadegan, Bruce H. Robison, Christian Tamburini, Tsuneo Tanaka, Karen F. Wishner, and Jing Zhang. 2010. “Mesopelagic Zone Ecology and Biogeochemistry—A Synthesis.” *Deep Sea Research Part II: Tropical Studies in Oceanography* 57(16): 1504–1518. https://doi.org/10.1016/j.dsr2.2010.02.018

Robison, Bruce H. 2009. “Conservation of Deep Pelagic Biodiversity.” *Conservation Biology* 23(4): 847–858. https://doi.org/10.1111/j.1523-1739.2009.01219.x

Robles, Carlos, and Robert Desharnais. 2002. “History and Current Development of a Paradigm of Predation in Rocky Intertidal Communities.” *Ecology* 83(6): 1521–1536. https://doi.org/10.1890/0012-9658(2002)0832.0.CO;2

Roemmich, Dean, Matthew H. Alford, Hervé Claustre, Kenneth Johnson, Brian King, James Moum, Peter Oke, W. Brechner Owens, Sylvie Pouliquen, Sarah Purkey, Megan Scanderbeg, Toshio Suga, Susan Wijffels, Nathalie Zilberman, Dorothee Bakker,

Molly Baringer, Mathieu Belbeoch, Henry C. Bittig, Emmanuel Boss, Paulo Calil, Fiona Carse, Thierry Carva, Fei Chai, Diarmuid Ó. Conchubhair, Fabrizio d'Ortenzio, Giorgio Dall'Olmo, Damien Desbruyeres, Katja Fennel, Ilker Fer, Raffaele Ferrari, Gael Forget, Howard Freeland, Tetsuichi Fujiki, Marion Gehlen, Blair Greenan, Robert Hallberg, Toshiyuki Hibiya, Shigeki Hosoda, Steven Jayne, Markus Jochum, Gregory C. Johnson, KiRyong Kang, Nicolas Kolodziejczyk, Arne Körtzinger, Pierre-Yves Le Traon, Yueng-Djern Lenn, Guillaume Maze, Kjell Arne Mork, Tamaryn Morris, Takeyoshi Nagai, Jonathan Nash, Alberto Naveira Garabato, Are Olsen, Rama Rao Pattabhi, Satya Prakash, Stephen Riser, Catherine Schmechtig, Claudia Schmid, Emily Shroyer, Andreas Sterl, Philip Sutton, Lynne Talley, Toste Tanhua, Virginie Thierry, Sandy Thomalla, John Toole, Ariel Troisi, Thomas W. Trull, Jon Turton, Pedro Joaquin Velez-Belchi, Waldemar Walczowski, Haili Wang, Rik Wanninkhof, Amy F. Waterhouse, Stephanie Waterman, Andrew Watson, Cara Wilson, Annie P. S. Wong, Jianping Xu, and Ichiro Yasuda. 2019. "On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array." *Frontiers in Marine Science* 6: 439. https://doi.org/10.3389/fmars.2019.00439

Rogers, Alex David. 2015. "Environmental Change in the Deep Ocean." *Annual Review of Environment and Resources* 40: 1–38. https://doi.org/10.1146/annurev-environ-102014-021415

Røstad, Anders, Stein Kaartvedt, and Dag Aksnes. 2016. "Light Comfort Zones of Mesopelagic Acoustic Scattering Layers in Two Contrasting Optical Environments." *Deep Sea Research Part I: Oceanographic Research Papers* 113: 1–6. https://doi.org/10.1016/j.dsr.2016.02.020

Ryther, John H. 1956. "The Measurement of Primary Production." *Limnology and Oceanography* 1(2): 72–84. https://doi.org/10.4319/lo.1956.1.2.0072

Sanders, Howard L. 1968. "Marine Benthic Diversity: A Comparative Study." *American Naturalist* 102(925): 243–282. https://www.jstor.org/stable/2459027

Schorr, Gregory S., Erin A. Falcone, David J. Moretti, and Russel D. Andrews. 2014. "First Long-Term Behavioral Records from Cuvier's Beaked Whales (*Ziphius cavirostris*) Reveal Record-Breaking Dives." *PLoS ONE* 9(3): e92633. https://doi.org/10.1371/journal.pone.0092633

Semeniuk, Vic, and Margaret Brocx. 2016. "Beach Processes." In *Encyclopedia of Estuaries*. Edited by Michael L. Kennish, 55–73. Dordrecht: Springer. https://doi.org/10.1007/978-94-017-8801-4_304

Shafer, Deborah J., Timothy D. Sherman, and Sandy Wyllie-Echeverria. 2007. "Do Dessication Tolerances Control the Vertical Distribution of Intertidal Seagrasses?" *Aquatic Botany* 87(2): 161–166. https://doi.org/10.1016/j.aquabot.2007.04.003

Sieburth, John McN. 1983. "Microbiological and Organic-Chemical Processes in the Surface and Mixed Layers." In *Air-Sea Exchange of Gases and Particles*. NATO ASI Series, vol. 108. Edited by P. S. Liss and W. G. N. Slinn, 121–172. Dordrecht: Springer. https://doi.org/10.1007/978-94-009-7169-1_3

Sigwart, Julia D., Angelika Brandt, Davide Di Franco, Elva Escobar Briones, Sarah Gerken, Andrew J. Gooday, Candace J. Grimes, Kamila Głuchowska, Sven Hoffmann, Anna Maria Jażdżewska, Elham Kamyab, Andreas Kelch, Henry Knauber, Katharina Kohlenbach, Olmo Miguez-Salas, Camille Moreau, Akito Ogawa, Angelo Poliseno, Andreu Santín Muriel, Anne Helene S. Tandberg, Franziska I. Theising, Thomas Walter, Anne-Cathrin Wölfl, and Chong Chen. 2023. "Heterogeneity on the Abyssal Plains: A Case Study in the Bering Sea." *Frontiers in Marine Science* 9: 1037482. https://doi.org/10.3389/fmars.2022.1037482

Simon, Matt. 2020. "These Scary Deep-Sea Fish Absorb Almost All the Light That Hits Them." *Wired*. July 19, 2020. https://www.wired.co.uk/article/deep-sea-fish

Skomal, G. B., C. D. Braun, J. H. Chisholm, and S. R. Thorrold. 2017. "Movements of the White Shark *Carcharodon carcharias* in the North Atlantic Ocean." *Marine Ecology Progress Series* 580: 1–16. https://doi.org/10.3354/meps12306

Smith, Craig R., Fabio C. De Leo, Angelo F. Bernardino, Andrew K. Sweetman, and Pedro Martinez Arbizu. 2008. "Abyssal Food Limitation, Ecosystem Structure, and Climate Change." *Trends in Ecology and Evolution* 23(9): 518–528. https://doi.org/10.1016/j.tree.2008.05.002

Snelgrove, Paul V. R. 1999. "Getting to the Bottom of Marine Biodiversity: Sedimentary Habitats: Ocean Bottoms Are the Most Widespread Habitat on Earth and Support High Biodiversity and Key Ecosystem Services." *BioScience* 49(2): 129–138. https://doi.org/10.2307/1313538

Snelgrove, Paul V. R., and Craig R. Smith. 2002. “A Riot of Species in an Environmental Calm: The Paradox of the Species-Rich Deep-Sea Foor.” In *Oceanography and Marine Biology: An Annual Review*. Vol. 40. Edited by R. N. Gibson, Margaret Barnes, and R. J. A. Atkinson, 311–342. London: CRC Press. https://doi.org/10.1201/9780203180594

Southern, R. 1911–1915. “Marine Ecology.” *Proceedings of the Royal Irish Academy. Section B: Biological, Geological, and Chemical Science Volume 31, A Biological Survey of Clare Island in the County of Mayo, Ireland and of the Adjoining District*. Pages 67.1-67.110. Dublin: Hodges, Figgis, and Co. https://www.jstor.org/stable/20517047

Staby, Arved, and Dag L. Aksnes. 2011. “Follow the Light—Diurnal and Seasonal Variations in Vertical Distribution of the Mesopelagic Fish *Maurolicus muelleri*.” *Marine Ecology Progress Series* 422: 265–273. https://doi.org/10.3354/meps08938

Steinbeck, John. 1945. *Cannery Row*. New York: Viking. https://archive.org/details/canneryrow0000stei/mode/2up

———. 1951. *The Log from the Sea of Cortez*. New York: Viking. https://archive.org/details/logfromseaofcort0000stei/mode/2up

Stephenson, T. A., and Anne Stephenson. 1949. “The Universal Features of Zonation Between Tide-Marks on Rocky Coasts.” *Journal of Ecology* 37(2): 289–305. https://doi.org/10.2307/2256610

———. 1972. *Life Between Tidemarks on Rocky Shores*. New York: W. H. Freeman. https://www.google.com/books/edition/Life_Between_Tidemarks_on_Rocky_Shores/3StuQgAACAAJ

Stewart, Heather A., and Alan J. Jamieson. 2018. “Habitat Heterogeneity of Hadal Trenches: Considerations and Implications for Future Studies.” *Progress in Oceanography* 161: 47–65. https://doi.org/10.1016/j.pocean.2018.01.007

St. John, Michael A., Angel Borja, Guillem Chust, Michael Heath, Ivo Grigorov, Patrizio Mariana, Adrian P. Martin, and Ricardo S. Santos. 2016. “A Dark Hole in Our Understanding of Marine Ecosystems and Their Services: Perspectives from the Mesopelagic Community.” *Frontiers in Marine Science* 3: 31. https://doi.org/10.3389/fmars.2016.00031

Stratmann, Tanja, Karline Soetaert, Daniel Kerksen, and Dick van Oevelen. 2021. “Polymetallic Nodules Are Essential for Food-Web Integrity of a Prospective Deep-Seabed Mining Area in Pacific Abyssal Plains.” *Scientific Reports* 11: 12238. https://doi.org/10.1038/s41598-021-91703-4

Suess, Erwin. 2014. “Marine Cold Seeps and Their Manifestations: Geological Control, Biogeochemical Criteria, and Environmental Conditions.” *International Journal of Earth Sciences* 103: 1889–1916. https://doi.org/10.1007/s00531-014-1010-0

———. 2020. “Marine Cold Seeps: Background and Recent Advances. In *Hydrocarbons, Oils and Lipids: Diversity, Origin, Chemistry and Fate*.” Edited by Heinz Wilkes, 747–767. Cham: Springer. https://doi.org/10.1007/978-3-319-90569-3_27

Sumner, Francis Bertody. 1910. *An Intensive Study of the Fauna and Flora of a Restricted Area of Sea Bottom*. Washington, DC: US Government Printing Office. https://www.google.com/books/edition/An_Intensive_Study_of_the_Fauna_and_Flor/jTYaAAAAYAAJ

Sutton, Tracey T. 2013. “Vertical Ecology of the Pelagic Ocean: Classical Patterns and New Perspectives.” *Journal of Fish Biology* 83(6): 1508–1527. https://doi.org/10.1111/jfb.12263

Sutton, Tracey T., and Rosanna J. Milligan. 2019. “Deep-Sea Ecology.” In *Encyclopedia of Ecology*. Vol. 1, 2nd ed. Edited by Brian Fath, 35–45. Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.11010-3

Sutton, Tracey T., Peter H. Wiebe, Laurence Madin, and Ann Bucklin. 2010. “Diversity and Community Structure of Pelagic Fishes to 5000 m Depth in the Sargasso Sea.” *Deep Sea Research Part II: Topical Studies in Oceanography* 57(24–26): 2220–2233. https://doi.org/10.1016/j.dsr2.2010.09.024

Sverdrup, H. U., Martin W. Johnson, and Richard H. Fleming. 1942. *The Oceans: Their Physics, Chemsitry, and General Biology*. New York: Prentice Hall. http://ark.cdlib.org/ark:/13030/kt167nb66r/

Talley, Lynne D., George L. Pickard, William J. Emery, and James H. Swift. 2011. *Descriptive Physical Oceanography, An Introduction*, 6th ed. London: Elsevier. https://doi.org/10.1016/C2009-0-24322-4

Tamm, Eric Enno. 2004. *Beyond the Outer Shores: The Untold Odyssey of Ed Ricketts, the Pioneering Ecologist Who Inspired John Steinbeck and Joseph Campbell*. Vancouver: Raincoast Books. https://www.perseusbooks.com/titles/eric-enno-tamm/beyond-the-outer-shores/9781560256892/

Trombley, Carolyn A., and Karl Cottenie. 2019. “Quantifying the Scientific Cost of Ambiguous Terminology in Community Ecology.” *Philosophical Topics* 47(1): 203–218. https://www.jstor.org/stable/26948099

Underwood, A. J. 2000. “Experimental Ecology of Rocky Intertidal Habitats: What Are We Learning?” *Journal of Experimental Marine Biology and Ecology* 250(1–2): 51–76. https://doi.org/10.1016/S0022-0981(00)00179-9

UNESCO. 2009. *Global Open Oceans and Deep Seabed (GOODS)—Biogeographic Classification*. IOC Technical Series 84. Paris: UNESCO-IOC. 87 pages. https://portals.iucn.org/library/node/28598

Vacquié-Garcia, Jade, François Royer, Anne-Cécile Dragon, Morgane Viviant, Frédéric Bailleul, and Christophe Guinet. 2012. “Foraging in the Darkness of the Southern Ocean: Influence of Bioluminescence on a Deep Diving Predator.” *PLoS ONE* 7(8): e43565. https://doi.org/10.1371/journal.pone.0043565

Valentine, Page C., Brian J. Todd, and Vladimir E. Kostylev. 2005. “Classification of Marine Sublittoral Habitats, with Application to the Northeastern North America Region.” *American Fisheries Society Symposium* 41: 183–200. https://doi.org/10.47886/9781888569605.ch18

Verrill, A. E., and S. I. Smith. 1874. “Report Upon the Invertebrate Animals of Vineyard Sound and Adjacent Waters, with an Account of the Physical Features of the Region.” Extracted from the report of Professor S. F. Baird, Commissioner of Fish and Fisheries, *On the Condition of the Sea-Fisheries of the South Coast of New England in 1871 and 1872*. Pages 295–513. Washington, DC: US Government Printing Office. https://doi.org/10.5962/bhl.title.11688

Walsh, Emily A., John B. Kirkpatrick, Scott D. Rutherford, David C. Smith, Mitchell Sogin, and Steven D’Hondt. 2016. “Bacterial Diversity and Community Composition from Seasurface to Subseafloor.” *ISME Journal* 10: 979–989. https://doi.org/10.1038/ismej.2015.175

Wang, Yuan, Jinhui Zhang, Jiancheng Yu, Qiaoyan Wu, and Dong Sun. 2023. “Anticyclonic Mesoscale Eddy Induced Mesopelagic Biomass Hotspot in the Oligotrophic Ocean.” *Journal of Marine Systems* 237: 103831. https://doi.org/10.1016/j.jmarsys.2022.103831

Wangersky, Peter J. 1976. “The Surface Film as a Physical Environment.” *Annual Review of Ecology and Systematics* 7: 161–176. https://doi.org/10.1146/annurev.es.07.110176.001113

Warming, Eugenius. 1909. *Oecology of Plants: An Introduction to the Study of Plant-Communities*. Oxford: Clarendon Press. https://doi.org/10.5962/bhl.title.23133

Washington Department of Fish and Wildlife (WADFW). 2023. “Striped Marlin (*Tetrapturus audax*): State Record.” Washington Department of Fish and Wildlife. Accessed February 12, 2023. https://wdfw.wa.gov/species-habitats/species/tetrapturus-audax#state-record

Waterhouse, Amy F., Jennifer A. MacKinnon, Jonathan D. Nash, Matthew H. Alford, Eric Kunze, Harper L. Simmons, Kurt L. Polzin, Louis C. St. Laurent, Oliver M. Sun, Robert Pinkel, Lynne D. Talley, Caitlin B. Whalen, Tycho N. Huussen, Glenn S. Carter, Ilker Fer, Stephanie Waterman, Alberto C. Naveira Garabato, Thomas B. Sanford, and Craig M. Lee. 2014. “Global Patterns of Diapycnal Mixing from Measurements of the Turbulent Dissipation Rate.” *Journal of Physical Oceanography* 44(7): 1854–1872. https://doi.org/10.1175/JPO-D-13-0104.1

Weitzman, Benjamin, Brenda Konar, Katrin Iken, Heather Coletti, Daniel Monson, Robert Suryan, Thomas Dean, Dominic Hondolero, and Mandy Lindeberg. 2021. “Changes in Rocky Intertidal Community Structure During a Marine Heatwave in the Northern Gulf of Alaska.” *Frontiers in Marine Science* 8: 556820. https://doi.org/10.3389/fmars.2021.556820

Whitney, Jonathan L., Jamison M. Gove, Margaret A. McManus, Katharine A. Smith, Joey Lecky, Philipp Neubauer, Jana E. Phipps, Emily A. Contreras, Donald R. Kobayashi, and Gregory P. Asner. 2021. “Surface Slicks Are Pelagic Nurseries for Diverse Ocean Fauna.” *Scientific Reports* 11: 3197. https://doi.org/10.1038/s41598-021-81407-0

Wishner, K. F. 1980. “The Biomass of the Deep-Sea Benthopelagic Plankton.” *Deep Sea Research Part A. Oceanographic Research Papers* 27(3–4): 203–204, IN1, 205–216. https://doi.org/10.1016/0198-0149(80)90012-6

Wishner, K. F., B. A. Seibel, C. Roman, C. Deutsch, D. Outram, C. T. Shaw, M. A. Birk, K. A. S. Mislan, T. J. Adams, D. Moore, and S. Riley. 2018. “Ocean Deoxygenation and Zooplankton: Very Small Oxygen Differences Matter.” *Science Advances* 4(12):

eaau5180. https://doi.org/10.1126/sciadv.aau5180

Woodall, Lucy C., Anna Sanchez-Vidal, Miquel Canals, Gordon L. J. Paterson, Rachel Coppock, Victoria Sleight, Antonio Calafat, Alex D. Rogers, Bhavani E. Narayanaswamy, and Richard C. Thompson. 2014. "The Deep Sea Is a Major Sink for Microplastic Debris." *Royal Society Open Science* 1(4): 140317. https://doi.org/10.1098/rsos.140317

World Weather and Climate Information. 2023. "Climate in Chino Hills (California, United States of America)." *World Weather and Climate Information*. Accessed February 19, 2023. https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine-fahrenheit,chino-hills-california-us,United-States-of-America

Wright, Justin P., and Clive G. Jones. 2006. "The Concept of Organisms as Ecosystem Engineers Ten Years On: Progress, Limitations, and Challenges." *BioScience* 56(3): 203–209. https://doi.org/10.1641/0006-3568(2006)0562.0.CO;2

Wu, Jinghui, Zhongping Lee, Yuyuan Xie, Joaquim Goes, Shaoling Shang, John F. Marra, Gong Lin, Lei Yang, and Bangqin Huang. 2021. "Reconciling between Optical and Biological Determinants of the Euphotic Zone Depth." *Journal of Geophysical Research: Oceans* 126(5): e2020JC016874. https://doi.org/10.1029/2020JC016874

Wurl, Oliver, Werner Ekau, William M. Landing, and Christopher J. Zappa. 2017. "Sea Surface Microlayer in a Changing Ocean—A Perspective." *Elementa: Science of the Anthropocene* 5:31. https://doi.org/10.1525/elementa.228

Wyrtki, Klaus. 1962. "The Oxygen Minima in Relation to Ocean Circulation." *Deep Sea Research and Oceanographic Abstracts* 9(1–2): 11–23. https://doi.org/10.1016/0011-7471(62)90243-7

Xing, Xiaogang, Emmanuel Boss, Jie Zhang, and Fei Chai. 2020. "Evaluation of Ocean Color Remote Sensing Algorithms for Diffuse Attenuation Coefficients and Optical Depths with Data Collected on BGC-Argo Floats." *Remote Sensing* 12(15): 2367. https://doi.org/10.3390/rs12152367

Xiu, Peng, Fei Chai, Enrique N. Curchitser, and Frederic S. Castruccio. 2018. "Future Changes in Coastal Upwelling Ecosystems with Global Warming: The Case of the California Current System." *Scientific Reports* 8: 2866. https://doi.org/10.1038/s41598-018-21247-7

Yancey, Paul H. 2020. "Cellular Responses in Marine Animals to Hydrostatic Pressure." *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology* 333(6): 398–420. https://doi.org/10.1002/jez.2354

Yancey, Paul H., Mackemzie E. Gerringer, Jeffrey C. Drazen, Ashley A. Rowden, and Alan Jamieson. 2014. "Marine Fish May Be Biochemically Constrained from Inhabiting the Deepest Ocean Depths." *PNAS* 111(12): 4461–4465. https://doi.org/10.1073/pnas.1322003111

Zäncker, Birthe, Michael Cunliffe, and Anja Engel. 2021. "Eukaryotic Community Composition in the Sea Surface Microlayer across an East–West Transect in the Mediterranean Sea." *Biogeosciences* 18: 2107–2118. https://doi.org/10.5194/bg-18-2107-2021

Zeppilli, Daniela, Daniel Leduc, Christophe Fontanier, Diego Fontaneto, Sandra Fuchs, Andrew J. Gooday, Aurélie Goineau, Jeroen Ingels, Viatcheslav N. Ivanenko, Reinhardt Møbjerg Kristensen, Ricardo Cardoso Neves, Nuria Sanchez, Roberto Sandulli, Jozée Sarrazin, Martin V. Sørensen, Aurélie Tasiemski, Ann Vanreusel, Marine Autret, Louis Bourdonnay, Marion Claireaux, Valérie Coquillé, Lisa De Wever, Durand Rachel, James Marchant, Lola Toomey, and David Fernandes. 2018. "Characteristics of Meiofauna in Extreme Marine Ecosystems: A Review." *Marine Biodiversity* 48: 35–71. https://doi.org/10.1007/s12526-017-0815-z

Zezina, O. N. 1997. "Biogeography of the Bathyal Zone." *Advances in Marine Biology* 32: 389–426. https://doi.org/10.1016/S0065-2881(08)60020-6

Zhang, Zhengguang, Yu Zhang, and Wei Wang. 2017. "Three-Compartment Structure of Subsurface-Intensified Mesoscale Eddies in the Ocean." *Journal of Geophysical Research Oceans* 122(3): 1653–1664. https://doi.org/10.1002/2016JC012376

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SECTION OVERVIEW

Appendices

17: Appendix A—Common Abbreviations

18: Appendix B- Ocean Science Abbreviations

19: Appendix C—Abbreviations for Ocean Currents*

20: Appendix D—Metric Prefixes

21: Appendix E—Useful Formulas

22: Appendix F—Estimating Water Pressure

23: In the Periscope- Tiny Treasures by Colleen Chamberlin

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17: Appendix A—Common Abbreviations

- **4K** 4,000 pixels
- **8K** 8,000 pixels
- **16K** 16,000 pixels
- **AI** artificial intelligence
- **AU** astronomical unit
- **BCE** Before Common Era
- **CC** Creative Commons
- **e.g.** for example (*exempli gratia* in Latin)
- **et al.** and others (*et alia* in Latin)
- **HD** high definition
- **HMS** His or Her Majesty's Ship
- **i.e.** that is (*id est* in Latin)
- **ROSL** roll on seafloor laughing
- **R/V or RV** research vessel
- **SI** International System of Units
- **SUV** sport utility vehicle
- **TV** television
- **UC** University of California
- **UN** United Nations
- **US** United States
- **USS** United States Ship

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18: Appendix B- Ocean Science Abbreviations

A

ADS atmospheric diving suit

ALAMO Air-Launched Autonomous Micro-Observer

Argo Array for Real-Time Geostrophic Oceanography

ATOC Acoustic Thermometry of Ocean Climate

AUV autonomous underwater vehicle

AVHRR Advanced Very-High-Resolution Radiometers

C

CalCOFI California Cooperative Oceanic Fisheries Investigation

CFC chlorofluorocarbon

Conshelf Continental Shelf Station

CTD conductivity-temperature-depth

CZCS Coastal Zone Color Scanner instrument

D

DART Deep-ocean Assessment and Reporting of Tsunami

DISCOL DIS-turbance and re-COL-onization

DSV deep submergence vehicle

D-TAG digital acoustic recording tag

G

GDP global drifter program

GEBCO General Bathymetric Chart of the Oceans

GESAMP Group of Experts on the Scientific Aspects of Marine Environmental Protection

GIS geographic information system

GOES Geostationary Operational Environmental Satellite

GPS global positioning system

H

H-D hypothetico-deductive

HOV human-occupied vehicle

HROV hybrid remotely operated vehicle

I

IFREMER French Research Institute for Exploitation of the Sea

IHO International Hydrographic Organization

IPCC Intergovernmental Panel on Climate Change

J

JAMSTEC Japan Agency for Marine-Earth Science and Technology

L

LED light-emitting diode

LUCA last universal common ancestor

M

M-AUE mini-autonomous underwater explorer

MODIS Moderate Resolution Imaging Spectroradiometer

MOSAiC Multidisciplinary drifting Observatory for the Study of Arctic Climate

MUR-SSTs Multi-scale Ultra-high-Resolution sea surface temperatures

N

NASA National Aeronautics and Space Administration

NASEM National Academy of Sciences, Engineering, and Medicine

NDBC National Data Buoy Center

NeXOS Next generation, Cost-effective, Compact, Multifunctional Web Enabled Ocean Sensor Systems

NOAA National Oceanic and Atmospheric Administration

NRC National Research Council

NSF National Science Foundation

O

OFP Ocean Flux Program

OOI Ocean Observatories Initiative

OMZ oxygen minimum zone

P

PMEL Pacific Marine Environmental Laboratory

PSAT pop-up satellite archival tag

PTEO Periodic Table of the Elements in the Ocean

PAR photosynthetically available radiation

R

RO reverse osmosis

ROV remotely operated vehicle

S

SAR synthetic aperture radar

SAS synthetic aperture sonar

SCICEX SCientific ICe EXercise

SciComm science communication

Seasat Seafaring Satellite

SeaWiFS Sea-viewing Wide Field-of-view Sensor

SIO Scripps Institution of Oceanography

SOFAR Sound Fixing and Ranging

SOOP Ships of Opportunity Program

SOSUS Sound Surveillance System

SSS sea surface salinity

SST sea surface temperature

Stratollite a portmanteau of stratosphere and satellite

SVP surface velocity program

T

TIROS Television Infrared Observation Satellite

TOPEX Ocean Topography Experiment

U

UNOLS University–National Oceanographic Laboratory System

USCG United States Coast Guard

USGS United States Geological Survey

USV uncrewed surface vessel

UUV uncrewed underwater vehicles

V

VIIRS Visible and Infrared Imager/Radiometer Suite

W

WHOI Woods Hole Oceanographic Institution

X

XBT expendable bathythermograph

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19: Appendix C—Abbreviations for Ocean Currents*

AG Alaska Gyre

BG Beaufort Gyre

BENC Benguela Current

BC Brazil Current

CACS California Current System

CANC Canary Current

CSEC Central South Equatorial Current

EAUC East Australian Current

EUC Equatorial Undercurrent

GUST Gulf Stream

HUMC Humboldt Current

KURO Kuroshio Current

LEEC Leeuwin Current

MC Malvinas Current

MINC Mindanao Current

NAC North Atlantic Current

NAG North Atlantic Gyre

NECC North Equatorial Countercurrent

NEC North Equatorial Current

NPC North Pacific Current

NPG North Pacific Gyre

NSEC North South Equatorial Current

OYAC Oyashio Current

PECH Peru–Chile Current

RG Ross Gyre

SAC South Atlantic Current

SAC South Atlantic Gyre

SECC South Equatorial Countercurrent

SEC South Equatorial Current

SIC South Indian Current

SIG South Indian Gyre

SPC South Pacific Current

SPG South Pacific Gyre

WG Weddell Gyre

WAUC West Australian Current

WSAG WSAG Western Subarctic Gyre

*Based (mostly) on Talley et al. 2011.

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20: Appendix D—Metric Prefixes

Prefix Symbol Name Power of 10 Multiplier

yotta Y 1 septillion 10^{24} 1,000,000,000,000,000,000,000,000

zetta Z 1 sextillion 10^{21} 1,000,000,000,000,000,000,000

exa E 1 quintillion 10^{18} 1,000,000,000,000,000,000

peta P 1 quadrillion 10^{15} 1,000,000,000,000,000

tera T 1 trillion 10^{12} 1,000,000,000,000

giga G 1 billion 10^{9} 1,000,000,000

mega M 1 million 10^{6} 1,000,000

kilo k 1 thousand 10^{3} 1,000

hecto h 1 hundred 10^{2} 1,00

deka da 1 ten 10^{1} 10

deci d 1 tenth 10^{-1} 0.1

centi c 1 hundredth 10^{-2} 0.01

milli m 1 thousandth 10^{-3} 0.001

micro µ 1 millionth 10^{-6} 0.000,001

nano n 1 billionth 10^{-9} 0.000,000,001

pico p 1 trillionth 10^{-12} 0.000,000,000,001

femto f 1 quadrillionth 10^{-15} 0.000,000,000,000,001

atto a 1 quintillionth 10^{-18} 0. 000,000,000,000,000,001

zepto z 1 sextillionth 10^{-21} 0. 000,000,000,000,000,000,001

yocto y 1 septillionth 10^{-24} 0. 000,000,000,000,000,000,000,001

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21: Appendix E—Useful Formulas

Length Conversions

to miles (mi) = km × 0.62

= nmi÷1.151

= ft÷5,280

to kilometers (km) = mi × 1.61

= nmi×1.852

= ft÷3,281

to nautical miles (nmi) = mi ÷ 1.51

= km÷1.852

= ft÷6,076

to feet (ft) = mi × 5,280

= km×3,281

= nmi×6,076

Area Conversions

to square miles (mi^2) = km^2 ÷ 2.59

= nmi^2 × 1.324

to square kilometers (km^2) = mi^2 × 2.59

= nmi^2 × 3.43

to square nautical miles (nmi^2) = mi^2 ÷ 1.324

= km^2 ÷ 3.43

Volume Conversions

to gallons (gal) = m^3 × 264.2

= L÷3.785

to cubic meters (m^3) = gal ÷ 264.2

= L÷1,000

to liters (L) = gal × 3.785

= m^3 × 1,000

Pressure Conversions

to atmospheres (atm) = mb ÷ 1,013

= in. Hg÷29.92

= lb/in^2 ÷ 14.7

= Pa÷101,300

to millibars (mb) = atm × 1,013

= in. Hg×33.864

= lb/in^2 × 68.948

= Pa÷100

to inches of Mercury (in. Hg) = atm × 29.92

= mb÷33.864

= lb/in^2 × 2.036

= Pa÷3,386

to Pascals (Pa) = atm × 101,300

= mb×100

= in. Hg×3,386

= lb/in^2 × 6,895

Speed Conversions

to miles per hour (mph) = knots × 1.151

= km/hr÷1.609

= ft/s÷1.467

= m/s×2.237

to nautical miles per hour (knots) = mph ÷ 1.151

= km/hr÷1.852

= ft/s÷1.688

= m/s×1.944

to kilometers per hour (km/hr) = mph × 1.609

= knots×1.852

= ft/s×1.097

= m/s×3.6

to feet per second (f/s) = mph × 1.467

= km/hr÷1.097

= knots×1.688

= m/s×3.281

to meters per second (m/s) = mph ÷ 2.237

= knots÷1.944

= km/hr÷3.6

= ft/s÷3.281

Temperature

To convert degrees Fahrenheit (°F) to degrees Celsius (°C): (°F – 32) ÷ 1.8

To convert degrees Celsius (°C) to degrees Fahrenheit (°F): (°C × 1.8) + 32)

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https://geo.libretexts.org/@go/page/31591

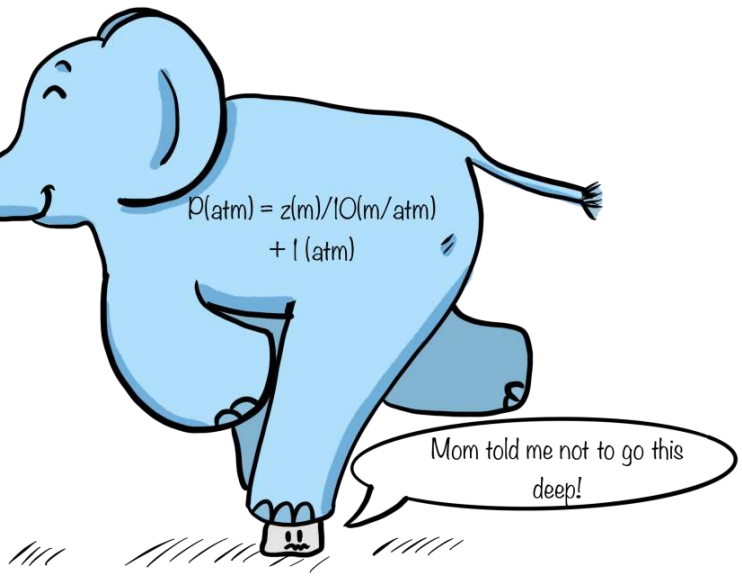
22: Appendix F—Estimating Water Pressure

Equation 3.1 (Chapter 3, p. 80) provides a convenient approximation for the calculation of water pressure in units of atmospheres from water depth in meters. Simply put, divide the depth (m) by 10 and add 1 atmosphere. Formally:

$$P\ (atm) = z\ (m) / 10\ (m/atm) + 1\ (atm)$$

(***Eq. 3.1***)

where P is water pressure, z is depth, and 1 atm represents the pressure at sea level.



At 700 feet, water pressure is equivalent to the weight of a baby elephant on every inch of a diver's body. Credit: Shaw and Chamberlin

For example, if the water depth is 80 meters, you would first divide by 10 (m/atm). The result, 8 atm, gives the water pressure for the water alone. But we must also take into account the force of the atmosphere, 1 atm. Adding 1 atm to 8 atm gives the correct answer of 9 atm for the water pressure at 80 meters. This is a reasonable estimate of water pressure at depth.

However, other factors, especially variations in the density of seawater, may affect water pressure. To more accurately calculate water pressure (formally known as hydrostatic pressure), you may wish to use the hydrostatic equation.

$$P\ (Pa) = \rho\ (kg\ m^{-3}) \times g\ (m\ s^{-2}) \times z\ (m)$$

(***Eq. A.1***)

where P is water pressure in Pascals (Pa, equivalent to Newtons per m^2), ρ (pronounced "row") is the density of the fluid in kilograms per cubic meter (kg m^{-3}), and g is the acceleration due to gravity, a constant at 9.8 m -2), and z is water depth in meters (m). Note that 1 Pa = 1 kg × m^{-1} × s^{-2} so the units work out (in case you were wondering).

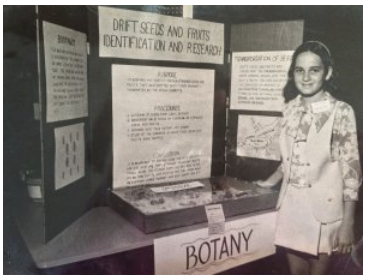
The hydrostatic equation comes into play in water columns composed of layers with different densities. Physical oceanographers will use a calculus version of the equation (we're not going there), but for instructional purposes, just imaging three layers each with a slightly different density all stacked on top of each other. To accurately determine water pressure, you would need to calculate the pressure for each layer and add them up.

Now, unless you are pursuing a degree in oceanography, physics, or engineering, it's not likely you'll need to be familiar with the hydrostatic equation. But having a look beneath the hood, so to speak, will give you a greater appreciation for the measurement of

pressure, on which so many things in the ocean depend. Should you ever descend in a submarine, you can rest assured the people who built it had a good understanding of this equation.

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23: In the Periscope- Tiny Treasures by Colleen Chamberlin



Colleen Chamberlin presents her prize-winning research on sea beans at the Palm Beach Regional Science Fair in 1971. Credit: Florida Naturalist Magazine

My love for the ocean began as a small child walking the beach with my mom. Nearly every weekend, just after sunrise and before other beachcombers were out, she would take me “treasure hunting” to see what had washed up on the shore. The beach was a magical place full of wonder and beauty. I would soon discover its tiny treasures.

As I walked along the beach, I noticed that the seashells on the beach presented themselves as a wide swath, gently laid at the high tide line. They didn’t seem to be in any particular order. Big shells lay next to small ones. Seaweed, baked by the sun, formed another line farther up the beach. Occasionally I found a dried seahorse in the seaweed. Small crabs and pieces of driftwood were among the many surprises tangled in the web of weeds.

But my most valued treasures were the various **sea beans** I uncovered—seeds transported by currents in the ocean. The first ones I found were shaped like hamburgers, a brownish red bean with a black band. Next I stumbled upon the knickernut, a small, hard bean, gray in color, and about the size of a nickel. I think “nicklenut” may have been a better name. What I loved about this bean was they could be made hot by rubbing them on the concrete. My most prized discovery was the sea heart. This large dark brown bean came in the shape of a heart. Where did it come from? Would it grow if I planted it?



Sea hearts (Entada gigas) come from a vine native to Africa, Central and South America, and the Caribbean. Credit: istock/Rajesh A

As I got older, my enthusiasm grew. At age ten, I would ride my bike to the library and rummage through stacks of books, magazines, and encyclopedias. So many questions to answer. How did the sea beans get here? How far had they traveled? Why were there more in the summer months than the winter?

When I was thirteen, I entered my sea bean collection in a science fair. I had already identified each bean by its Latin and common names. My goal was to create a map that would show the countries where the beans originated and the currents that brought them to my beach. That’s when I learned about the Gulf Stream, how its flows could change the trajectory of these tiny little beans. It was through this project that I really began to understand the connections between beaches all over the world. And I won a prize!

The ocean is a place where you can discover all sorts of treasures. Fifty years later, I find the same species lying on the beach near my home on the west coast of Mexico. I fell in love with the ocean at an early age and I still live near the beach today. I’m fascinated by the ocean. And it all started with a treasure hunt on the beach.



Colleen Chamberlin looking for “tiny treasures” on a beach at Sanibel Island, Florida, in 2004. Credit: Laurie Chamberlin

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Glossary

Example and Directions

Words (or words that have the same definition): (Eg. "Genetic, Hereditary, DNA ...")

The definition is case sensitive: (Eg. "Relating to genes or heredity")

(Optional) Image to display with the definition [Not displayed in Glossary, only in pop-up on pages]: 

(Optional) Caption for Image: The infamous double helix

(Optional) External or Internal Link: https://bio.libretexts.org/

(Optional) Source for Definition: CC-BY-SA; Delmar Larsen

Glossary Entries

Word(s): **macronutrient**

Definition: a biologically important nutrient required in high concentrations.

Image:

Caption:

Link:

Source:

Word(s): **Madden–Julian Oscillation**

Definition: an

intraseasonal, eastward-traveling, globe-trotting atmospheric wave that influences weather.

Image:

Caption:

Link:

Source:

Word(s): **magma**

Definition: molten rock beneath Earth’s surface.

Image:

Caption:

Link:

Source:

Word(s): **major constituent**

Definition: an element whose concentration exceeds 1 part per million in seawater.

Image:

Caption:

Link:

Source:

Word(s): **Malvinas Current**

Definition: a cold, northward-flowing current off the coasts of Uruguay and Argentina.

Image:

Caption:

Link:

Source:

Word(s): **manganese nodule**

Definition: See

Definition: See polymetallic nodule.

Image:

Caption:

Link:

Source:

Word(s): **manipulator arm**

Definition: human-controlled, mechanical extension on an ROV for collecting samples, drilling holes, or deploying instruments in the ocean.

Image:

Caption:

Link:

Source:

Word(s): **marine big data**

Definition: the enormous volumes of oceanographic data now available and growing daily.

Image:

Caption:

Link:

Source:

Word(s): **marine geomorphometry**

Definition: the quantitative study of the seafloor.

Image:

Caption:

Link:

Source:

Word(s): **marine layer**

Definition: a low-altitude cover of stratus clouds that forms over a cool ocean.

Image:

Caption:

Link:

Source:

Word(s): **marine phosphorite**

Definition: a phosphate-rich sedimentary rock formed in oceanic upwelling regions with high biological productivity.

Image:

Caption:

Link:

Source:

Word(s): **marine virus**

Definition: a noncellular entity inhabiting the ocean with a protein shell that encapsulates genetic information.

Image:

Caption:

Link:

Source:

Word(s): **mass extinction**

Definition: a rapid and global decrease in the abundance and diversity of organisms.

Image:

Caption:

Link:

Source:

Word(s): **matground**

Definition: surface crust formed as a result of interactions between microbes and sediments.

Image:

Caption:

Link:

Source:

Word(s): **mathematical models**

Definition: simple or complex mathematical expressions or sets of expressions to describe or simulate how something works.

Image:

Caption:

Link:

Source:

Word(s): **mean sea level**

Definition: the average sea level.

Image:

Caption:

Link:

Source:

Word(s): **mega-evaporite**

Definition: enormous deposit of salt formed by evaporation of seawater trapped during uplift of extensive ocean basins.

Image:

Caption:

Link:

Source:

Word(s): **megacity**

Definition: a city whose population exceeds 10 million people.

Image:

Caption:

Link:

Source:

Word(s): **meltwater**

Definition: water that originates from frozen sources.

Image:

Caption:

Link:

Source:

Word(s): **membrane-based desalination**

Definition: a process that uses membranes to produce freshwater.

Image:

Caption:

Link:

Source:

Word(s): **meridional current**

Definition: a current flowing along a line of longitude.

Image:

Caption:

Link:

Source:

Source:

Word(s): **meridional overturning circulation**

Definition: the combined three-dimensional surface and deep circulation of the ocean; *see also* world ocean circulation.

Image:

Caption:

Link:

Source:

Word(s): **mesopelagic zone**

Definition: a zone characterized by dim and diffuse light, extending from the bottom of the euphotic zone to approximately 1,000 meters.

Image:

Caption:

Link:

Source:

Word(s): **mesophotic coral ecosystems**

Definition: coral reefs that grow in dimly lit waters.

Image:

Caption:

Link:

Source:

Word(s): **mesoscale**

Definition: distances on the order of a few to a hundred kilometers.

.

Image:

Caption:

Link:

Source:

Word(s): **mesoscale structure**

Definition: the regional scale of physical, chemical, or biological features of the ocean, from a few to a few hundred miles.

Image:

Caption:

Link:

Source:

Word(s): **mesosphere**

Definition: the layer above the stratosphere in the middle of Earth’s atmospheric layers, where meteors become visible as they are heated through friction.

Image:

Caption:

Link:

Source:

Word(s): **metamorphic rock**

Definition: a rock transformed by heat, pressure, and fluids.

Image:

Caption:

Link:

Source:

Word(s): **metazoan**

Definition:

Definition: true animals; multicellular animals with differentiated cells.

Image:

Caption:

Link:

Source:

Word(s): **meteorology**

Definition: the scientific study of the atmosphere.

Image:

Caption:

Link:

Source:

Word(s): **methane**

Definition: a molecule composed of one carbon and four hydrogen atoms that acts as a greenhouse gas in Earth’s atmosphere.

Image:

Caption:

Link:

Source:

Word(s): **methane hydrate**

Definition: a frozen form of methane found on the seafloor.

Image:

Caption:

Link:

Source:

Word(s): **methanogen**

Definition: a type of microbe that converts organic matter into

methane.

Image:

Caption:

Link:

Source:

Word(s): **metric system**

Definition: *See* International System of Units.

Image:

Caption:

Link:

Source:

Word(s): **microbial mat**

Definition: a carpet of photosynthetic and sediment-dwelling bacteria.

Image:

Caption:

Link:

Source:

Word(s): **microfossil**

Definition: the hardened remains of a microscopic organism.

Image:

Caption:

Link:

Source:

Word(s): **microlayer**

Definition: the lower part of the sea surface microlayer, inhabited by a unique assemblage of microbes and various abiogenic and biogenic

particles, found from 1 to 1,000 micrometers in depth.

Image:

Caption:

Link:

Source:

Word(s): **micronutrient**

Definition: a biologically important nutrient required in low concentrations.

Image:

Caption:

Link:

Source:

Word(s): **microwave**

Definition: electromagnetic radiation with wavelengths between 1 millimeter and a meter.

Image:

Caption:

Link:

Source:

Word(s): **middle intertidal**

Definition: in the North American West Coast littoral classification system, the second zone (Zone 2), occupying the region at tide heights of zero to 1.5 meters.

Image:

Caption:

Link:

Source:

Word(s): **midnight zone**

Definition: *See* bathypelagic zone.

Image:

Caption:

Link:

Source:

Word(s): **Milky Way**

Definition: the galaxy in which Earth resides.

Image:

Caption:

Link:

Source:

Word(s): **Mindanao Current**

Definition: the southward flow of the North Equatorial Current at its western terminus.

Image:

Caption:

Link:

Source:

Word(s): **mineral**

Definition: a solid of inorganic material with a unique chemical composition and crystalline structure.

Image:

Caption:

Link:

Source:

Word(s): **mini-autonomous underwater explorer**

underwater explorer

Definition: small, autonomous, sensor- and GPS-enabled platform that works in a swarm beneath the surface of the ocean to track currents or carry out other kinds of observations and measurements.

Image:

Caption:

Link:

Source:

Word(s): **minor constituent**

Definition: an element whose concentration in seawater is less than 1 part per million.

Image:

Caption:

Link:

Source:

Word(s): **minus tide**

Definition: a tide whose tide height is less than zero.

Image:

Caption:

Link:

Source:

Word(s): **mitochondria**

Definition: the cell structure that supplies energy to eukaryotic cells.

Image:

Caption:

Link:

Source:

Word(s): **mixed layer depth**

Definition: the depth to which the surface mixed layer extends, usually the top of the thermocline.

Image:

Caption:

Link:

Source:

Word(s): **mixed semidiurnal tide**

Definition: a twice-daily tide with unequal heights.

Image:

Caption:

Link:

Source:

Word(s): **mixed tide**

Definition: *See* mixed semidiurnal tide.

Image:

Caption:

Link:

Source:

Word(s): **mixed-type distribution**

Definition: the existence of different distributions of a trace element in seawater depending on its form.

Image:

Caption:

Link:

Source:

Word(s): **mixground**

Definition: a slurry of soft seafloor sediments formed by the activities of organisms.

Image:

Caption:

Link:

Source:

Word(s): **mixing**

Definition: the homogenization of seawater.

Image:

Caption:

Link:

Source:

Word(s): **mixture**

Definition: a collection of molecules with an indefinite or varying composition, such as air or seawater.

Image:

Caption:

Link:

Source:

Word(s): **molecule**

Definition: two or more atoms bound together.

Image:

Caption:

Link:

Source:

Word(s): **Mollusca**

Definition: a phylum that includes bivalves, gastropods, chitons, and cephalopods.

Image:

Caption:

Link:

Source:

Word(s): **molting**

Definition: the shedding of an exoskeleton by an organism.

Image:

Caption:

Link:

Source:

Word(s): **momentum**

Definition: the product of a molecule’s mass and its velocity.

Image:

Caption:

Link:

Source:

Word(s): **momentum transfer**

Definition: the transfer of momentum from a moving molecule to a nonmoving molecule.

Image:

Caption:

Link:

Source:

Word(s): **monophyletic**

Definition: descending from a common ancestor.

Image:

Caption:

Link:

Source:

Word(s): **monsoon**

Definition: the wind that arises from seasonal heating of the interior of continental regions.

Image:

Caption:

Link:

Source:

Word(s): **Mount Erebus**

Definition: the world’s southernmost active volcano.

Image:

Caption:

Link:

Source:

Word(s): **Mount Everest**

Definition: the highest mountain on Earth.

Image:

Caption:

Link:

Source:

Word(s): **mouth (of river or watershed)**

Definition: the lowermost elevation of a river; where it ends.

Image:

Caption:

Link:

Source:

Word(s): **moving water**

Definition: flow of water.

Image:

Caption:

Link:

Source:

Word(s): **multicellular organism**

Definition: an organism with many different specialized cells which carry out specific functions and cannot independently create a whole organism.

Image:

Caption:

Link:

Source:

Word(s): **multiple thermocline**

Definition: the presence of two or more thermoclines in a water column.

Image:

Caption:

Link:

Source:

Word(s): **multispectral imager**

Definition: sensor capable of detecting multiple wide bands of electromagnetic radiation.

Image:

Caption:

Link:

Source:

Word(s): **mystery zone**

Definition: *See* abyssopelagic zone.

Image:

Caption:

Link:

Source:

Word(s): **nanolayer**

Definition: the thin organic coating at the very surface of the ocean, from zero to 1 micrometer in depth.

Image:

Caption:

Link:

Source:

Word(s): **National Tidal Datum Epoch**

Definition: a 19-year average of low or low low tide heights used to establish that tidal datum at different locations around the US.

Image:

Caption:

Link:

Source:

Word(s): **natural gas hydrate**

Definition: a potential source of energy found in great quantities on the seafloor.

Image:

Caption:

Link:

Source:

Word(s): **neap tide**

Definition: a tide of minimum range occurring at the first and the third quarters of the Moon.

Image:

Caption:

Link:

Source:

Word(s): **near-bottom zone**

Definition: *See* benthopelagic zone.

Image:

Caption:

Link:

Source:

Word(s): **negative buoyancy**

Definition: the tendency of a fluid or object to sink in a fluid.

Image:

Caption:

Link:

Source:

Word(s): **negative feedback loop**

Definition: a process that acts to maintain, reduce, or reverse changes in a system.

Image:

Caption:

Link:

Source:

Word(s): **negative tide**

Definition: *See* minus tide.

Image:

Caption:

Link:

Source:

Word(s): **nekton**

Definition: organisms that propel themselves through the water column.

Image:

Caption:

Link:

Source:

Word(s): **Neoproterozoic Oxygenation Event**

Definition: a period of increase in atmospheric oxygen sufficient to oxygenate at least some deep ocean basins around 570 million years ago.

Image:

Caption:

Link:

Source:

Word(s): **neritic waters**

Definition: *See* coastal waters.

Image:

Caption:

Link:

Link:

Source:

Word(s): **neutrally buoyant**

Definition: the tendency of a fluid or object to remain at rest in a fluid.

Image:

Caption:

Link:

Source:

Word(s): **neutron**

Definition: a neutrally charged subatomic particle found in the nucleus of an atom.

Image:

Caption:

Link:

Source:

Word(s): **new Moon**

Definition: when the side of the Moon facing Earth is not visible.

Image:

Caption:

Link:

Source:

Word(s): **night vision technology**

Definition: devices that detect infrared radiation and permit viewing of objects in the dark.

Image:

Caption:

Link:

Source:

Source:

Word(s): **Niskin bottle**

Definition: a type of seawater sampling bottle that can be triggered electronically.

Image:

Caption:

Link:

Source:

Word(s): **nitrogen-fixing bacteria**

Definition: microbes capable of turning nitrogen gas into biologically available forms of nitrogen.

Image:

Caption:

Link:

Source:

Word(s): **nitrous oxide**

Definition: a molecule composed of nitrogen and oxygen produced naturally by microbial activity; acts as a greenhouse gas in Earth’s atmosphere.

Image:

Caption:

Link:

Source:

Word(s): **nondispersive**

Definition: waves that do not separate according to their wavelength or wave period.

Image:

Caption:

Link:

Source:

Word(s): **noon sun angle**

Definition: the angle of the Sun above the equatorward horizon at noon.

Image:

Caption:

Link:

Source:

Word(s): **North America**

Definition: the third-largest continent.

Image:

Caption:

Link:

Source:

Word(s): **North Atlantic Current**

Definition: the eastward-flowing west wind drift current in the North Atlantic Ocean.

Image:

Caption:

Link:

Source:

Word(s): **North Atlantic Gyre**

Definition: the subtropical gyre circulation in the North Atlantic Ocean.

Image:

Caption:

Caption:

Link:

Source:

Word(s): **North Equatorial Countercurrent**

Definition: a west-to-east current just north of the equator.

Image:

Caption:

Link:

Source:

Word(s): **North Equatorial Current**

Definition: the equatorial current that flows just north of the equator.

Image:

Caption:

Link:

Source:

Word(s): **North Pacific Current**

Definition: the eastward-flowing west wind drift current in the North Pacific Ocean.

Image:

Caption:

Link:

Source:

Word(s): **North Pacific Gyre**

Definition: the subtropical gyre circulation in the North Pacific Ocean.

.

Image:

Caption:

Link:

Source:

Word(s): **North South Equatorial Current**

Definition: the northerly branch of the South Equatorial Current in the Atlantic Ocean.

Image:

Caption:

Link:

Source:

Word(s): **Northeast Monsoon Current**

Definition: the westward-flowing current that occurs during the winter monsoon.

Image:

Caption:

Link:

Source:

Word(s): **northeast trade wind**

Definition: the trade wind that blows from northeast to southwest north of the equator.

Image:

Caption:

Link:

Source:

Word(s): **Norwegian Current**

Definition: a northerly current along the coast of

Norway.

Image:

Caption:

Link:

Source:

Word(s): **nowcast**

Definition: forecast of ocean or atmospheric conditions in near real time.

Image:

Caption:

Link:

Source:

Word(s): **nucleus (in biology)**

Definition: the cell structure in which most of a cell’s genetic material is housed.

Image:

Caption:

Link:

Source:

Word(s): **nucleus (in chemistry)**

Definition: the central portion of an atom, composed of protons and neutrons.

Image:

Caption:

Link:

Source:

Word(s): **nuisance flooding**

Definition: local flooding caused by sea level rise

caused by sea level rise that now occurs at high tides.

Image:

Caption:

Link:

Source:

Word(s): **numerical models**

Definition: computer models that solve sets of mathematical equations to make forecasts or projections of natural processes at some time in the future.

Image:

Caption:

Link:

Source:

Word(s): **nutrient**

Definition: *See* biologically important nutrient.

Image:

Caption:

Link:

Source:

Word(s): **obligate anaerobe**

Definition: an organism that cannot tolerate oxygen in its environment.

Image:

Caption:

Link:

Source:

Word(s): **ocean basin**

Word(s): ocean basin

Definition: a depression in Earth's crust covered by seawater extending from the shelf break to the deepest trench.

Image:

Caption:

Link:

Source:

Word(s): ocean climate

Definition: the average of ocean conditions over a specified period of time.

Image:

Caption:

Link:

Source:

Word(s): ocean color

Definition: the colors of visible light emanating from the surface of the ocean.

Image:

Caption:

Link:

Source:

Word(s): ocean depth zone

Definition: a system for classifying the general conditions for organisms present at various depth ranges in the water column and on the seafloor.

Image:

Caption:

Link:

Source:

Source:

Word(s): **ocean eddy**

Definition: a self-sustaining, rotating loop of water tens to hundreds of miles wide.

Image:

Caption:

Link:

Source:

Word(s): **ocean heat content**

Definition: the heat stored in the ocean.

Image:

Caption:

Link:

Source:

Word(s): **ocean life zone**

Definition: *See* ocean depth zone.

Image:

Caption:

Link:

Source:

Word(s): **ocean mining**

Definition: the extraction of mineral resources from the seafloor.

Image:

Caption:

Link:

Source:

Word(s): **ocean mooring**

Definition: a self-

Definition: seafloor-anchored cable on which various ocean sensors can be attached and held vertically by a float.

Image:

Caption:

Link:

Source:

Word(s): **ocean observatory**

Definition: an integrated array of ocean-observing sensors and platforms on and above the seafloor designed to address questions of scientific and societal importance.

Image:

Caption:

Link:

Source:

Word(s): **ocean tide**

Definition: the daily rising and falling of sea level.

Image:

Caption:

Link:

Source:

Word(s): **ocean tracer**

Definition: a substance used to track the movement and evolution of water masses.

Image:

Caption:

Link:

Source:

Word(s): **ocean wave**

Definition: the physical expression of energy moving forward at the interface between two fluids of different density, including surface and internal waves.

Image:

Caption:

Link:

Source:

Word(s): **ocean weather**

Definition: the instantaneous state of the ocean.

Image:

Caption:

Link:

Source:

Word(s): **ocean-observing systems**

Definition: a broad category of sensor-outfitted platforms that fly above, glide on top of, or dive below the surface of the ocean.

Image:

Caption:

Link:

Source:

Word(s): **oceangoing investigation**

Definition: a scientific investigation carried out at sea.

Image:

Caption:

Link:

Source:

Word(s): **oceanic crust**

Definition: the part of Earth’s crust that forms the ocean basins.

Image:

Caption:

Link:

Source:

Word(s): **oceanic gyre**

Definition: the rotation of currents around a common center in an ocean basin.

Image:

Caption:

Link:

Source:

Word(s): **oceanic plateau**

Definition: flat or nearly flat region of the seafloor that drops off abruptly on one or more sides.

Image:

Caption:

Link:

Source:

Word(s): **oceanic ridge**

Definition: a narrow region of varying complexity whose height exceeds 1,000 meters and whose length-to-width ratio is greater than 2.

Image:

Caption:

Link:

Source:

Word(s): **oceanic trench**

Definition: a V-shaped depression in the seafloor with steep walls.

Image:

Caption:

Link:

Source:

Word(s): **oceanic waters**

Definition: waters overlying the ocean basins.

Image:

Caption:

Link:

Source:

Word(s): **oceanographer**

Definition: any person, robot, or animal engaged in the scientific study of the ocean.

Image:

Caption:

Link:

Source:

Word(s): **oceanography**

Definition: the scientific study of the world ocean.

Image:

Caption:

Link:

Source:

Word(s): **offshore**

Definition: the region beyond the surf zone.

Image:

Caption:

Link:

Source:

Word(s): **offshore wind**

Definition: a wind that blows from the land to the ocean.

Image:

Caption:

Link:

Source:

Word(s): **onshore wind**

Definition: a wind the blows from the ocean to the land.

Image:

Caption:

Link:

Source:

Word(s): **ooid**

Definition: light-colored oval of calcium carbonate.

Image:

Caption:

Link:

Source:

Word(s): **Oort Cloud**

Definition: a spherical-shaped system of dust, icy objects, and comets

icy objects, and comets at the far reaches of our solar system.

Image:

Caption:

Link:

Source:

Word(s): **open ocean oceanography**

Definition: *See* blue water oceanography.

Image:

Caption:

Link:

Source:

Word(s): **open ocean**

Definition: the oceanic waters beyond the continental shelves.

Image:

Caption:

Link:

Source:

Word(s): **operational oceanography**

Definition: the acquisition and dissemination of oceanographic and meteorological information useful to navigating or carrying out activities in the ocean.

Image:

Caption:

Link:

Source:

Word(s): **orbital plane**

Definition: the imaginary

Definition: the imaginary horizontal plane on which Earth orbits the Sun.

Image:

Caption:

Link:

Source:

Word(s): **ordinal direction**

Definition: northeast, southeast, northwest, southwest.

Image:

Caption:

Link:

Source:

Word(s): **ordinary gravity wave**

Definition: waves with periods from 1 to 30 seconds.

Image:

Caption:

Link:

Source:

Word(s): **Ordovician**

Definition: a geologic period from 485.4 to 443.8 million years ago.

Image:

Caption:

Link:

Source:

Word(s): **organelle**

Definition: a subcellular, specialized structure present in eukaryotes and possibly Archaea and

and possibly Archaea and bacteria.

Image:

Caption:

Link:

Source:

Word(s): **oxygen minimum zone**

Definition: a region of reduced or absent dissolved oxygen in the water column.

Image:

Caption:

Link:

Source:

Word(s): **oxygenic photosynthesis**

Definition: photosynthesis that yields oxygen as a by-product.

Image:

Caption:

Link:

Source:

Word(s): **Oyashio Current**

Definition: a southward-flowing current off the island of Hokkaido, Japan.

Image:

Caption:

Link:

Source:

Word(s): **ozone hole**

Definition: a region where stratospheric

ozone concentrations are greatly reduced.

Image:

Caption:

Link:

Source:

Word(s): **ozone layer**

Definition: the part of the stratosphere containing ozone.

Image:

Caption:

Link:

Source:

Word(s): **Pacific Ocean**

Definition: the largest ocean in the world.

Image:

Caption:

Link:

Source:

Word(s): **pale blue dot**

Definition: the name given to the blue speck of Earth as seen from millions of miles away in outer space.

Image:

Caption:

Link:

Source:

Word(s): **paleoshoreline**

Definition: an ancient shoreline formed during lowstands of sea level.

Image:

Caption:

.

Link:

Source:

Word(s): **Pangea**

Definition: a supercontinent that formed and broke apart over an interval from 320 to 195 million years ago.

Image:

Caption:

Link:

Source:

Word(s): **paraphyletic**

Definition: not including all descendants of a common ancestor.

Image:

Caption:

Link:

Source:

Word(s): **parent rock**

Definition: the source material for sediments.

Image:

Caption:

Link:

Source:

Word(s): **particulate organic carbon**

Definition: anything living or once living that occurs as a particle in seawater.

Image:

Caption:

Link:

Source:

Source:

Word(s): **particulate organic matter**

Definition: living and dead particles of organic matter.

Image:

Caption:

Link:

Source:

Word(s): **passive microwave sensor**

Definition: sensor that measures the intensity of microwave radiation emanating from Earth's land, ice, and sea surface.

Image:

Caption:

Link:

Source:

Word(s): **passive sensor**

Definition: sensor that measures the electromagnetic properties of the ocean.

Image:

Caption:

Link:

Source:

Word(s): **peer review**

Definition: the process whereby scientists receive feedback on their work by other scientists and experts.

Image:

Caption:

Link:

Source:

Word(s): **pelagic depth zones**

Definition: ocean depth zones within the water column from the surface to the deepest trenches.

Image:

Caption:

Link:

Source:

Word(s): **pelagic organism**

Definition: organism that inhabits the water column.

Image:

Caption:

Link:

Source:

Word(s): **perihelion**

Definition: the point in Earth’s slightly elliptical orbit where its distance from the Sun is smallest.

Image:

Caption:

Link:

Source:

Word(s): **periodic table of elements**

Definition: a chart depicting all of the known elements.

Image:

Caption:

Caption:

Link:

Source:

Word(s): **Periodic Table of the Elements in the Ocean**

Definition: an online chart of the elements found in seawater and their concentrations with depth in the ocean.

Image:

Caption:

Link:

Source:

Word(s): **permanent thermocline**

Definition: the boundary between polar water masses and seasonally mixed water masses.

Image:

Caption:

Link:

Source:

Word(s): **Peru Current**

Definition: *See* Peru–Chile Current.

Image:

Caption:

Link:

Source:

Word(s): **Peru–Chile Current**

Definition: the equatorward-flowing eastern boundary current in the South Pacific Ocean.

Image:

Caption:

Link:

Source:

Word(s): **Pettersson–Nansen bottle**

Definition: a type of sampling bottle for obtaining seawater at depth.

Image:

Caption:

Link:

Source:

Word(s): **Phaeophyta**

Definition: a phylum that includes multicellular brown algae.

Image:

Caption:

Link:

Source:

Word(s): **Phanerozoic**

Definition: the eon of visible life from 541 million years ago to the present.

Image:

Caption:

Link:

Source:

Word(s): **photic zone**

Definition: the lighted waters of the upper ocean.

Image:

Caption:

Caption:

Link:

Source:

Word(s): **photoautotroph**

Definition: an organism that uses light to manufacture its own food.

Image:

Caption:

Link:

Source:

Word(s): **photophore**

Definition: the light organ of bioluminescent animals.

Image:

Caption:

Link:

Source:

Word(s): **photosynthesis**

Definition: the manufacture of organic carbon from carbon dioxide and inorganic substances using energy obtained from sunlight.

Image:

Caption:

Link:

Source:

Word(s): **photosynthetically available radiation**

Definition: the wavelengths of visible light that stimulate photosynthesis in plants.

photosynthesis in plants, generally from 400 to 700 nanometers.

Image:

Caption:

Link:

Source:

Word(s): **phylogenetic tree**

Definition: a branching diagram that illustrates the hypothetical evolutionary relationships between organisms.

Image:

Caption:

Link:

Source:

Word(s): **physical model**

Definition: a scaled-down, three-dimensional, semirealistic representation of a physical object or part of nature.

Image:

Caption:

Link:

Source:

Word(s): **physical oceanography**

Definition: the scientific study of the physical properties and processes in the world ocean.

Image:

Caption:

Link:

Source:

Word(s): **physical state**

Definition: the state of matter: solid, liquid, or gas.

Image:

Caption:

Link:

Source:

Word(s): **physical weathering**

Definition: the breakdown of rocks by physical processes.

Image:

Caption:

Link:

Source:

Word(s): **physisorption**

Definition: the physical attraction of elements to particles.

Image:

Caption:

Link:

Source:

Word(s): **phytoplankton**

Definition: photosynthetic microbes that drift with the currents in the sunlit waters of the ocean.

Image:

Caption:

Link:

Source:

Word(s): **phytoplankton**

thin layer

Definition: narrow layer with high concentrations of phytoplankton.

Image:

Caption:

Link:

Source:

Word(s): **pillow basalt**

Definition: a basaltic rock formation that resembles pillows.

Image:

Caption:

Link:

Source:

Word(s): **Pineapple Express**

Definition: the popular name given to the subtropical jet stream when it carries humid subtropical air from Hawaii to California.

Image:

Caption:

Link:

Source:

Word(s): **plasma**

Definition: a fourth state of matter consisting of free-moving electrons and ions.

Image:

Caption:

Link:

Source:

Word(s): **plunging**

Word(s): plunging breaker

Definition: wave that creates a tube with a lip that shoots over the face of the wave in a kind of waterfall.

Image:

Caption:

Link:

Source:

Word(s): plus tide

Definition: a tide whose height is greater than zero.

Image:

Caption:

Link:

Source:

Word(s): point break

Definition: a type of breaking wave that wraps around a headland.

Image:

Caption:

Link:

Source:

Word(s): polar cell

Definition: the atmospheric cell that occurs over polar regions.

Image:

Caption:

Link:

Source:

Word(s): polar day

Definition: the six-month

Definition: the six month period of continual or near-continual sunlight in polar regions.

Image:

Caption:

Link:

Source:

Word(s): **polar easterlies**

Definition: the easterly directed prevailing winds that blow at polar latitudes.

Image:

Caption:

Link:

Source:

Word(s): **polar gyre**

Definition: a gyre circulation at polar latitudes.

Image:

Caption:

Link:

Source:

Word(s): **polar jet stream**

Definition: a high-altitude flow of cold air that meanders like a river around the North and South Poles.

Image:

Caption:

Link:

Source:

Word(s): **polar molecule**

Definition:

Definition: a molecule that exhibits a separation of charges.

Image:

Caption:

Link:

Source:

Word(s): **polar night**

Definition: the six-month period of continual or near-continual darkness in polar regions.

Image:

Caption:

Link:

Source:

Word(s): **polar submarine canyon**

Definition: submarine canyon found on Arctic and Antarctic continental shelves.

Image:

Caption:

Link:

Source:

Word(s): **polar zone**

Definition: region north of the Arctic Circle or south of the Antarctic Circle characterized by freezing weather.

Image:

Caption:

Link:

Source:

Word(s): **polychaete**

Definition: a segmented

Definition: a segmented marine worm with bristles.

Image:

Caption:

Link:

Source:

Word(s): **polymetallic crust**

Definition: similar to nodules in composition, forming as a coating on rocks along the flanks and summits of seamounts.

Image:

Caption:

Link:

Source:

Word(s): **polymetallic nodule**

Definition: tennis ball–sized globe of different metals that precipitates slowly around a nucleus (a shell or bone fragment, for example) on the seafloor.

Image:

Caption:

Link:

Source:

Word(s): **poorly sorted**

Definition: having grain sizes that vary widely.

Image:

Caption:

Link:

Source:

Word(s): **Porifera**

Definition: a phylum that includes sponges.

Image:

Caption:

Link:

Source:

Word(s): **positive buoyancy**

Definition: the tendency of a fluid or object to rise in a fluid.

Image:

Caption:

Link:

Source:

Word(s): **positive feedback loop**

Definition: a process that acts to amplify or accelerate changes in a system.

Image:

Caption:

Link:

Source:

Word(s): **positive tide**

Definition: *See* plus tide.

Image:

Caption:

Link:

Source:

Word(s): **potential energy**

Definition: stored energy or energy inherent in an object in a gravitational

object in a gravitational field.

Image:

Caption:

Link:

Source:

Word(s): **practical salinity scale**

Definition: a unitless scale used to define salinity.

Image:

Caption:

Link:

Source:

Word(s): **precipitation**

Definition: the gravity-driven falling of liquid or solid water from the atmosphere.

Image:

Caption:

Link:

Source:

Word(s): **pressure gradient force**

Definition: the force that arises when two locations have different air pressure.

Image:

Caption:

Link:

Source:

Word(s): **pressure**

Definition: the force exerted by a fluid (a gas or a liquid) on an object

immersed within it.

Image:

Caption:

Link:

Source:

Word(s): **principle of constant proportions**

Definition: the observation of constant proportions among the major constituents of seawater.

Image:

Caption:

Link:

Source:

Word(s): **principle of unity**

Definition: the idea that there is but one ocean on Earth, the world ocean.

Image:

Caption:

Link:

Source:

Word(s): **progressive wave**

Definition: a wave moving forward along a density boundary.

Image:

Caption:

Link:

Source:

Word(s): **prokaryote**

Definition: a cell lacking a visible nucleus and other organelles.

other organelles.

Image:

Caption:

Link:

Source:

Word(s): **Proterozoic**

Definition: the eon of early life, from 2.5 billion to 541 million years ago.

Image:

Caption:

Link:

Source:

Word(s): **protist**

Definition: a single-celled or multicellular species with a eukaryotic cell type.

Image:

Caption:

Link:

Source:

Word(s): **proton**

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    - 1: The World Ocean System - *CC BY 4.0*
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      - 1.8: Your Mission - *CC BY 4.0*
      - 1.9: Chapter References - *CC BY 4.0*
    - 2: Team Oceanography - *CC BY 4.0*
      - 2.1: Channel Your Inner Scientist - *CC BY 4.0*
      - 2.2: Investigate the Natural World - *CC BY 4.0*
      - 2.3: Ask a Good Question - *CC BY 4.0*
      - 2.4: Propose an Idea or Model - *CC BY 4.0*
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      - 2.6: Conduct an Investigation - *CC BY 4.0*
      - 2.7: Analyze Your Results - *CC BY 4.0*
      - 2.8: Form Your Conclusions - *CC BY 4.0*
      - 2.9: Communicate Your Science - *CC BY 4.0*
      - 2.10: Chapter References - *CC BY 4.0*
    - 3: Science Aboard Ships - *CC BY 4.0*
      - 3.1: The Birth of Oceanography - *CC BY 4.0*
      - 3.2: Sampling over Space - *CC BY 4.0*
      - 3.3: Sampling over Time - *CC BY 4.0*
      - 3.4: The Challenge of Pressure - *CC BY 4.0*
      - 3.5: The Undersampling Problem - *CC BY 4.0*
      - 3.6: Modern Oceanographic Vessels - *CC BY 4.0*
      - 3.7: Beneath the Surface - *CC BY 4.0*
      - 3.8: Chapter References - *CC BY 4.0*
    - 4: Robots, Satellites, and Observatories - *CC BY 4.0*
      - 4.1: Bottles, Drifters, and Floats - *CC BY 4.0*
      - 4.2: Gliders - *CC BY 4.0*
      - 4.3: Towfish - *CC BY 4.0*
      - 4.4: Remotely Operated Vehicles - *CC BY 4.0*
      - 4.5: Autonomous Underwater Vehicles - *CC BY 4.0*
      - 4.6: Hybrid Platforms - *CC BY 4.0*
      - 4.7: Benthic Landers - *CC BY 4.0*
      - 4.8: Mini-Autonomous Underwater Explorers - *CC BY 4.0*
      - 4.9: Ocean Moorings - *CC BY 4.0*
      - 4.10: Uncrewed Aerial Platforms - *CC BY 4.0*
      - 4.11: Satellite Oceanography - *CC BY 4.0*
      - 4.12: Ocean Observatories - *CC BY 4.0*
      - 4.13: Chapter References - *CC BY 4.0*
  - Voyage II Ocean Geology and Chemistry - *Undeclared*
    - 5: The Beach - *CC BY 4.0*
      - 5.1: What Is a Beach? - *CC BY 4.0*
      - 5.2: Anatomy of a Beach - *CC BY 4.0*
      - 5.3: The Origins of Beach Sand - *CC BY 4.0*
      - 5.4: From the Mountains to the Sea - *CC BY 4.0*
      - 5.5: Wave-Driven Sediment Transport - *CC BY 4.0*
      - 5.6: The Littoral Cell - *CC BY 4.0*
      - 5.7: Human Impacts on Beaches - *CC BY 4.0*
      - 5.8: The Last Beach? - *CC BY 4.0*
      - 5.9: Chapter References - *CC BY 4.0*
    - 6: The Seafloor - *CC BY 4.0*

- 6.1: Planet Earth vs. Planet Ocean - *CC BY 4.0*
- 6.2: A Few Words About “Seafloor” - *CC BY 4.0*
- 6.3: Marine Geomorphometry - *CC BY 4.0*
- 6.4: Seafloor Provinces - *CC BY 4.0*
- 6.5: Deep-Sea Mining - *CC BY 4.0*
- 6.6: Chapter References - *CC BY 4.0*

- 7: Seawater and Its Elements - *CC BY 4.0*
  - 7.1: Anatomy of a Molecule - *CC BY 4.0*
  - 7.2: The Periodic Table of the Elements - *CC BY 4.0*
  - 7.3: The Name’s Bond, Chemical Bond - *CC BY 4.0*
  - 7.4: Chemical Formulas - *CC BY 4.0*
  - 7.5: The Water Molecule - *CC BY 4.0*
  - 7.6: What Are Salts? - *CC BY 4.0*
  - 7.7: Seawater Constituents - *CC BY 4.0*
  - 7.8: Chapter References - *CC BY 4.0*
- 8: The Water Cycle and Ocean Salinity - *CC BY 4.0*
  - 8.1: A Useful and Simple Model - *CC BY 4.0*
  - 8.2: The Global Water Cycle - *CC BY 4.0*
  - 8.3: The Three States of Water - *CC BY 4.0*
  - 8.4: Water, the Dissolver of Rocks - *CC BY 4.0*
  - 8.5: Salinity over Long Timescales - *CC BY 4.0*
  - 8.6: Salinity over Short Timescales - *CC BY 4.0*
  - 8.7: Airborne Sources of Salts - *CC BY 4.0*
  - 8.8: Biological Sources and Sinks - *CC BY 4.0*
  - 8.9: Residence Time - *CC BY 4.0*
  - 8.10: Measuring Salinity - *CC BY 4.0*
  - 8.11: The Global Water Crisis - *CC BY 4.0*
  - 8.12: Chapter References - *CC BY 4.0*

- Voyage III Ocean Physics - *Undeclared*
  - 9: The Sun and the Earth - *CC BY 4.0*
    - 9.1: Interesting Facts About the Sun - *CC BY 4.0*
    - 9.2: Electromagnetic Radiation - *CC BY 4.0*
    - 9.3: How the Sun Warms the Earth - *CC BY 4.0*
    - 9.4: Earth’s Energy Imbalance - *CC BY 4.0*
    - 9.5: Chapter References - *CC BY 4.0*
  - 10: The Surface Circulation - *CC BY 4.0*
    - 10.1: Main Features - *CC BY 4.0*
    - 10.2: Boundary Currents - *CC BY 4.0*
    - 10.3: West Wind Drift Currents - *CC BY 4.0*
    - 10.4: Polar Ocean Currents - *CC BY 4.0*
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      - 3.3: Sampling over Time - *CC BY 4.0*
      - 3.4: The Challenge of Pressure - *CC BY 4.0*
      - 3.5: The Undersampling Problem - *CC BY 4.0*
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      - 3.7: Beneath the Surface - *CC BY 4.0*
      - 3.8: Chapter References - *CC BY 4.0*
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      - 4.2: Gliders - *CC BY 4.0*
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      - 4.8: Mini-Autonomous Underwater Explorers - *CC BY 4.0*
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      - 5.4: From the Mountains to the Sea - *CC BY 4.0*
      - 5.5: Wave-Driven Sediment Transport - *CC BY 4.0*
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      - 5.7: Human Impacts on Beaches - *CC BY 4.0*
      - 5.8: The Last Beach? - *CC BY 4.0*
      - 5.9: Chapter References - *CC BY 4.0*
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- 6.3: Marine Geomorphometry - *CC BY 4.0*
- 6.4: Seafloor Provinces - *CC BY 4.0*
- 6.5: Deep-Sea Mining - *CC BY 4.0*
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  - 7.2: The Periodic Table of the Elements - *CC BY 4.0*
  - 7.3: The Name’s Bond, Chemical Bond - *CC BY 4.0*
  - 7.4: Chemical Formulas - *CC BY 4.0*
  - 7.5: The Water Molecule - *CC BY 4.0*
  - 7.6: What Are Salts? - *CC BY 4.0*
  - 7.7: Seawater Constituents - *CC BY 4.0*
  - 7.8: Chapter References - *CC BY 4.0*
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  - 8.2: The Global Water Cycle - *CC BY 4.0*
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  - 8.5: Salinity over Long Timescales - *CC BY 4.0*
  - 8.6: Salinity over Short Timescales - *CC BY 4.0*
  - 8.7: Airborne Sources of Salts - *CC BY 4.0*
  - 8.8: Biological Sources and Sinks - *CC BY 4.0*
  - 8.9: Residence Time - *CC BY 4.0*
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    - 10.1: Main Features - *CC BY 4.0*
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