INTRODUCTION TO EARTH SCIENCE (C-ID: GEOL 121)



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This text was compiled on 09/10/2026

TABLE OF CONTENTS

Licensing

Preface and Acknowledgements

Book Introduction

1: Introduction to Earth Science

1.1: Introduction and Objectives

1.2: Earth Systems Overview

1.3: Components of the Earth System

1.4: Components of Earth System- Relationships between human activities and Earth's spheres

1.5: Human Activities- The Implications of Resource Extraction for the Climate and Earth Systems

1.6: Human Activities- Case Study- Major Threats to California's Water

1.7: Why Study Earth Science?

1.8: The Branches of Earth Science

1.9: Understanding Science

1.10: Understanding Science- What is it?

1.11: Understanding Science- The Scientific Method

1.12: Understanding Science- Outcome- Scientific Processes in Earth Science

1.13: Understanding Science- Early Scientific Thought

1.14: Understanding Science- Foundations of Earth Science

1.15: Understanding Science- Denial and Evaluating Sources

2: The Geosphere

2.1: Introduction to Geosphere and Objectives

2.2: Minerals

2.3: Rocks

2.4: Layers of the Earth

2.5: Plate Tectonics- Continental Drift

2.6: Plate Tectonics- Convergent Boundaries

2.7: Plate Tectonics- Divergent Boundaries

2.8: Plate Tectonics- Transform Boundaries

2.9: Plate Tectonics- The Wilson Cycle

2.10: Plate Tectonics- Hotspots

2.11: Plate Tectonics- Continental Margins

2.12: Measuring Geological Time- The Geological Time Scale

2.13: Measuring Geological Time- Relative Dating Methods

2.14: Measuring Geological Time- Fossils and Evolution

2.15: Measuring Geological Time- Fossils and Evolution- Dating Rocks Using Fossils

2.16: Measuring Geological Time- Isotopic Dating Methods

2.17: Measuring Geological Time- Other Dating Methods

2.18: Measuring Geological Time- Understanding Geological Time
2.19: Measuring Geological Time- Summary

3: The Hydrosphere

3.1: Introduction to the Hydrosphere and Objectives
3.2: Distribution of Earth's Water
3.3: Properties of Water
3.4: The Hydrologic Cycle
3.5: Water Resources and Climate Change
3.6: Review and Additional Resources
3.7: Overview of the Oceans
3.8: Ocean Circulation
3.9: Waves
3.10: Wave Basics
3.11: Waves at Sea
3.12: Waves on the Shore
3.13: Tsunamis
3.14: Coastal Oceanography
3.15: Beaches
3.16: Longshore Transport
3.17: Landforms of Coastal Erosion
3.18: Landforms of Coastal Deposition
3.19: Human Interference with Shorelines
3.20: Estuaries
3.21: Sea Level Change
3.22: Tides
3.23: Tidal Forces
3.24: Dynamic Theory of Tides
3.25: Tide Classification
3.26: Surface Water
3.27: Groundwater
3.28: Prelude to Galciers
3.29: Types of Glaciers
3.30: Glacier Formation and Movement
3.31: Glacial Budget
3.32: Glacial Landforms
3.33: Ice Age Glaciations
3.34: Anthropogenic Effects on Water Quality

4: The Atmosphere

4.1: Introduction to the Atmosphere and Objectives
4.2: Atmosphere- Composition and Properties

4.3: Atmospheric Circulation
4.4: Atmospheric Pollution

5: Weather

5.1: Introduction to Weather and Objectives
5.2: Weather Processes and Systems
5.3: Extreme Weather Events
5.4: Collecting Weather Data and Forecasting Weather

6: Climate and Climate Change

6.1: Introduction to Climate Change and Objectives
6.2: The Sun – Earth Relationship and the Seasons
6.3: The Sun and the Earth-Moon System
6.4: Weather vs Climate
6.5: Earth's Heat Budget and the Greenhouse Effect
6.6: What Makes the Climate Change?
6.7: Prehistoric Climate Change and Proxys for Studying Past Climates
6.8: Anthropogenic Climate Change
6.9: Implications of Climate Change

7: Universe and Solar System

7.1: Introduction to the Universe and Objectives
7.2: The Universe
7.3: Galaxies and Stars
7.4: The Solar System
7.5: The Sun
7.6: Terrestrial Planets
7.7: Gas Giants
7.8: Other Objects in the Solar System
7.9: Attributions and References

8: Resources and Energy

8.1: Energy and Resources- Why It Matters- Geological Resources
8.2: Energy and Resources- Ecosystems and Humans
8.3: Energy and Resources- Metal Deposits
8.4: Energy and Resources- Mining and Ore Processing
8.5: Energy and Resources- Industrial Minerals
8.6: Energy and Resources- Reading- Effects of Mining
8.7: Energy and Resources- The Implications of Resource Extraction for the Climate and Earth Systems
8.8: Energy and Resources- Fossil Fuels
8.9: Energy and Resources- Nuclear Energy
8.10: Energy and Resources- Solar and Wind
8.11: Energy and Resources- Hydro

8.12: Energy and Resources- Wave and Tidal Energy
8.13: Energy and Resources- Geothermal and Geo-Exchange
8.14: Energy and Resources- Our Energy Future

Index

Glossary

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Preface and Acknowledgements

Welcome to *Introduction to Earth Science*. This book was designed to serve California community college students by meeting the requirements for C-ID GEOL 121. The textbook is a remix, drawing from peer-reviewed Open Educational Resources (OER) to provide an academically rigorous yet accessible introduction to Earth's dynamic systems.

Concepts covered include geology, hydrology, meteorology, oceanography, and astronomy, emphasizing scientific methodology and environmental stewardship. The textbook will take you on a virtual journey to explore the processes that created and shape our planet, including the unifying theory of plate tectonics (e.g., directly or indirectly responsible for Earth's mountains, valleys, oceans, varied topography, and granite countertops), the rock cycle, the heat engines of oceanic and atmospheric circulation, climate, weather, and the complex interactions between Earth's systems and human activity.

This textbook synthesizes OER educational materials from authors who have generously contributed their work to advance scientific education. The goal of incorporating peer-reviewed OER materials is to maintain high academic standards while ensuring accessibility and adaptability for our diverse California community college student population. This approach reflects our commitment to academic excellence and educational equity, removing financial barriers while maintaining scholarly rigor.

It is hoped that this textbook will enable you to develop a greater understanding and abiding appreciation for our amazing planet!

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Book Introduction

The *Introduction to Earth Science OER Textbook* is designed to support California community college students in developing a comprehensive understanding of the physical processes that shape and sustain Earth's interconnected systems: the hydrosphere, biosphere, atmosphere, and geosphere. By exploring Earth science from an interdisciplinary perspective, this textbook emphasizes the spatial and temporal connections between these spheres, helping students see how each system influences the others. Aligned with C-ID GEOL 121 requirements, this resource is tailored for Earth Science courses and also serves as a foundational preparation for those pursuing a career in teaching Earth and Space Sciences at the K-12 level. The textbook integrates core concepts from geology, meteorology, oceanography, and environmental science, fostering a well-rounded grasp of Earth's dynamic processes and their relevance to California's diverse landscapes and ecosystems.

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1: INTRODUCTION TO EARTH SCIENCE

1.1: Introduction and Objectives

1.2: Earth Systems Overview

1.3: Components of the Earth System

1.4: Components of Earth System- Relationships between human activities and Earth's spheres

1.5: Human Activities- The Implications of Resource Extraction for the Climate and Earth Systems

1.6: Human Activities- Case Study- Major Threats to California's Water

1.7: Why Study Earth Science?

1.8: The Branches of Earth Science

1.9: Understanding Science

1.10: Understanding Science- What is it?

1.11: Understanding Science- The Scientific Method

1.12: Understanding Science- Outcome- Scientific Processes in Earth Science

1.13: Understanding Science- Early Scientific Thought

1.14: Understanding Science- Foundations of Earth Science

1.15: Understanding Science- Denial and Evaluating Sources

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1.1: Introduction and Objectives

Chapter Introduction

Welcome to the fascinating study of Planet Earth! In this chapter, we begin our exploration of the dynamic planet we call home. From the fiery core to the outermost atmosphere, Earth is a complex, interconnected system composed of diverse components that work in harmony. We'll study several of the components in detail, commonly referred to as Earth's major spheres—the geosphere, hydrosphere, atmosphere, and biosphere—and examine how they interact with each other and with human activities.

Understanding Earth Science isn't just about memorizing facts; it's about appreciating the intricate relationships that sustain life and recognizing the impact of our actions on these delicate systems. Through case studies like California's water crisis, we'll see the real-world implications of human impacts on this system, including pollution, resource extraction, and climate change. By examining the branches of Earth Science, the scientific method, and the foundations of early scientific thought, we'll build a solid framework for evaluating sources and confronting science denial. Let's embark on this adventure together and unravel the mysteries of our ever-changing planet!

Learning Objectives

1. Explain the components and interactions of Earth's systems, including the geosphere, hydrosphere, atmosphere, and biosphere.
2. Analyze the significance of Earth Science in understanding natural phenomena and addressing environmental challenges.
3. Evaluate the impact of human activities on Earth's spheres, with a focus on climate change and resource extraction.
4. Apply the scientific method and principles of early scientific thought to investigate Earth Science phenomena and assess scientific claims.
5. Critically assess sources of information in Earth Science, distinguishing between credible scientific evidence and science denial.

Let's begin!

Throughout its entire 4.5 Ga (i.e., giga annum, or billion years) history, every event in the history of our planet happened because something forced it to happen. An asteroid once caused an extinction. Extinctions led to novel new evolutionary pathways for species origination. As we will see, Earth's surface if comprised of lithospheric plates that are in continual, albeit gradual, motion. This process, referred to as plate tectonics, led to the current spatial arrangement of the continents. We might be tempted to describe each of these events as was explained in the preceding sentences, linearly (e.g., A caused B). We could leave it at that. However, is it rarely that simple!

Contained within our galactic system is a solar system powered by an average G type star. “On a mote of dust suspended in a sunbeam” (Carl Sagan) resides our Earth system. Like any system, it is composed of many moving parts, powered by flows of energy and sustained in a state of dynamic equilibrium. A system is a naturally occurring group of interacting, interrelated, or interdependent elements that form a complex whole.



Figure 1.1.1
Earth systems science seeks to understand the interconnectedness of our planet's air, water, land, and life (M. Ruzek 1999).

Within the Earth system, there are subsystems. These subsystems encompass the space environment (exosphere), gaseous environment (atmosphere), water environment (hydrosphere), solid environment (geosphere and its subcomponent the lithosphere), and living environment (biosphere). In some cases, the icy environment (cryosphere) is broken away from the hydrosphere and the anthroposphere (human environment) from the biosphere, for emphasis. Energy, coming from the Sun on one hand and the Earth's interior on the other, powers these systems. As energy flows through and between these systems, so too does matter, such as nutrients and elements. These flows of matter are often referred to as biogeochemical cycles. Examples of these include the carbon and nitrogen cycles.

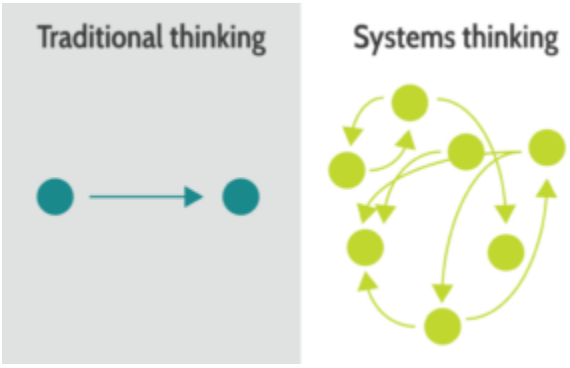


Figure 1.1.2: Systems thinking transcends linear approaches to problems and ways of understanding how things work (Image: Kindling.xyz)

Energy does not flow through these systems in a linear fashion. Its pathways are complex, taking advantage of the points where systems interact to transfer from one system to another and back again. In order to understand how our planet works today and how it has worked in the past (uniformitarianism), we need to use the principles of systems analysis. If we think in terms of systems, we begin to think in terms of cycles, feedbacks, forcing mechanisms, storage, sinks, and flows of energy and material.

Remember the extinction caused by an asteroid mentioned above? While the asteroid (from the exosphere) did indeed cause the extinction, it was the effect that asteroid had on the hydrosphere, atmosphere, and lithosphere that led to the subsequent destruction of life that occurred in the biosphere. In systems thinking, the asteroid was a forcing mechanism that disrupted the entire Earth system, past a tipping point of no return. While some organisms were directly crushed by the impending rock from space, most were killed by the subsequent cascading effects as energy rippled across the interconnected systems.

"To everything, there is a season".

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1.2: Earth Systems Overview

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The Earth system is made up of four fundamental subsystems, or spheres. These are referred to as spheres due to the spherical shape of planet Earth, which results in a spherical distribution of the subsystem. The four major spheres are the atmosphere, hydrosphere, biosphere, and lithosphere/geosphere. In the diagram below and to the left, these are abbreviated. In a moment, we will explore an expanded view of these spheres that includes three additional subsystems.

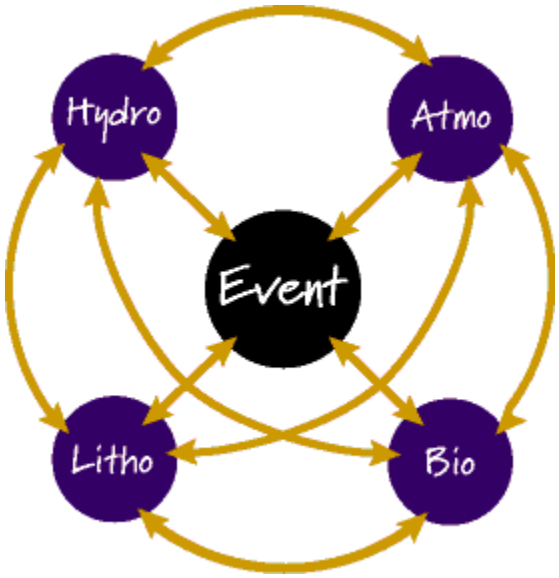


Figure 1.2.1: Earth system interactions due to an "Event". Events can be a wide variety of things that trigger interactions, or forcings, within the Earth system. (Wheeling Jesuit University/NASA Classrooms of the Future; reproduced with permission.)

Events effect the Earth system as a whole, though they usually begin within a particular sphere. Let us explore a volcanic eruption as an example. When a volcanic eruption occurs, what happens?

- Ash and rock are blasted into the atmosphere;
- Gases are emitted into the atmosphere;
- Lava may run downslope;
- Pyroclastic flows, superheated ash, may rush downslope at great velocity;
- Lahars, or mudflows, may result from the rapid melting of snow and ice, bringing large amounts of debris downslope;
- Flora and fauna in the immediate vicinity of the volcano may be killed.

There are other effects associated with volcanic eruptions. If you were to place the eruption in the very center of this diagram and write some of these interactions along the golden arrows toward a sphere, where would you place them? These are direct effects on each sphere from the event.

These direct effects are not the end of the story. You can see that arrows also connect each sphere to every other sphere. What are some of the indirect interactions (forcings) that result from the eruption? For example, how is the biosphere affected by alterations in the lithosphere? Ultimately, understanding the interconnectedness of the Earth system is critical for gaining a holistic view of how our planet is affected by individual events. In the history of our planet, there are no shortage of such events!

Earth System Forcing Events

Types of forcing events and their effects on the lithosphere/geosphere, hydrosphere, atmosphere, and biosphere.

Forcing Event	Lithosphere/ Geosphere	Hydrosphere	Atmosphere	Biosphere
Melting of Polar Ice	Direct - Isostatic adjustment as ice located on land melts	Direct - influx of freshwater into the marine realm affects thermohaline circulation. Change in planetary albedo leading to warmer seawater due to the loss of light-colored ice	Direct - Loss of sea ice leads to warming of oceans and changes in evaporation and weather patterns	Habitat fragmentation of organism ranges in polar regions
Stratovolcanic Eruption	Direct - Release of eruptive materials in the vicinity of the mountain and the creation of volcanic strata	Indirect via Atmosphere - influx of sulfur and carbon dioxide may lead to lower water pH	Direct - influx of ash, sulfur and carbon dioxide	Direct - Major effects on life in the vicinity of the volcano; Temporary regional or even global cooling affects some groups of organisms
Supervolcano Eruption	Direct - Major new volcanic deposits form over a large area. Vicinity of eruption subject to collapse.	Indirect via Atmosphere - surge of carbon and sulfur dioxide in atmosphere leads to lower pH in marine and freshwater environments.	Direct - Major influxes of volcanic gases and ash for extended periods of time.	Direct - Local, regional, and perhaps global extinctions due to deposits of massive amounts of volcanic material and extended global cooling
Deforestation	Indirect via Biosphere - Loss of vegetation leads to more mass wasting events	Indirect via Biosphere - Loss of vegetation affects regional transpiration, water storage, and drainage patterns	Direct - Loss of plant life leads to higher concentrations of carbon dioxide in the atmosphere	Direct - Habitat fragmentation and biodiversity loss. Possible localized or regional extinctions
Asteroid Impact	Direct - Major crater formed, ejecta deposits created over large area; high-pressure metamorphism in zone of impact; Seismic energy release	Direct - Vaporization of large amounts of surface and groundwater from a local to global level, depending upon size and composition of impactor	Direct - Frictional heating as impactor enters atmosphere; Heating as hot ejecta is thrown into atmosphere and exosphere that rains back down on Earth; Introduction of impact related particulate matter	Direct - local to global extinction event
Earthquake	Direct - Local to regional changes in landscape near fault	Indirect via Geosphere - Possible tsunamis or coastal landslides and turbidity currents	Indirect via Geosphere - Release of dust, debris, and toxic gases in some instances	Direct and Indirect - Depending on the species, building collapse and liquefaction can lead to death; Ecosystem changes are possible

Forcing Event	Lithosphere/ Geosphere	Hydrosphere	Atmosphere	Biosphere
Burning of Fossil Fuels	Indirect via Atmosphere - Addition of particulate matter and black carbon to sedimentary deposits; Climate change leads to other downstream effects	Direct - Changes in regional evaporation rates due to warming; Changes in hydrologic cycle	Direct - addition of carbon dioxide warms the troposphere; Changes in weather patterns	Direct - Climate warming leads to biodiversity loss, extinction, etc.
Viral Pandemic Among Human Population	Indirect - Social isolation and pause in economic activity leads to lower ambient seismic activity	Indirect - Reduction in pollution; Reduction in habitat disturbance from recreational boating	Indirect - Reduction in air pollution due to changes in economic activity and energy production	Direct - Widespread sickness and mortality among human species

This table lists a few examples of forcing events in the Earth system and some of their direct influences on one or more spheres. Some forcing events may not directly influence every sphere, rather only have an indirect secondary effect.

Earth Systems Interactions - Quiz



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Exercise 1.2.1

A volcanic eruption emits sulfur dioxide gas.



a. Between event and hydrosphere

b. Between event and atmosphere

c. Between event and biosphere

d. Between event and lithosphere/geosphere

Answer available at the end of this section.

Exercise 1.2.2

A volcanic eruption creates pyroclastic flows of super-heated gas and ash that rush downslope.



a. Between event and atmosphere

b. Between event and hydrosphere

c. Between event and lithosphere/geosphere

d. Between event and biosphere

Answer available at the end of this section.

Exercise 1.2.3

When volcanoes erupt, rapid melting of snow and ice can lead to lahars, or mudflows.



a. Event to Atmosphere

b. Event to Biosphere

c. Event to Hydrosphere

d. Event to Lithosphere/Geosphere

Answer available at the end of this section.

Exercise 1.2.4

Pyroclastic flows from a volcanic eruption event, in this case Mt. St. Helens in 1980, can have a downstream effect connecting the lithosphere/geosphere to...



a. Hydrosphere

b. Atmosphere

c. Biosphere

Answer available at the end of this section.

Answers

Exercise 1.2.1

b. Between event and atmosphere

Exercise 1.2.2

d. Between event and biosphere

Exercise 1.2.3

c. Event to Hydrosphere

Exercise 1.2.4

c. Biosphere

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1.3: Components of the Earth System

The following provides a brief overview of Earth's four major "spheres" as well as three additional components of the Earth system. In total, these are the:

- Exosphere
- Atmosphere
- Hydrosphere
- Cryosphere
- Lithosphere
- Biosphere
- Anthroposphere

Exosphere – Space Environment

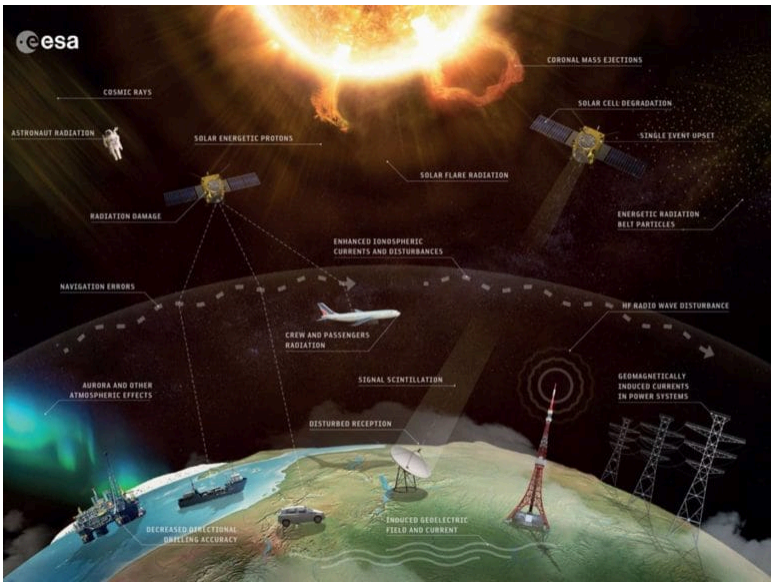


Figure 1.3.1: The exosphere, or the space environment in which our planet resides, has many effects on our planet. (ESA)

The exosphere is the space environment. Thought of from the perspective of the Earth, it is the location of our planet in the solar system, around our particular star, as well as the location of our solar system within the Milky Way galaxy, and so forth. All of the energy that powers the other systems on our planet, with the exception of the geosphere, comes from the Sun – outside our planet. This solar radiation, ranging from gamma radiation through long-wave radio waves, is critical for the normal operation of the biosphere, atmosphere, and hydrosphere. The exosphere is also the source of dangerous radiation in the form of galactic cosmic rays and solar particle events. Ultimately, the exosphere is hostile to life, but paradoxically critical to life as well.

Atmosphere – Gaseous Earth (Troposphere, Greenhouse Gases, etc)

The atmosphere is the gaseous envelope that surrounds our planet. Our current atmosphere can be thought of as the third atmosphere our planet has had. The primordial atmosphere of the Hadean (a widely used term referring to the earliest 500 - 700 million years of Earth's history) and outgassing processes eventually gave way to one dominated by volcanic gases and rich in CO_2. Photosynthesis evolved around 3.8 Ga, after which the atmosphere increased in oxygen and nitrogen. Since about 600 Ma, the concentration of oxygen in the lower atmosphere (troposphere) has been pretty consistent with what we have today.

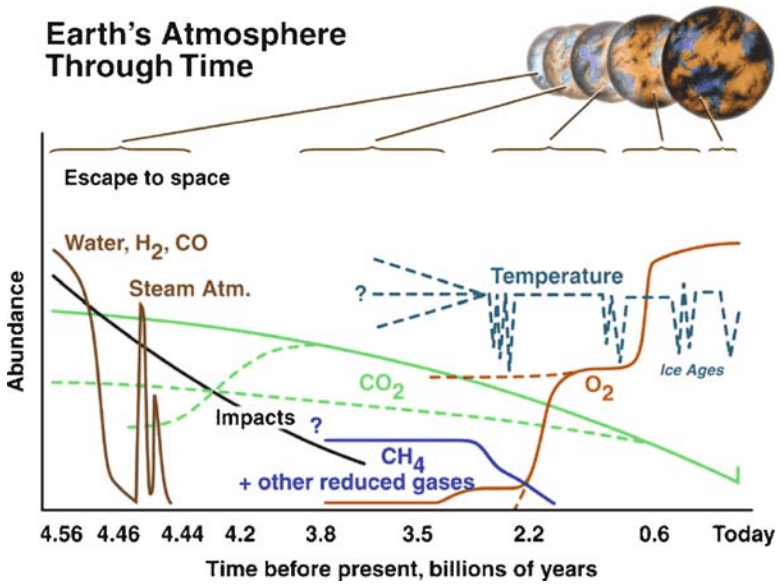


Figure 1.3.2: Evolutionary history of the atmosphere over Earth history. (NASA)

Our atmosphere is layered, with the densest portion at the bottom. This bottom layer of the atmosphere, the troposphere, is where most of the action occurs. We refer to much of that activity as weather. It is also in this layer that human activity has the greatest impact. It is affected on a daily basis by the uneven heating of the Earth's surface on land and sea and the rotation of the Earth, creating what is called the planetary boundary layer. As Earth's surface absorbs solar radiation, it heats up, warming the air at the Earth surface. This warm air rises, creating turbulence. Above the troposphere is the stratosphere. In contrast to the troposphere, the temperature increases with elevation in the stratosphere, creating stability and minimizing turbulence. In the stratosphere, exospheric UV radiation is absorbed by photochemically produced ozone and diatomic oxygen. Ozone at this level of the atmosphere is critical for protecting terrestrial life. Human activity, through the release of chlorofluorocarbon compounds contained in hairspray, refrigerants, and more, destroyed stratospheric ozone molecules, resulting in an ozone-depleted region centered around the South Pole that was first measured in 1985. In 1987, the world came together to ratify the Montreal Protocol. This protocol banned these classes of chemicals and prevented stratospheric ozone from deteriorating to an even more dangerous state. These actions are subsequently resulting in a gradual reduction in the extent of the ozone hole.

Above the stratosphere lies the mesosphere (middle atmosphere) and thermosphere. As you ascend upward into the mesosphere, temperatures and pressure decrease. At the thermopause, the lower boundary of the thermosphere, pressure continues to drop but temperatures suddenly begin to rise sharply.

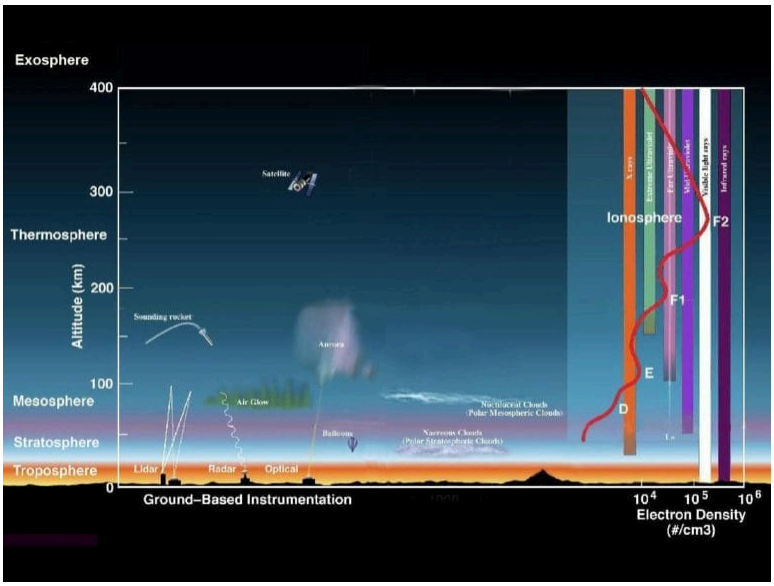


Figure 1.3.3:The layers of our atmosphere also depicted with cloud tops and the penetrating ability of various portions of the electromagnetic spectrum. Visible light, some UV light, Infrared energy, and radio waves are the principle sources that reach the ground. (NASA)

The atmosphere regulates Earth's climate in several significant ways. The most important of these is the concentration of gases in the troposphere that trap heat and prevent it from escaping to the exosphere. Solar radiation, incoming primarily as UV (8%), shortwave infrared (49%), and visible light (42%) radiation, will warm the surface (land and water) and then be re-radiated as longwave radiation. The longwave radiation gets trapped by greenhouse gases like CO_2, CH_4, and NO_x. All of these gases are increasing in concentration due to human activity. This heat thus gets trapped in the atmosphere, which has a much lower specific heat capacity than water. Generally, this means that the hydrosphere ends up absorbing this heat in all of its uneven nature around the planet, leading to increases in evaporation in some places and precipitation in others. The trapped heat also generally warms the oceans and land surfaces, leading to higher ocean and land temperatures.

YouTube Video

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The uneven heating of the atmosphere is important for normal weather patterns. As identified in the figure below, there are three atmospheric convection cells between the equator and each of Earth's poles. Each cell has a rising limb with warm moist air and descending limb with cool dry air. These cells play critical roles in atmospheric heat and moisture transfers. The rotation of the Earth produces the Coriolis Effect, which deflects the movement of air in these cells in an easterly direction at the poles (Polar Cell), westerly direction in the mid-latitudes (Ferrell Cell), and again in an easterly direction in the tropics (Hadley Cell). We will learn more about this in Chapter 4.

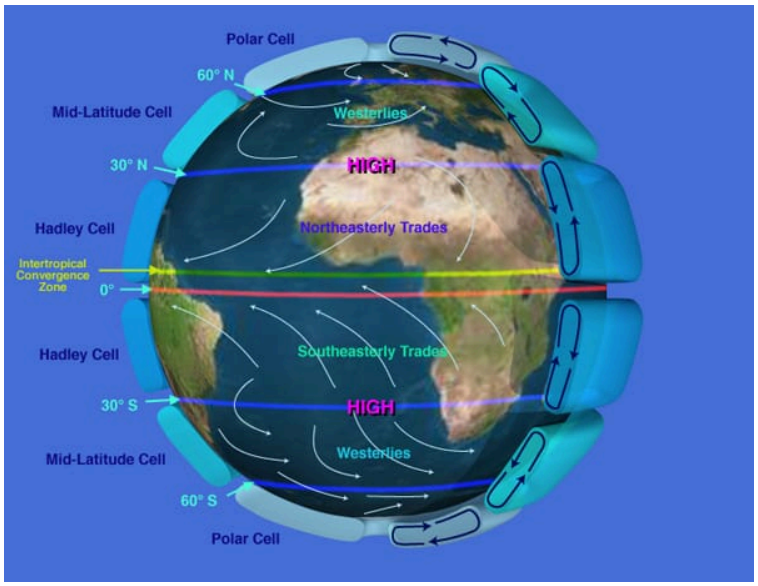


Figure 1.3.4: Atmospheric circulation patterns at equinox position (Spring or Autumn). Note the positions of Hadley Cells through Polar Cells by latitude and their deflection due to the Coriolis Effect. (NASA)

These latitudinal variations drive our weather and lead to important gradients in the biosphere, called Latitudinal Biodiversity Gradients (LBG). Generally, biodiversity decreases from the tropics to the poles. This change in biodiversity is directly related to precipitation patterns and temperature changes with latitude...today. It is important to note here that today's LBG is not the norm for Earth's past. In fact, approximately 50 Ma, it is very likely that the temperate regions of the planet were the most diverse. This is because it was so much hotter in the tropics.

Hydrosphere – Earth's Water (Fresh, Marine, Ground, etc.)

The hydrosphere includes all water on earth, even that in the atmosphere as water vapor and clouds. It also consists of the oceans

and freshwater in groundwater, lakes, rivers, and streams. While it is considered separately here, the cryosphere (e.g., glacial ice) is a critical element of the hydrosphere as it provides a significant storage sink for water.

Freshwater and marine systems have many similarities as well as many differences. The key feature of all water in the hydrosphere is its ability to regulate heat in various ways.

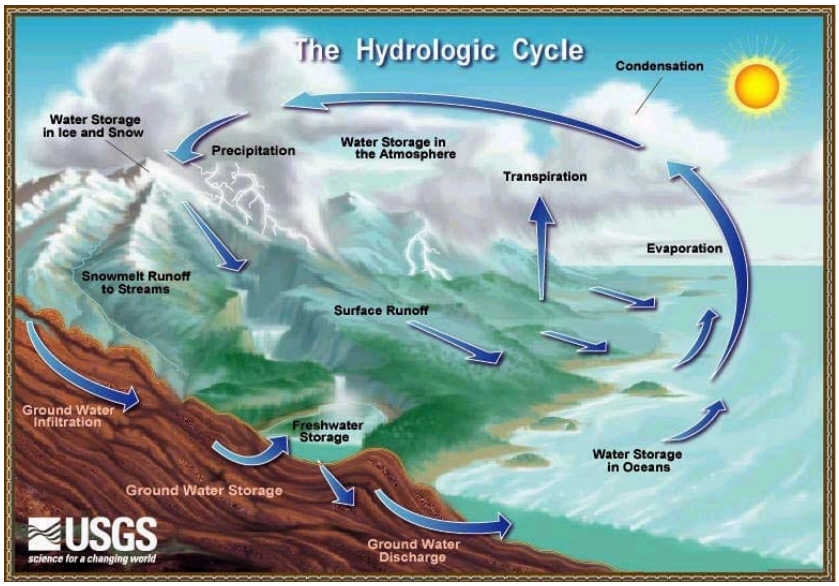


Figure 1.3.5: The hydrologic cycle and hydrosphere. (USGS graphic)

Water has a high heat capacity (specific heat). That is, it will absorb a great deal of heat energy before it gets hot itself. It also requires considerable energy to convert liquid water to water vapor (i.e., the latent heat of evaporation). Thus, when water evaporates, it absorbs a significant amount of heat from the surrounding environment. This heat is stored in the water vapor and is not released until the vapor condenses back into liquid. When water vapor condenses into liquid water, it releases the stored latent heat of vaporization back into the atmosphere. This release of heat warms the surrounding air. Because of these properties, water is a critical regulator of energy on the planet. 1 kg of water has to absorb 4,184 J of energy for its temperature to rise 1 °C. By comparison with rock, in this case, only 385 J are needed to increase the temperature of 1 kg of copper one degree Celsius. Not only does the heat capacity of water make fish happy, it also means that excess heat from the atmosphere, the Sun, or the land during the day can be absorbed by water with little effect. Ultimately, while the hydrosphere is driven by the exchange of heat itself (the hydrologic cycle), it also regulates the planet's temperature in much the same way as sweat helps regulate your body temperature during a workout.

Another critical heat-regulating feature of the hydrosphere is ocean currents. Whether the continents are combined into a single supercontinent or split into what we have today, warm surface waters move and exchange with cool nutrient-rich bottom waters. This exchange, or convection, produces currents. These rivers in the ocean move heat around the planet. Temperature is not the only physical property in play when it comes to marine currents, as the salinity of marine water can vary enough to produce density-driven currents. The combined thermohaline circulation patterns in the ocean regulate our climate.

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Cryosphere – Frozen portion of the hydrosphere

The cryosphere is the solid portion of the hydrosphere. It is worth discussing separately from the hydrosphere because of the particular importance of ice in exchanges of heat and light between Earth's systems. Like water, ice has a heat regulation effect.



Figure 1.3.6: A view of the Antarctic cryosphere (NASA)

Polar ice caps provide an important counterweight to the extreme heat experienced in the mid-latitudes. The temperature differences between these regions drives the movement of air in the atmosphere, forming atmospheric convection cells (warm air rising and cool air descending) that, while deflected by the Earth's rotation and Coriolis Effect, drive our weather. Polar ice is also a critical water storage sink. As it melts, sea level rises and isostatic adjustment of continents occurs.

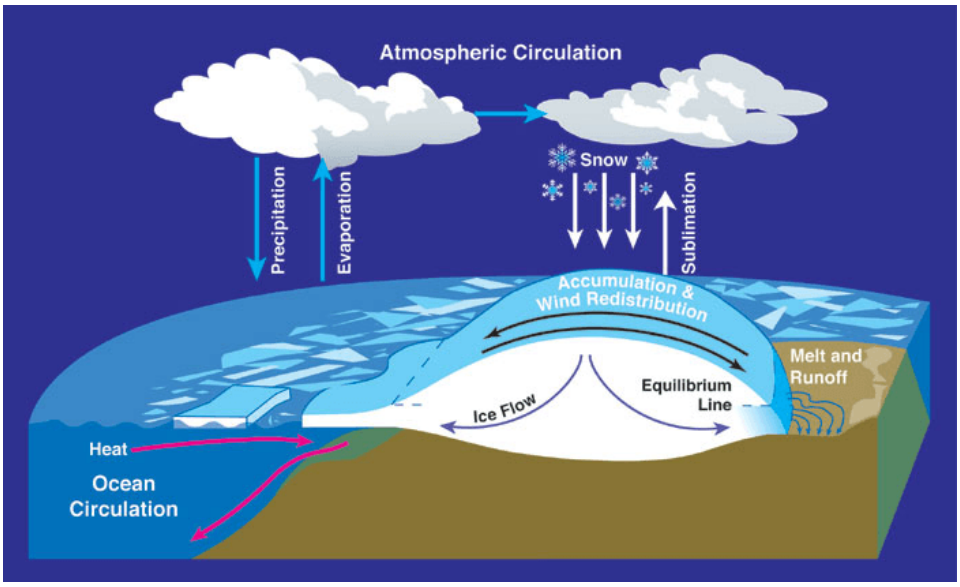


Figure 1.3.7: Earth's Cryosphere (NASA)

The Earth has not always had polar ice. Just 40 Ma ago, the planet's climate was so warm that there was no ice at the poles. With the rising of the Himalayas and Andes came increased erosion and chemical weathering of silicate minerals. As mountains rise, this form of weathering results in a net depletion of carbon dioxide from the atmosphere and deposits the byproduct of that carbon into the oceans as bicarbonate ions. The removal of carbon dioxide from the atmosphere results in a general cooling of the planet. This eventually resulted in ice storage on land over Antarctica, as a continental glacier. Later, ice would form over the northern polar regions in the sea.

The polar ice caps are only part of the story of the cryosphere. The ebb and flow of continental glaciers in places like Greenland and valley glaciers all over the world provide us with important visual thermometers for global temperature changes.

As glaciers and sea ice retreat, there are changes in the color distribution on the Earth's surface. Albedo, a measure of this, is highest on ice and lowest on ocean water. When sunlight hits ice, it reflects nearly 100% of the energy. When sunlight hits water, water acts similar to a blackbody (an object that absorbs all radiation it receives). As the climate warms, ice recedes, and the climate warms more. We will return to this dynamic later in the textbook.

Lithosphere/Geosphere – Solid Earth (Rock, including molten rock)

The geosphere makes up the solid portion of the planet. If you have taken a course in Physical Geology, you know all about the rocks and minerals that make up the various layers of our planet from the inner core outward to the crust. Chapter 2 in this book will introduce you to the minerals and rocks of the geosphere.

Unique among the spheres, the geosphere produces its own energy. There are three sources. Radioactive decay of unstable elements within our planet's interior produces a great deal of heat energy. Another heat source comes from remnant primordial heat still yet to dissipate from the planet's formation. Finally, frictional heating plays a role, descending material rubs against other materials. Earth is hottest near the center and is cooler at the surface. This collective heat leads to the geothermal gradient, the increase in temperature as you descend further into the Earth. It also drives plate tectonics and resulting volcanism, earthquakes, and natural hazards.

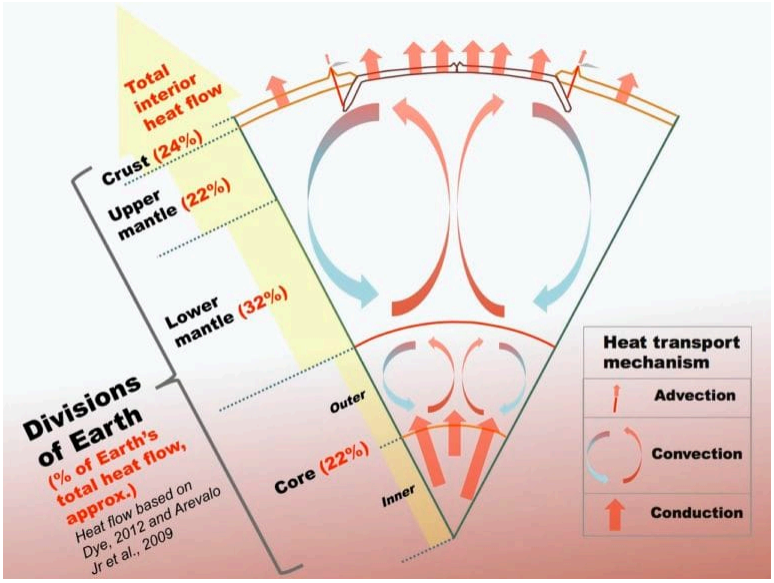


Figure 1.3.8: Cross-section of the Earth showing its main divisions and their approximate contributions to Earth's total internal heat flow to the surface, and the dominant heat transport mechanisms within the Earth (Wikimedia, Bkilli[1])

Because of this independent heat energy, the solid Earth is much more dynamic than any other terrestrial planet we know of. Mercury, Venus, and Mars are very different places with differing amounts of interior activity. Some natural satellites in our solar system likely also produce their own interior heat. Examples may include Saturn's natural satellite Titan. Earth, because of plate tectonics, is a much more active planet and one where the rocks are constantly interacting with and having an effect on the liquid and gaseous portions of the planet.

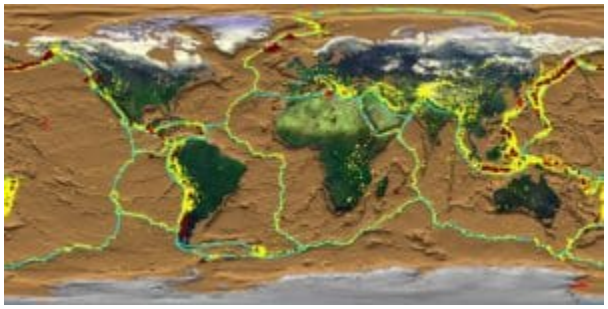


Figure 1.3.9: Crustal dynamics in the Earth's geosphere. Red triangles indicate volcanoes and yellow dots indicate earthquake epicenters. Blue lines are plate boundaries. (NASA SVS)

It is hard to pin down the most important geosphere elements for driving climatic change on the Earth. Volcanism is very likely most important, due to the input of gases like SO_2 into the atmosphere, which can have a cooling effect due to its ability to reflect solar radiation back to space. There is also airborne dust, sometimes referred to as loess and measured as a component of particular matter. This airborne dust has the ability to absorb heat and heat the atmosphere, causing warming in places where

dust is moved from elsewhere.

Biosphere – Life

Without a tectonically active geosphere, an atmosphere with the right concentration of gases, and a hydrosphere made up so heavily of liquid water, there would likely be little to no biosphere on Earth. Unique among planets in our solar system and perhaps anywhere, Earth contains an amazing array of life. The origins of life on Earth are still somewhat elusive, but we do know that over time it has evolved to live in balance with the other spheres to the point where because the biosphere is such a critical influence on the other spheres, it can be considered on its own terms. Being located in the habitable zone (Goldilocks Zone) of a G-type star has its perks. Is Earth unique in this? A number of exoplanets have been identified that are located in the habitable zones around their stars, but as yet, no extraterrestrial life has been confirmed.

The video below provides a sense of life on Earth. You are viewing the ebb and flow of life forms in the oceans through the lens of chlorophyll from space, with data collected by the MODIS sensor. This data was collected by NASA between 2002 and 2010 and displays visually the intricate link between photosynthetic life and seasonality.

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The biosphere plays a very important role in the climate, particularly when it comes to the regulation of greenhouse gases. Of course, the decomposition of organic matter is a major source of $\mathrm{CH_4}$ and NO_x gases, aside from what humans contribute. But, the real effect is the planet-wide exchange of $\mathrm{CO_2}$ and $\mathrm{O_2}$ that is so critical to regulating temperature and providing breathable oxygen.

Check out the supercomputer simulation of $\mathrm{CO_2}$, offered by NASA Goddard below. The red concentrations mostly represent $\mathrm{CO_2}$, but you will see as the animation and narration progress that, during the southern hemisphere summer, CO concentrations from fires in Africa and South American increase significantly. As the animation progresses, note the role that the biosphere plays in the annual fluctuations of $\mathrm{CO_2}$ in various places around the planet, but particularly in the Amazon and Congo basins.

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3.8 Ba ago, the biosphere began to alter the Earth's atmosphere for its own purposes. The evolution of photosynthesis and the subsequent Great Oxygenation Event have left a long legacy that lives on today, in the form of algae and other plants that provide the base of the trophic levels so critical to our existence. Today, the biosphere is once again altering the Earth's atmosphere, but through the actions of a single species.

Anthroposphere – Human portion of the biosphere



Figure 1.3.10: Earth at night (NASA)

The anthroposphere has been suggested to account for human interactions with Earth's spheres. Humans are a force of nature. No single species in the history of life can claim such a mantle. Yet, humans are a part of the biosphere. Because of our outsized impact, it is useful and perhaps even appropriate to consider the human element of the planet independently from the other spheres. Thus, the anthroposphere. The human impact on the planet goes well beyond altering the atmosphere and climate, leading some scientists to argue that the Earth has entered a new geological epoch. However, the Subcommission on Quaternary Stratigraphy of the International Commission on Stratigraphy uniformly rejected this proposal in March 2024.

Did I Get It? - Quiz

Exercise 1.3.1

Which of the Earth's spheres encompasses frozen water?

a. Hydrosphere

b. Cryosphere

c. Lithosphere

Answer available at the end of this section.

Exercise 1.3.2

Which of the Earth's spheres do you see interacting here?



a. Biosphere, Atmosphere, Hydrosphere

b. Biosphere, Anthroposphere, Lithosphere

c. Biosphere, Lithosphere, Atmosphere

Answer available at the end of this section.

Answers

Exercise 1.3.1

b. Cryosphere

Exercise 1.3.2

c. Biosphere, Lithosphere, Atmosphere

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1.4: Components of Earth System- Relationships between human activities and Earth's spheres

Human interactions with Earth's systems have profoundly altered the planet. The geosphere, comprising the solid Earth has been extensively modified by activities such as mining, construction, and agriculture. These activities alter the physical landscape and trigger processes like erosion and sedimentation, influencing the stability and composition of the Earth's surface. Moreover, the extraction of fossil fuels has led to significant geological changes, including mild earthquakes (from fracking), land subsidence, and the formation of artificial structures like quarries and landfills.

The hydrosphere, encompassing all water bodies on Earth, has also been significantly impacted by human activities. Freshwater resources are under pressure from over-extraction, pollution, and climate change. Rivers are dammed for hydroelectric power, altering their natural flow and affecting ecosystems both upstream and downstream. Industrial and agricultural runoff introduces pollutants into lakes, rivers, and oceans, leading to water quality degradation and the disruption of aquatic life. Additionally, climate change, driven by human-induced greenhouse gas emissions, is causing sea levels to rise and altering precipitation patterns, further stressing water resources.

Human activities have a profound impact on the atmosphere, the layer of gases surrounding the Earth. The burning of fossil fuels for energy and transportation releases large amounts of carbon dioxide and other greenhouse gases into the atmosphere, contributing to global warming and climate change. Air pollution from industrial processes, vehicle emissions, and deforestation leads to smog and acid rain, which harm human health, reduce air quality, and damage ecosystems. Efforts to mitigate these effects include transitioning to renewable energy sources, enhancing energy efficiency, and implementing stricter air quality regulations.



Figure 1.4.1 "Bathed in air pollution, Henan Province, China" by vtpoly is licensed under CC BY-NC-ND 2.0.

The biosphere, which includes all living organisms on Earth, is directly affected by human actions. Habitat destruction, overexploitation of resources, pollution, and the introduction of invasive species have led to significant biodiversity loss. Agricultural practices, urban expansion, and deforestation disrupt natural habitats, reducing the available space for wildlife and altering ecosystems. Conservation efforts, such as protecting endangered species, restoring habitats, and promoting sustainable practices, are essential to preserve biodiversity and maintain the balance of ecosystems.

Human interactions with Earth's four spheres are interconnected and complex, with each sphere influencing and being influenced by the others. Understanding these interactions is crucial for developing sustainable practices that minimize negative impacts and enhance the resilience of Earth's systems. By recognizing the importance of each sphere and their interdependencies, we can make informed decisions to protect and sustain our planet for future generations.

The following subsections provide two examples of these interactions.

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1.5: Human Activities- The Implications of Resource Extraction for the Climate and Earth Systems

Mining and ore-processing require a huge amount of energy for operating machinery, transportation, and, especially, for smelting and refining. That includes about 15% of total global electricity and 11% of total global energy overall,[1] and therefore acquiring the metals used to make all the things we buy has a huge climate impact. We need to think carefully about that every time we buy something that has metal in it. And, of course, we need to think about that every time we buy a manufactured product that has *anything* in it.

Recovering fossil fuels is also energy intensive and leads to emissions of greenhouse gases at every step in the process, but the really significant climate cost of fossil fuels is in their use, and that's why we can no longer consider fossil fuels as an energy source for the future, and we have to stop looking for and developing more fossil fuel resources.

Mining and ore-processing have implications for Earth systems in a number of ways:

- Mining results in exposure of rock to weathering, both within the mines (especially surface mines) and because ore-processing involves crushing and grinding rock into small pieces, producing waste materials that are highly susceptible to weathering.
- Weathering includes oxidation of sulphide minerals, releasing acid into the environment, leading to some of the outcomes summarized in Box 8.1, and might also include hydrolysis of silicates, in which case it could consume CO_2 from the atmosphere.
- Refining metals (especially smelting) introduces a wide range of toxic materials into the atmosphere, as well as acidity, that can have significant negative for plant life, and so for ecosystems in general.
- Production of cement by heating of calcium carbonate results in the release of carbon dioxide, and so contributes to climate change.
- Mining, and the related construction of roads and railways, contributes to slope failures and that can have a range of Earth systems implications, some of which are described in Chapter 1.

1. Igogo, T. et al. (2020). I*ntegrating clean energy in mining operations: Opportunities, challenges, and enabling approaches* (technical report, NREL/TP-6A50-76156). The Joint Institute for Strategic Energy Analysis (JISEA). https://www.nrel.gov/docs/fy20osti/76156.pdf ↵

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1.6: Human Activities- Case Study- Major Threats to California's Water

Case Study: Major Threats to California's Water

California's water supply faces numerous threats that exemplify the significant human impacts on the hydrosphere. One of the most pressing issues is drought, a recurrent problem exacerbated by climate change. Extended periods of low precipitation and high temperatures reduce the availability of surface water and groundwater, leading to water shortages. These conditions strain water resource availability. In a typical year, approximately 50% of the state's water is allocated to the environment, 40% to agriculture, and 10% for urban use. Climate models predict that droughts will become more frequent and severe, challenging the state's ability to manage its water supply effectively.



Figure 1.6.1 "California Drought 2015" by Ben Amstutz is licensed under CC BY-NC-ND 2.0.

Water quality is another critical concern. Agricultural runoff, industrial discharges, and urban wastewater introduce pollutants into California's water bodies. Pesticides, fertilizers, heavy metals, and other contaminants degrade water quality, posing risks to human health and aquatic ecosystems. The contamination of drinking water sources by nitrates and other pollutants is particularly alarming in rural areas reliant on groundwater. Efforts to improve water quality involve stringent regulation of pollutants, investment in water treatment infrastructure, and the promotion of best management practices in agriculture and industry.

Agriculture is a major consumer of California's water. The Central Valley, one of the most productive agricultural regions in the world, relies heavily on irrigation. However, the over-extraction of water for farming has led to the depletion of groundwater reserves and the reduction of surface water flows. Groundwater overdraft is especially exorbitant during periods of drought and has led to a myriad of problems including groundwater subsidence and plummeting groundwater levels. This unsustainable use of water resources not only threatens the long-term viability of agriculture but also impacts the environment, leading to the loss of wetlands and the decline of fish populations. The 2014 Sustainable Groundwater Management Act (SGMA) is intended to ensure sustainable use of groundwater resources. Sustainable agricultural practices, including fallowing farmland, more efficient irrigation techniques, and the cultivation of drought-tolerant crops, are addressing these issues.

Urban demand for water has plateaued, partly due to conservation efforts and a modest reduction in population. Major cities like Los Angeles, San Francisco, and San Diego require vast and reliable water supply for residential, commercial, and industrial purposes. The challenge is further compounded by aging water infrastructure and the need for substantial investment in maintenance and upgrades. Urban water conservation measures, such as water recycling, the use of drought-resistant

landscaping, and public awareness campaigns, are critical to reducing per capita water use and ensuring a reliable water supply for urban areas. To incentivize such practices, new legislation, Making Conservation a Way of Life in California, was passed in 2024 and aims to decrease urban water use.

In conclusion, the major threats to California's water supply—drought, water quality issues, agricultural demands, and urban consumption—highlight the complex interactions between human activities and the hydrosphere. Addressing these challenges requires an integrated approach that balances the needs of agriculture, urban areas, and the environment. Sustainable water management practices, technological innovations, and comprehensive policy frameworks are essential to safeguarding California's water resources for future generations. This case study underscores the importance of understanding and mitigating human impacts on the hydrosphere to ensure the sustainability of vital water supplies.

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1.7: Why Study Earth Science?

Why Do People Study Earth Science?

A lot of people are attracted to study the earth sciences because they love to be outdoors. These people wonder how the magnificent rock formations that they see, like those in Yosemite in California (see figure 1), were formed. They want to study the processes that create and modify landforms.



Figure 1.7.1. Half dome in Yosemite, National Park, California, USA

But earth science is not just about what we can see with the naked eye—the molten lava, icy mountain peaks, steep canyons, and towering waterfalls. Some people want to go deeper, to learn about what drives the surface processes and other features of the planet; for example, why does Earth have a magnetic field? These people are interested in learning about the layers of material that lie beneath the surface, the mantle and the core. Since more than 70 percent of Earth is covered with oceans, it's not surprising that many people wonder what lies within and at the bottom of the seas.



Figure 1.7.2. The "Blue Marble"

Some people look up and wonder what lies beyond our skies. These people are interested in applying what we know about Earth to our more distant surroundings. They want to understand our near neighbors, the planets and satellites of our Solar System, and objects that lie far beyond.

What is Earth Science?

In its broadest sense, earth science is the study of the Earth — and encompasses a range of scientific disciplines that focus on understanding the planet's structure, properties, processes, and history. This field of science seeks to uncover the mysteries of Earth's formation, its dynamic changes over time, and the complex interactions between its various components. By exploring the geosphere, hydrosphere, atmosphere, and biosphere, earth scientists gain insights into the natural world and can thereby address some of the most pressing environmental challenges we face today. In earth science, deductive reasoning and scientific methods are used to understand and address challenges and problems.

It can be argued that earth science is the most integrated of all sciences because it involves understanding and applications of physics, chemistry, biology, mathematics, astronomy, and other science disciplines. Earth science generally adheres to a system approach to understanding the earth. Understanding and modeling the interactions and interdependencies between earth's spheres is a central focus of this system approach. Taking these dependencies and interactions into account results in an understanding of the whole system that is much greater than the sum of the individual components. In addition, unlike most sciences, earth science has an extra dimension, that of time—billions of years of it. Earth scientists study the evidence that they see around them, but in most cases, they are observing the results of processes that happened thousands, millions, and even billions of years in the past. Those were processes that took place at incredibly slow rates—millimeters per year to centimeters per year—but because of the amount of time available, they produced massive results.



Figure 1.7.3. Rearguard Mountain and Robson Glacier in the Rocky Mountains of British Columbia

Earth science is displayed on a grand scale in mountainous regions, for example, consider the Rocky Mountains in Canada (Figure 3). The peak on the right is Rearguard Mountain, which is a few kilometers northeast of Mount Robson, the tallest peak in the Canadian Rockies (3,954 m). The large glacier in the middle of the photo is the Robson Glacier. The river flowing from Robson Glacier drains into Berg Lake in the bottom right.

The sedimentary rock that these mountains are made of formed in ocean water over 500 million years ago. A few hundred million years later, these beds were pushed east for tens to hundreds of kilometers by tectonic plate convergence and also pushed up to thousands of meters above sea level. Over the past two million years this area—like most of the rest of Canada—has been repeatedly glaciated, and the erosional effects of those glaciations are obvious. The Robson Glacier is now only a small remnant of its size during the Little Ice Age of the fifteenth to eighteenth centuries, as shown by the distinctive line on the slope on the left. Like almost all other glaciers in the world, it is now receding even more rapidly because of human-caused climate change.

Earth science is also about understanding the evolution of life on Earth; about discovering resources such as metals and energy; about recognizing and minimizing the environmental implications of our use of those resources; and about learning how to mitigate the hazards related to earthquakes, volcanic eruptions, and slope failures. All of these aspects of earth science, and many more, are covered in this textbook.

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1.8: The Branches of Earth Science

As we mentioned, there are many aspects of earth science. There is so much to know about our home planet that most geologists become specialists in one area. These specialties are known as **branches of earth science**, and have specific titles. For example, a mineralogist studies minerals while a seismologist monitors earthquakes to help protect people and property from harm (figure 1).

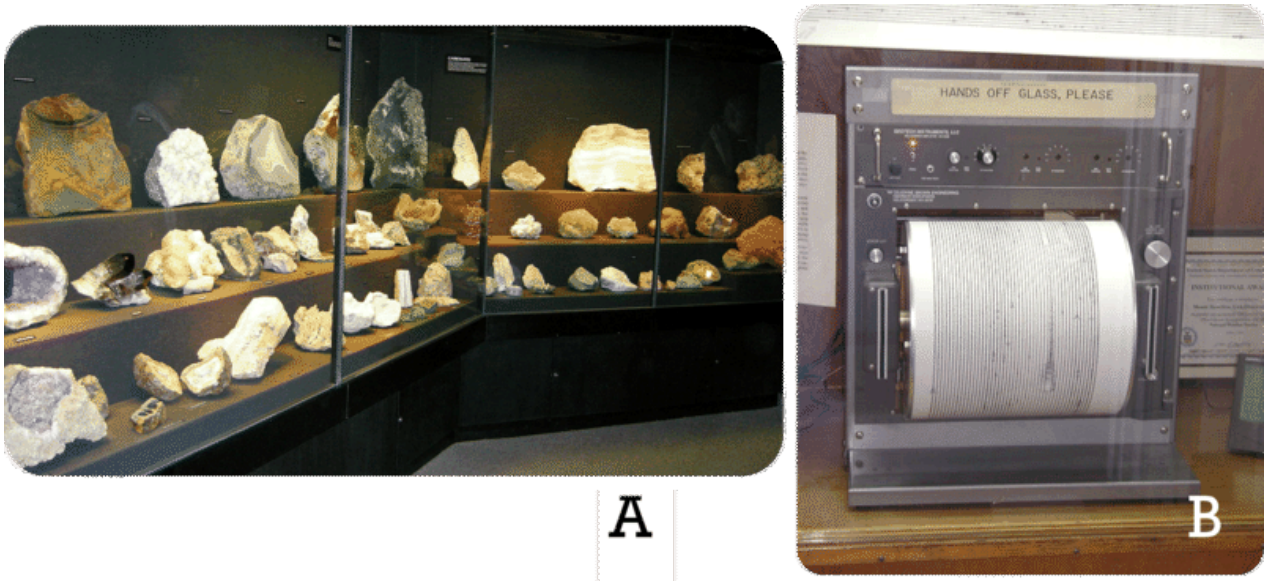


Figure 1.8.1. (A) Mineralogists focus on all kinds of minerals. (B) Seismographs are used to measure earthquakes and pinpoint their origins.

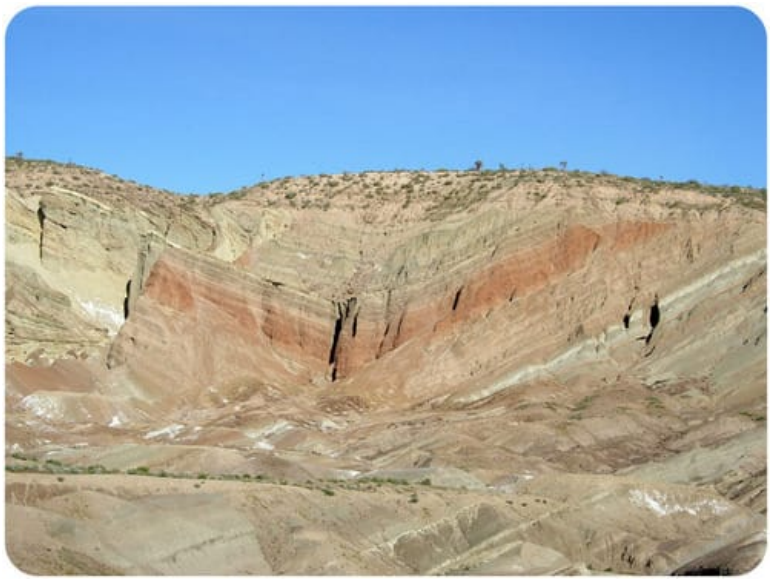


Figure 1.8.2. These folded rock layers have bent over time. Studying rock layers helps scientists to explain these layers and the geologic history of the area.

Geology is perhaps the scientific discipline most closely aligned with earth science. Volcanologists, traditionally considered as geologists, brave molten lava to study volcanoes. Scientists who compare the geology of other planets to Earth are planetary geologists. Some geologists study the Moon. Others look for petroleum. Still others specialize in studying soil. Some geologists can tell how old rocks are and determine how different rock layers formed (figure 2). There is probably an expert in almost anything you can think of related to Earth!

Earth scientists might study rivers and lakes, the underground water found between soil and rock particles, or even water that is

frozen in glaciers. Earth scientists also need geographers who explore the features of Earth's surface and work with cartographers, who make maps. Studying the layers of rock beneath the surface helps us to understand the history of planet Earth.

Some Branches of Earth Science

As you've seen, different branches of earth science study one particular part of earth. Since all of the branches are connected, specialists work together to answer complicated questions. Let's look at some other important branches of earth science.

Geochemistry

Geochemistry is the study of the chemical processes which form and shape the Earth. It includes the study of the cycles of matter and energy which transport the Earth's chemical components and the interaction of these cycles with the hydrosphere and the atmosphere.

It is a subfield of inorganic chemistry, which is concerned with the properties of all the elements in the periodic table and their compounds. Inorganic chemistry investigates the characteristics of substances that are not organic, such as nonliving matter and minerals found in the Earth's crust.

Oceanography

Oceanography is the study of the composition and motion of the water column and the processes which are responsible for that motion. The principal oceanographic processes influencing continental shelf waters include waves and tides as well as wind-driven and other oceanic currents. Understanding the oceanography of shelf waters and the influence this has on seabed dynamics, contributes to a wide range of activities such as the following:

- assessment of offshore petroleum production infrastructure
- seabed mapping and characterisation for environmental management
- marine biodiversity surrogacy research
- assessment of renewable energy potential

Paleontology

Paleontologists are interested in fossils and how ancient organisms lived. Paleontology is the study of fossils and what they reveal about the history of our planet. In marine environments, microfossils collected within in layers of sediment cores provide a rich source of information about the environmental history of an area.

Sedimentology

Sedimentology is the study of sediment grains in marine and other deposits, with a focus on physical properties and the processes which form a deposit. Deposition is a geological process where geological material is added to a landform. Key physical properties of interest include:

- the size and shape of sediment grains
- the degree of sorting of a deposit
- the composition of grains within a deposit
- sedimentary structures.

These properties together provide a record of the mechanisms active during sediment transportation and deposition which allows the interpretation of the environmental conditions that produced a sediment deposit, either in modern settings or in the geological record.

Additional Branches

- **Benthic Ecology.** Benthic ecology is the study of living things on the seafloor and how they interact with their environment.
- **Biostratigraphy.** Biostratigraphy is the branch of stratigraphy that uses fossils to establish relative ages of rock and correlate successions of sedimentary rocks within and between depositional basins.
- **Geochronology.** Geochronology is a discipline of geoscience which measures the age of earth materials and provides the temporal framework in which other geoscience data can be interpreted in the context of Earth history.
- **Geophysics.** Information relating to various techniques including: airborne electromagnetics, gravity, magnetics, magnetotellurics, radiometrics, rock properties and seismic.
- **Marine Geochemistry.** Marine geochemistry is the science used to help develop an understanding of the composition of coastal and marine water and sediments.
- **Marine Geophysics.** Marine geophysics is a scientific discipline which uses the quantitative observation of physical properties to understand the seafloor and sub-seafloor geology.
- **Marine Surveying.** The survey environment varies from oceanographic studies in the water column to investigating sediment and geochemical processes on the seafloor and imaging the sub-seafloor rocks. Surveys are carried over Australia's entire marine jurisdiction, from coastal estuaries and bays, across the continental shelf and slope, to the deep abyssal plains.
- **Spectral Geology.** Spectral geology is the measurement and analysis of portions of the electromagnetic spectrum to identify spectrally distinct and physically significant features of different rock types and surface materials, their mineralogy and their alteration signatures.

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1.9: Understanding Science



Learning Objectives

- Contrast objective versus subjective observations, and quantitative versus qualitative observations
- Identify a pseudoscience based on its lack of falsifiability
- Contrast the methods used by Aristotle and Galileo to describe the natural environment
- Explain the scientific method and apply it to a problem or question
- Describe the foundations of modern geology, such as the principle of uniformitarianism
- Contrast uniformitarianism with catastrophism
- Explain why studying geology is important
- Identify how Earth materials are transformed by rock cycle processes
- Describe the steps involved in a reputable scientific study
- Explain rhetorical arguments used by science deniers

Science is a process, with no beginning and no end. Science is never finished because a full truth can never be known. However, science and the scientific method are the best way to understand the universe we live in. Scientists draw conclusions based on objective evidence; they consolidate these conclusions into unifying models. Geologists likewise understand studying the Earth is an ongoing process, beginning with James Hutton who declared the Earth has "...no vestige of a beginning, no prospect of an end." Geologists explore the 4.5 billion-year history of Earth, its resources, and its many hazards. From a larger viewpoint, geology can teach people how to develop credible conclusions, as well as identify and stop misinformation.

Thumbnail: Sunset at Delicate Arch (Arches National Park, Utah). (CC-SA-BY; 3.0; Palacemusic).

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1.10: Understanding Science- What is it?

Scientists seek to understand the fundamental principles that explain natural patterns and processes. Science is more than just a body of knowledge, science provides a means to evaluate and create new knowledge without bias. Scientists use objective evidence over subjective evidence, to reach sound and logical conclusions. An objective observation is without personal bias and the same by all individuals. Scientists use objective evidence over subjective evidence, to reach sound and logical conclusions.

An objective observation is without personal bias and the same by all individuals. Humans are biased by nature, so they cannot be completely objective; the goal is to be as unbiased as possible. A subjective observation is based on a person's feelings and beliefs and is unique to that individual.



Figure 1.10.1: This is Grand Canyon of the Yellowstone in Yellowstone National Park. An objective statement about this would be: "The picture is of a waterfall." A subjective statement would be: "The picture is beautiful." An inference would be "The waterfall is there because of erosion."

Another way scientists avoid bias is by using quantitative over qualitative measurements whenever possible. A quantitative measurement is expressed with a specific numerical value. Qualitative observations are general or relative descriptions. For example, describing a rock as red or heavy is a qualitative observation. Determining a rock's color by measuring wavelengths of reflected light or its density by measuring the proportions of minerals it contains is quantitative. Numerical values are more precise than general descriptions, and they can be analyzed using statistical calculations. This is why quantitative measurements are much more useful to scientists than qualitative observations.



Figure 1.10.2: Canyons like this, carved in the deposit left by the May 18th, 1980 eruption of Mt. St. Helens, are sometimes used by purveyors of pseudoscience as evidence for the Earth being very young. In reality, the non-lithified volcanic deposit is carved much more easily than other canyons like the Grand Canyon.

Establishing truth in science is difficult because all scientific claims are falsifiable, which means any initial hypothesis may be tested and proven false. Only after exhaustively eliminating false results, competing ideas, and possible variations does a hypothesis become regarded as a reliable scientific theory. This meticulous scrutiny reveals weaknesses or flaws in a hypothesis

and is the strength that supports all scientific ideas and procedures. In fact, proving current ideas are wrong has been the driving force behind many scientific careers.

Falsifiability separates science from pseudoscience. Scientists are wary of explanations of natural phenomena that discourage or avoid falsifiability. An explanation that cannot be tested or does not meet scientific standards is not considered science, but pseudoscience. Pseudoscience is a collection of ideas that may appear scientific but does not use the scientific method. Astrology is an example of pseudoscience. It is a belief system that attributes the movement of celestial bodies to influencing human behavior. Astrologers rely on celestial observations, but their conclusions are not based on experimental evidence and their statements are not falsifiable. This is not to be confused with astronomy which is the scientific study of celestial bodies and the cosmos [2,3].



Figure 1.10.3: Geologists share information by publishing, attending conferences, and even going on field trips, such as this trip to western Utah by the Utah Geological Association in 2009.

Science is also a social process. Scientists share their ideas with peers at conferences, seeking guidance and feedback. Research papers and data submitted for publication are rigorously reviewed by qualified peers, scientists who are experts in the same field. The scientific review process aims to weed out misinformation, invalid research results, and wild speculation. Thus, it is slow, cautious, and conservative. Scientists tend to wait until a hypothesis is supported by an overwhelming amount of evidence from many independent researchers before accepting it as a scientific theory [46].

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1.11: Understanding Science- The Scientific Method

The Scientific Method

Modern science is based on the scientific method, a procedure that follows these steps:

- Formulate a question or observe a problem
- Apply objective experimentation and observation
- Analyze collected data and Interpret results
- Devise an evidence-based theory
- Submit findings to peer review and/or publication

This has a long history in human thought but was first fully formed by Ibn al-Haytham over 1,000 years ago. At the forefront of the scientific method are conclusions based on objective evidence, not opinion or hearsay [4].

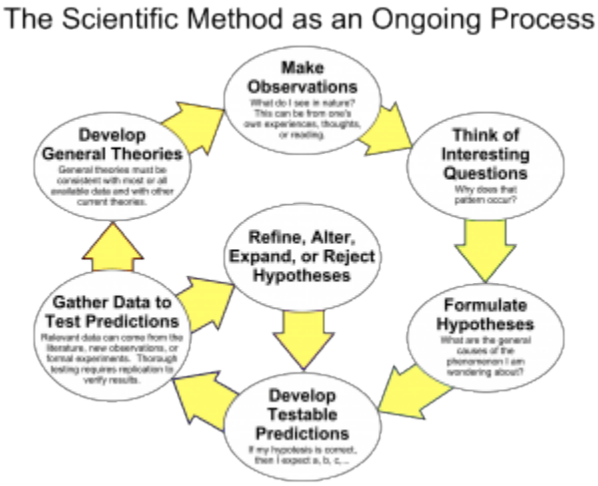


Figure 1.11.1: Diagram of the cyclical nature of the scientific method.

Step 1: Observation, Problem, or Research Question

The procedure begins with identifying a problem or research question, such as a geological phenomenon that is not well explained in the scientific community's collective knowledge. This step usually involves reviewing the scientific literature to understand previous studies that may be related to the question.

Step 2: Hypothesis

Once the problem or question is well defined, the scientist proposes a possible answer, a hypothesis, before conducting an experiment or fieldwork. This hypothesis must be specific, falsifiable, and should be based on other scientific work. Geologists often develop multiple working hypotheses because they usually cannot impose strict experimental controls or have limited opportunities to visit a field location [5; 6; 7].



Figure 1.11.2: A famous hypothesis: Leland Stanford wanted to know if a horse lifted all 4 legs off the ground during a gallop since the legs are too fast for the human eye to perceive it. These series of photographs by Eadweard Muybridge proved the horse, in fact, does have all four legs off the ground during the gallop.

Step 3: Experiment and Hypothesis Revision

The next step is developing an experiment that either supports or refutes the hypothesis. Many people mistakenly think experiments are only done in a lab; however, an experiment can consist of observing natural processes in the field. Regardless of what form an experiment takes, it always includes the systematic gathering of objective data. This data is interpreted to determine whether it contradicts or supports the hypothesis, which may be revised and tested again. When a hypothesis holds up under experimentation, it is ready to be shared with other experts in the field.



Figure 1.11.3: An experiment at the University of Queensland has been going since 1927. A petroleum product called pitch, which is highly viscous, drips out of a funnel about once per decade.

Step 4: Peer Review, Publication, and Publication

Scientists share the results of their research by publishing articles in scientific journals, such as *Science* and *Nature*. Reputable journals and publishing houses will not publish an experimental study until they have determined its methods are scientifically rigorous and the conclusions are supported by evidence. Before an article is published, it undergoes a rigorous peer review by scientific experts who scrutinize the methods, results, and discussion. Once an article is published, other scientists may attempt to replicate the results. This replication is necessary to confirm the reliability of the study's reported results. A hypothesis that seemed compelling in one study might be proven false in studies conducted by other scientists. New technology can be applied to published studies, which can aid in confirming or rejecting once-accepted ideas and/or hypotheses.

Step 5: Theory Development

In casual conversation, the word *theory* implies guesswork or speculation. In the language of science, an explanation or conclusion made in a *theory* carries much more weight because it is supported by experimental verification and widely accepted by the scientific community. After a hypothesis has been repeatedly tested for falsifiability through documented and independent studies, it eventually becomes accepted as a scientific theory.

While a hypothesis provides a tentative explanation *before* an experiment, a theory is the best explanation *after* being confirmed by multiple independent experiments. Confirmation of a theory may take years, or even longer. For example, the continental drift hypothesis first proposed by Alfred Wegener in 1912 was initially dismissed. After decades of additional evidence collection by other scientists using more advanced technology, Wegener's hypothesis was accepted and revised as the theory of plate tectonics.

The theory of evolution by natural selection is another example. Originating from the work of Charles Darwin in the mid-19th century, the theory of evolution has withstood generations of scientific testing for falsifiability. While it has been updated and revised to accommodate knowledge gained by using modern technologies, the theory of evolution continues to be supported by the latest evidence.



Figure 1.11.4: Wegener later in his life, ca. 1924-1930.

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1.12: Understanding Science- Outcome- Scientific Processes in Earth Science

Identify and use scientific processes and the scientific methods as used by geologists and with other related scientific disciplines

This section discusses the importance of the scientific process as it relates to geology and other scientific disciplines.

What You'll Learn to Do

- Order the steps of the scientific process.
- Form a hypothesis and use it to design a scientific experiment.

Learning Activities

The learning activities for this section include the following:

- Reading: The Nature of Science
- Self Check: Scientific Processes in Earth Science

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1.13: Understanding Science- Early Scientific Thought



Western scientific thought began in the ancient city of Athens, Greece [8]. Athens was governed as a democracy, which encouraged individuals to think independently, at a time when most civilizations were ruled by monarchies or military conquerors. Foremost among the early philosopher/scientists to use empirical thinking was Aristotle, born in 384 BCE. Empiricism emphasizes the value of evidence gained from experimentation and observation. Aristotle studied under Plato and tutored Alexander the Great. Alexander would later conquer the Persian Empire, and in the process spread Greek culture as far east as India.

Aristotle applied an empirical method of analysis called deductive reasoning, which applies known principles of thought to establish new ideas or predict new outcomes. Deductive reasoning starts with generalized principles and logically extends them to new ideas or specific conclusions. If the initial principle is valid, then it is highly likely the conclusion is also valid. An example of deductive reasoning is if A=B, and B=C, then A=C. Another example is if all birds have feathers, and a sparrow is a bird, then a sparrow must also have feathers. The problem with deductive reasoning is if the initial principle is flawed, the conclusion will inherit that flaw. Here is an example of a flawed initial principle leading to the wrong conclusion; if all animals that fly are birds, and bats also fly, then bats must also be birds.

This type of empirical thinking contrasts with inductive reasoning, which begins from new observations and attempts to discern underlying generalized principles. A conclusion made through inductive reasoning comes from analyzing measurable evidence, rather than making a logical connection. For example, to determine whether bats are birds a scientist might list various characteristics observed in birds–the presence of feathers, a toothless beak, hollow bones, lack of forelegs, and externally laid eggs. Next, the scientist would check whether bats share the same characteristics, and if they do not, draw the conclusion that bats are not birds.

Both types of reasoning are important in science because they emphasize the two most important aspects of science: observation and inference. Scientists test existing principles to see if they accurately infer or predict their observations. They also analyze new observations to determine if the inferred underlying principles still support them [9; 10].



Figure 1.13.1: drawing of Avicenna (Ibn Sina). He is among the first to link mountains to earthquakes and erosion.

Greek culture was spread by Alexander and then absorbed by the Romans, who help further extend Greek knowledge into Europe through their vast infrastructure of roads, bridges, and aqueducts [11]. After the fall of the Roman Empire in 476 CE, scientific progress in Europe stalled [8]. Scientific thinkers of medieval time had such high regard for Aristotle's wisdom and knowledge they faithfully followed his logical approach to understanding nature for centuries. By contrast, science in the Middle East flourished and grew between 800 and 1450 CE, along with culture and the arts.

Near the end of the medieval period, empirical experimentation became more common in Europe. During the Renaissance, which lasted from the 14th through 17th centuries, artistic and scientific thought experienced a great awakening [12; 13; 14]. European scholars began to criticize the traditional Aristotelian approach and by the end of the Renaissance period, empiricism was poised to become a key component of the scientific revolution that would arise in the 17th century [15].



Figure 1.13.2: Geocentric drawing by Bartolomeu Velho in 1568

An early example of how Renaissance scientists began to apply a modern empirical approach is their study of the solar system. In the second century, the Greek astronomer Claudius Ptolemy observed the Sun, Moon, and stars moving across the sky. Applying Aristotelian logic to his astronomical calculations, he deductively reasoned all celestial bodies orbited around the Earth, which was located at the center of the universe. Ptolemy was a highly regarded mathematician, and his mathematical calculations were widely accepted by the scientific community. The view of the cosmos with Earth at its center is called the geocentric model. This geocentric model persisted until the Renaissance period when some revolutionary thinkers challenged the centuries-old hypothesis.

By contrast, early Renaissance scholars such as astronomer Nicolaus Copernicus (1473-1543) proposed an alternative explanation for the perceived movement of the Sun, Moon, and stars. Sometime between 1507 and 1515, he provided credible mathematical

proof for a radically new model of the cosmos, one in which the Earth and other planets orbited around a centrally located Sun. After the invention of the telescope in 1608, scientists used their enhanced astronomical observations to support this heliocentric, Sun-centered, model [16; 17].



Figure 1.13.3: Copernicus' heliocentric model Galileo's first mention of moons of Jupiter.

Two scientists, Johannes Kepler and Galileo Galilei, are credited with jump-starting the scientific revolution [15]. They accomplished this by building on Copernicus' work and challenging long-established ideas about nature and science.

Johannes Kepler (1571-1630) was a German mathematician and astronomer who expanded on the heliocentric model—improving Copernicus' original calculations and describing planetary motion as elliptical paths. Galileo Galilei (1564 – 1642) was an Italian astronomer who used the newly developed telescope to observe the four largest moons of Jupiter [18]. This was the first piece of direct evidence to contradict the geocentric model since moons orbiting Jupiter could not also be orbiting Earth.

Galileo strongly supported the heliocentric model and attacked the geocentric model, arguing for a more scientific approach to determine the credibility of an idea [19]. Because of this, he found himself at odds with prevailing scientific views and the Catholic Church. In 1633 he was found guilty of heresy and placed under house arrest, where he would remain until his death in 1642 [18; 19].

Galileo is regarded as the first modern scientist because he conducted experiments that would prove or disprove falsifiable ideas and based his conclusions on mathematical analysis of quantifiable evidence—a radical departure from the deductive thinking of Greek philosophers such as Aristotle [15; 18]. His methods marked the beginning of a major shift in how scientists studied the natural world, with an increasing number of them relying on evidence and experimentation to form their hypotheses. It was during this revolutionary time that geologists such as James Hutton and Nicolas Steno also made great advances in their scientific fields of study [15].

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1.14: Understanding Science- Foundations of Earth Science

As part of the scientific revolution in Europe, modern earth science principles developed in the 17th and 18th centuries. One major contributor was Nicolaus Steno (1638-1686), a Danish priest who studied anatomy and earth science. Steno was the first to propose the Earth's surface could change over time. He suggested sedimentary rocks, such as sandstone and shale, originally formed in horizontal layers with the oldest on the bottom and progressively younger layers on top [20].



Figure 1.14.1: Illustration by Steno showing a comparison between fossil and modern shark teeth.

In the 18th century, Scottish naturalist James Hutton (1726–1797) studied rivers and coastlines and compared the sediments they left behind to exposed sedimentary rock strata. He hypothesized that ancient rocks must have been formed by processes like those producing the features in the oceans and streams. Hutton also proposed the Earth was much older than previously thought. In his book The Theory of Earth, he expressed this thought as "We find no vestige of a beginning, - no prospect of an end". Modern earth science processes operate slowly. Hutton realized if these processes formed rocks, then the Earth must be very old, possibly hundreds of millions of years old [21; 22].

Hutton's idea is called the principle of uniformitarianism and states that natural processes operate the same now as in the past, i.e. the laws of nature are uniform across space and time. Geologists and other earth scientists often state that "the present is the key to the past," meaning they can understand ancient rocks by studying modern processes. In light of his contributions to understanding the earth, James Hutton is often referred to as the founder of modern geology.

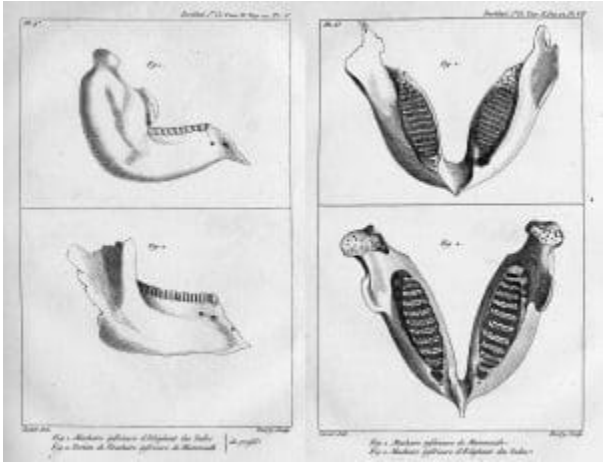


Figure 1.14.2: Cuvier's comparison of modern elephant and mammoth jawbones.

Prior to the acceptance of uniformitarianism, scientists such as German geologist Abraham Gottlob Werner (1750-1817) and French anatomist Georges Cuvier (1769-1832) thought rocks and landforms were formed by great catastrophic events. Cuvier championed this view, known as catastrophism, and stated, “The thread of operation is broken; nature has changed course, and none of the agents she employs today would have been sufficient to produce her former works.” He meant processes that operate today did not operate in the past [21; 23]. Known as the father of vertebrate paleontology, Cuvier made significant contributions to the study of ancient life and taught at Paris’s Museum of Natural History. Based on his study of large vertebrate fossils, he was the first to suggest species could go extinct. However, he thought new species were introduced by special creation after catastrophic floods [21; 24].

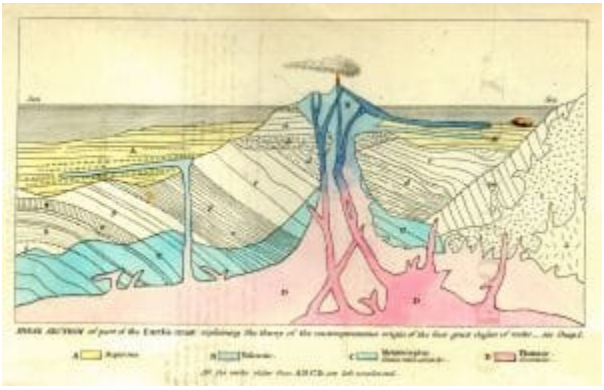


Figure 1.14.3: Inside cover of Lyell’s Elements of Geology

Hutton’s ideas about uniformitarianism and Earth’s age were not well received by the scientific community of his time. His ideas were falling into obscurity when Charles Lyell, a British lawyer and geologist (1797-1875), wrote the *Principles of Geology* in the early 1830s and later, *Elements of Geology* [21, 25]. Lyell’s books promoted Hutton’s principle of uniformitarianism, his studies of rocks and the processes that formed them, and the idea that Earth was possibly over 300 million years old. Lyell and his three-volume *Principles of Geology* had a lasting influence on the geologic community and public at large, who eventually accepted uniformitarianism and millionfold age for the Earth [21]. The principle of uniformitarianism became so widely accepted, that earth scientists regarded catastrophic change as heresy. This made it harder for ideas like the sudden demise of the dinosaurs by asteroid impact to gain traction.

A contemporary of Lyell, Charles Darwin (1809-1882) took *Principles of Geology* on his five-year trip on the HMS Beagle [27]. Darwin used uniformitarianism and deep geologic time to develop his initial ideas about evolution. Lyell was one of the first to publish a reference to Darwin’s idea of evolution [28].

The next big advancement, and perhaps the largest in the history of earth science, is the theory of plate tectonics and continental drift. Dogmatic acceptance of uniformitarianism inhibited the progress of this idea, mainly because of the permanency placed on the continents and their positions. Ironically, the slow and steady movement of plates would fit well into a uniformitarianism model. However, much time passed and a great deal of scientific resistance had to be overcome before the idea took hold. This happened for several reasons. Firstly, the movement was so slow it was overlooked. Secondly, the best evidence was hidden under the ocean. Finally, the accepted theories were anchored by a large amount of inertia. Instead of being bias-free, scientists resisted and ridiculed the emerging idea of plate tectonics. This example of dogmatic thinking is still to this day a tarnish on the earth science community.

Plate tectonics is most commonly attributed to Alfred Wegener, the first scientist to compile a large data set supporting the idea of continents shifting places over time. He was mostly ignored and ridiculed for his ideas, but later workers like Marie Tharp, Bruce Heezen, Harry Hess, Laurence Morley, Frederick Vine, Drummond Matthews, Kiyoo Wadati, Hugo Benioff, Robert Coats, and J. Tuzo Wilson benefited from advances in subsea technologies. They discovered, described, and analyzed new features like the mid-ocean ridge, alignment of earthquakes, and magnetic striping. Gradually these scientists introduced a paradigm shift that revolutionized earth science into the science we know today.

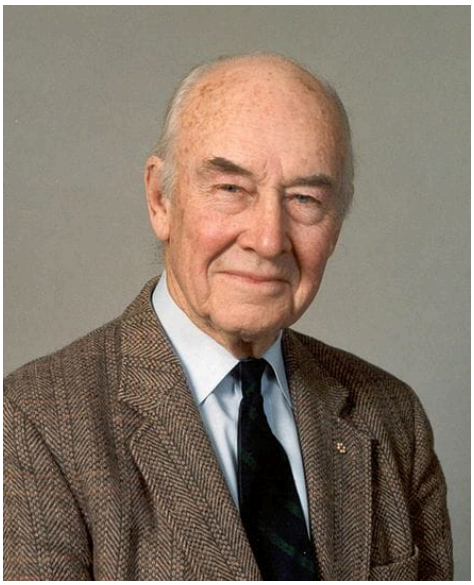


Figure 1.14.3: J. Tuzo Wilson

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1.15: Understanding Science- Denial and Evaluating Sources

Science Denial & Evaluating Sources

Introductory science courses usually deal with accepted scientific theory and do not include opposing ideas, even though these alternate ideas may be credible. This makes it easier for students to understand complex material. Advanced students will encounter more controversies as they continue to study their discipline. In addition, some concepts are presented in a simplified manner in an introductory course even though in reality the concepts are often much more complex than described. This section focuses on how to identify evidence-based information and differentiate it from pseudoscience.



Figure 1.15.1: Anti-evolution league at the infamous Tennessee v. Scopes trial.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Some groups of people argue that some established scientific theories are wrong, not based on their scientific merit but rather on the ideology of the group. This section focuses on how to identify evidence-based information and differentiate it from pseudoscience.

Science Denial and Critical Thought



Figure 1.15.2: 2017 March for Science in Salt Lake City. This and other similar marches were in response to funding cuts and anti-science rhetoric.

Science denial happens when people argue that established scientific theories are wrong, not based on scientific merit but rather on subjective ideology—such as for social, religious, political, or economic reasons. Organizations and people use science denial as a rhetorical argument against issues or ideas they oppose. Three examples of science denial versus science are:

1. Teaching evolution in public schools
2. Linking tobacco smoke to cancer
3. Linking human activity to climate change.

Among these, denial of climate change is strongly connected with earth science. A climate denier specifically denies or doubts the objective conclusions of the overwhelming consensus among scientists concerning human impacts on the climate (for example, "More than 99.9% of peer-reviewed scientific papers agree that climate change is mainly caused by humans, according to a recent survey of 88,125 climate-related studies." https://iopscience.iop.org/article/10.1088/1748-9326/ac2966).

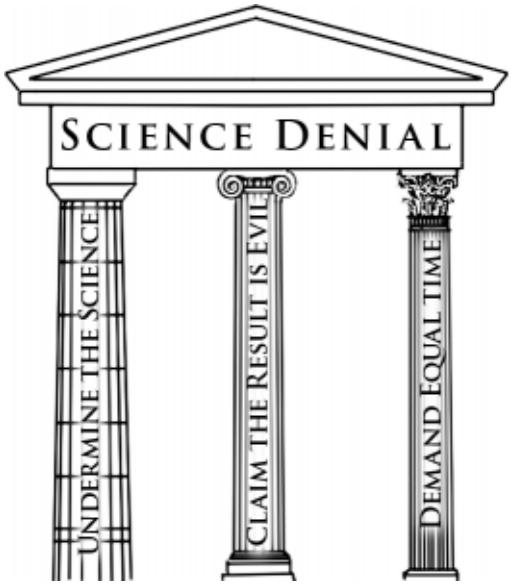


Figure 1.15.3: Three false rhetorical arguments of science denial (Source: National Center for Science Education)

Science denial generally uses three false arguments. The first argument tries to undermine the credibility of the scientific conclusion by claiming the research methods are flawed or the theory is not universally accepted—the science is unsettled. The notion that scientific ideas are not absolute creates doubt for non-scientists; however, a lack of universal truths should not be confused with scientific uncertainty. Because science is based on falsifiability, scientists avoid claiming universal truths and use language that conveys uncertainty. This allows scientific ideas to change and evolve as more evidence is uncovered.

The second argument claims the researchers are not objective and motivated by ideology or economic agenda. This is an *ad hominem* argument in which a person's character is attacked instead of the merit of their argument. They claim results have been manipulated so researchers can justify asking for more funding. They claim that because the researchers are funded by a federal grant, they are using their results to lobby for expanded government regulation.

The third argument is to demand a balanced view, equal time in media coverage and educational curricula, and to engender the false illusion of two equally valid arguments. Science deniers frequently demand equal coverage of their proposals, even though the scientific evidence supporting their ideology is sparse or lacking. For example, science deniers (e.g., Creationists) might demand religious explanations to be taught as an alternative to the well-established theory of evolution [39; 40]. Or that all possible causes of climate change be discussed as equally probable, regardless of the body of evidence. Conclusions derived using the scientific method should not be confused with those based on ideologies.

Furthermore, conclusions about nature derived from ideologies have no place in science research and education. For example, it would be inappropriate to teach the flat earth model in a modern earth science course because this idea has been disproved by the scientific method. Unfortunately, widespread scientific illiteracy allows the use of these arguments to suppress scientific knowledge and spread misinformation.

The progression of understanding based on evidence developed using the scientific method is the only way to change scientific conclusions. We wouldn't teach Flat Earth ideology along with plate tectonics because Flat Earthers do not support their conclusions with scientific evidence (e.g., as discovered via the scientific method). The fact that scientists avoid universal truths and change their ideas as more evidence is uncovered shouldn't be seen as meaning that the science is unsettled. Science progresses through effort and objectivity. Herbert Spencer, who coined the phrase "Survival of the fittest", eloquently expressed these ideas in the following quote.

"There is a principle which is a bar against all information, which is proof against all arguments, and which cannot fail to keep a man in everlasting ignorance—that principle is contempt prior to investigation."

— Attributed to Herbert Spencer

Because of widespread scientific illiteracy, arguments noting scientific conclusions may change over time are used by those who wish to suppress science and misinform the general public.

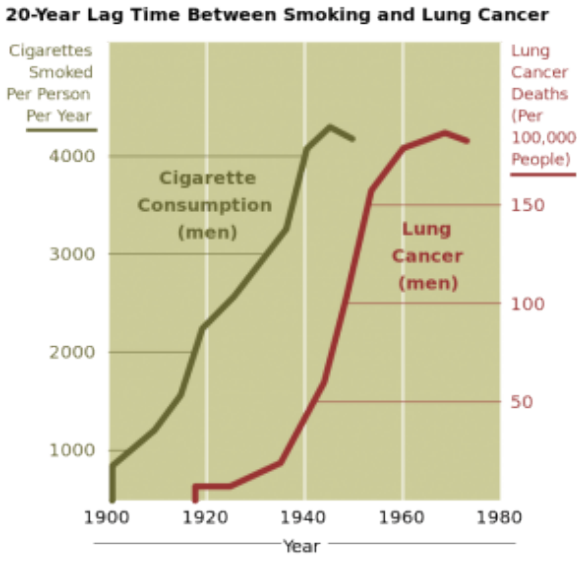


Figure 1.15.4: The lag time between cancer after smoking, plus the ethics of running human trials, delayed the government in taking action against tobacco.

In a classic case of science denial, beginning in the 1960s and for the next three decades, the tobacco industry scientists used rhetorical arguments to deny a connection between tobacco usage and cancer. Once it became clear scientific studies overwhelmingly found that using tobacco dramatically increased a person's likelihood of getting cancer, their next strategy was to create a sense of doubt about the science. The tobacco industry suggested the results were not yet fully understood and more study was needed. They used this doubt to lobby for delaying legislative action that would warn consumers of the potential

health hazards [39, 41]. This same tactic is currently being employed by those who deny the significance of human involvement in climate change.

Critical Thinking and Evaluating Sources of Information

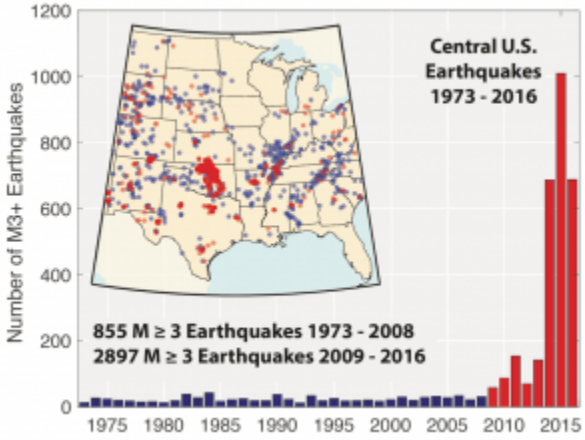


Figure 1.15.5: This graph shows the earthquake data. To call this data induced, due to fracking/drilling, would be an interpretation. Since the USGS (a reputable institution) has interpreted these earthquakes are caused by humans, it is a more reliable interpretation.

The progress and sustainability of society and our quality of life depend on public understanding and appreciation oof scientific reasoning and the scientific process. Carl Sagan, a renowned astronomer and planetary scientist who passed away nearly 3 decades ago, expressed his concerns about the decay of scientific reasoning in American society. In his words,

> "I have a foreboding of an America in my children's or grandchildren's time -- when the United States is a service and information economy; when nearly all the manufacturing industries have slipped away to other countries; when awesome technological powers are in the hands of a very few, and no one representing the public interest can even grasp the issues; when the people have lost the ability to set their own agendas or knowledgeably question those in authority; when, clutching our crystals and nervously consulting our horoscopes, our critical faculties in decline, unable to distinguish between what feels good and what's true, we slide, almost without noticing, back into superstition and darkness...The dumbing down of America is most evident in the slow decay of substantive content in the enormously influential media, the 30-second sound bites (now down to 10 seconds or less), lowest common denominator programming, credulous presentations on pseudoscience and superstition, but especially a kind of celebration of ignorance."

Similar concerns were recently expressed by Michael Mann, who is the Presidential Distinguished Professor and Director of the Penn Center for Science, Sustainability and the Media at the University of Pennsylvania. He noted that we are now living "at a time when social media has increasingly been weaponized by bad actors to promote conspiracy theories and lies, and to undermine faith in governmental and civic institutions, our traditional media, expert opinion and, yes, scientists-indeed, anyone, whose views or findings might prove inconvenient to their political, financial, or ideological agenda. That includes....climate scientists offering..informed advice when it comes to the greatest challenge and threat of all - the climate crisis."

In the age of the internet, information is plentiful. Earth scientists, or anyone exploring scientific inquiry must discern valid sources of information from pseudoscience and misinformation. This evaluation is critical in scientific research because scientific knowledge directs policy and progress [42]. Textbooks such as this one can aid this complex and crucial task. At its roots, quality information comes from the scientific method [43], beginning with the empirical thinking of Aristotle. The application of the scientific method helps produce unbiased results. A valid inference or interpretation is based on objective evidence or data. Credible data and inferences are clearly labeled, separated, and differentiated. Anyone looking over the data can understand how the author's conclusion was derived or come to an alternative conclusion. Scientific procedures are clearly defined so the investigation can be replicated to confirm the original results or expanded further to produce new results. These measures make a scientific inquiry valid and its use as a source reputable. Of course, substandard work occasionally slips through and retractions are published from time to time. An infamous article linking the MMR vaccine to autism appeared in the highly reputable journal *Lancet* in 1998. Journalists discovered the author had multiple conflicts of interest and fabricated data, and the article was retracted in 2010.



Figure 1.15.6: Logo for The Geological Society of America, one of the leading geoscience organizations. They also publish GSA Bulletin, a reputable geology journal.

When looking into any research, in addition to methodology, data, and results, the author(s) should be investigated [44]. An author's credibility is based on multiple factors, such as having a degree in a relevant topic or being funded from an unbiased source.

The same rigor should be applied to evaluating the publisher, ensuring the results reported come from an unbiased process [45]. The publisher should be easy to discover. Good publishers will show the latest papers in the journal and make their contact information and identification clear. Reputable journals show their peer-review style. Some journals are predatory, where they use unexplained and unnecessary fees to submit and access journals. Reputable journals have recognizable editorial boards. Often, a reliable journal will associate with a trade, association, or recognized open-source initiative.

One of the hallmarks of scientific research is peer review. Research should be transparent to peer review. This allows the scientific community to reproduce experimental results, correct and retract errors, and validate theories. This allows the reproduction of experimental results, corrections of error, and justification of the research to experts.

Citation is imperative to avoid plagiarism. It also allows readers to investigate an author's line of thought and conclusions. When reading scientific works, it is important to confirm the citations are from reputable scientific research. Most often, scientific citations are used to reference paraphrasing rather than quotes. The number of times a work is cited is said to measure the influence an investigation has within the scientific community, although this technique is inherently biased [46].

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2: THE GEOSPHERE

2.1: Introduction to Geosphere and Objectives

2.2: Minerals

2.3: Rocks

2.4: Layers of the Earth

2.5: Plate Tectonics- Continental Drift

2.6: Plate Tectonics- Convergent Boundaries

2.7: Plate Tectonics- Divergent Boundaries

2.8: Plate Tectonics- Transform Boundaries

2.9: Plate Tectonics- The Wilson Cycle

2.10: Plate Tectonics- Hotspots

2.11: Plate Tectonics- Continental Margins

2.12: Measuring Geological Time- The Geological Time Scale

2.13: Measuring Geological Time- Relative Dating Methods

2.14: Measuring Geological Time- Fossils and Evolution

2.15: Measuring Geological Time- Fossils and Evolution- Dating Rocks Using Fossils

2.16: Measuring Geological Time- Isotopic Dating Methods

2.17: Measuring Geological Time- Other Dating Methods

2.18: Measuring Geological Time- Understanding Geological Time

2.19: Measuring Geological Time- Summary

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2.1: Introduction to Geosphere and Objectives

Introduction to Geosphere

This chapter explores the geosphere, beginning with minerals, the building blocks of rocks, the rock cycle, and then plate tectonics, the grand unifying theory that explains the dynamic processes underlying volcanoes, earthquakes, mountain building, and the forces driving landscape uplift and transformation. The chapter will also cover energy and mineral resources and then uncover the vast timescales of geologic time. This foundation provides the key to understanding the physical structure of our planet and the forces that have shaped it over billions of years.

We'll first study rocks and minerals, examining how they form and transform through the rock cycle. Then we will examine the layers of the Earth and how plate tectonics drives the movements that create continents and oceans. As we investigate energy resources, we'll explore their origins and impacts on the planet. Finally, we'll navigate the immense timescales of geological time, learning to measure and interpret the Earth's ancient history. Get ready for an exciting journey into the depths of the geosphere, where every rock tells a story of Earth's dynamic past!

Learning Objectives

1. Describe the formation and classification of minerals and rocks, and explain their roles in the rock cycle.
2. Explain the principles of plate tectonics, including the processes and features associated with divergent, convergent, and transform boundaries, as well as the Wilson Cycle and hotspots.
3. Analyze the structure and composition of Earth's layers and the geodynamic processes that drive landscape uplift, mountain building, and geological transformations.
4. Evaluate the significance of energy and mineral resources, including their extraction, processing, and impact on ecosystems and human societies.
5. Interpret geological time scales and dating methods, including relative dating and the use of fossils to understand Earth's history and evolution.



Figure 2.1.1 "The big rock" by bluesbby is licensed under CC BY 2.0.



Figure 2.1.2 "Moon Over Earth (Archive: NASA, International Space Station, 10/12/09)" by NASA's Marshall Space Flight Center is licensed under CC BY-NC 2.0.

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2.2: Minerals

Electrons, Protons, Neutrons and Atoms

Minerals are made up of atoms, and all atoms are made up of three main sub-atomic particles known as protons, neutrons and electrons. As summarized in Table 2.1.1, protons are positively charged, neutrons are uncharged and electrons are negatively charged. The negative charge of one electron balances the positive charge of one proton. Both protons and neutrons have a mass of 1, while electrons have almost no mass (a proton has a mass that is 2000 times greater than that an electron).

Table 2.1.1 Charges and Masses of the Particles within Atoms

Elementary particle	Charge	Mass
Electron	-1	~0
Proton	1	1
Neutron	0	1

The simplest atom is that of hydrogen (atomic number 1) which has one proton and one electron. The proton forms the nucleus, while the electron spins around it. The nucleus of all other elements consists of both neutrons and protons, such as helium (atomic number 2). The positively-charged protons tend to repel each other, and the neutrons help to hold the nucleus together. The atomic number is the number of protons and the atomic mass is the number of protons plus neutrons. For hydrogen both the atomic number and mass are 1 because there is one proton and no neutrons. For helium the atomic number is 2 and the atomic mass is 4 because there are 2 protons and 2 neutrons. Figure 2.1.1 provides a simplified view of the elements up to number 36.

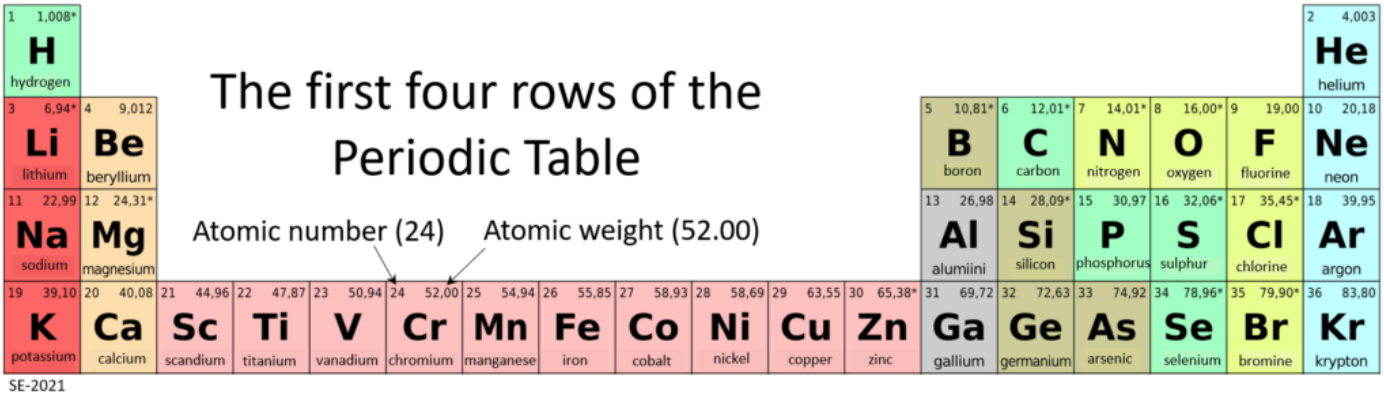


Figure 2.1.1 A Part of the Periodic Table Showing Element Symbols (e.g., Cr), Names (e.g., chromium), Atomic Numbers and Atomic Weights

Electron orbits around the nucleus of an atom are arranged in what we call shells—also known as energy levels. The first shell can hold only two electrons, while the next shell will hold up to eight electrons. Subsequent shells can hold more electrons, but the outermost shell of any atom will hold no more than eight electrons. These outermost shells are important in bonding between atoms, and bonding takes place between atoms that do not have the full complement of eight electrons in their outer shells (or two in the first shell for the very light elements).

Bonding and Lattices

An atom seeks to have a full outer shell (i.e., 8 electrons for most elements, or 2 electrons for hydrogen, helium, lithium and beryllium)[1] to be atomically stable. This is accomplished by lending, borrowing, or sharing electrons with other atoms. The noble gases, such as helium, neon, argon etc., already have their outer orbits filled so they don't need to lose or gain electrons.

Sodium has 11 electrons, 2 in the first shell, 8 in the second, and 1 in the third (Figure 2.1.2). Sodium readily gives up this third shell electron, and when it does it loses one negative charge and becomes positively charged. Chlorine, on the other hand, has 17 electrons, 2 in the first shell, 8 in the second, and 7 in the third. Chlorine readily accepts an eighth electron for its third shell, and

therefore becomes negatively charged. In changing their number of electrons these atoms become ions—the sodium a positive ion or cation, the chlorine a negative ion or anion. The resulting electronic attraction between these ions is known as an ionic bond. Electrons can be thought of as being transferred from one atom to another in an ionic bond.

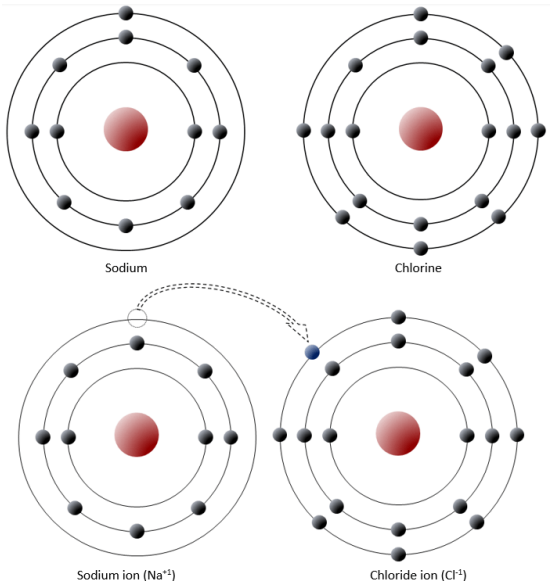


Figure 2.1.2 The Electron Configuration of Sodium and Chlorine Atoms (top). Sodium gives up an electron to become a cation (bottom left) and chlorine accepts an electron to become an anion (bottom right).

Common table salt (NaCl) is a mineral composed of chlorine and sodium linked together with ionic bonds (Figure 2.1.3). The mineral name for NaCl is halite and its structure is cubic, meaning that all of the bonds are at right angles to each other. This why halite grows as cubic crystals (Figure 2.1.3, right), and it's also why it breaks along three planes at right angles to each other (cleavage).

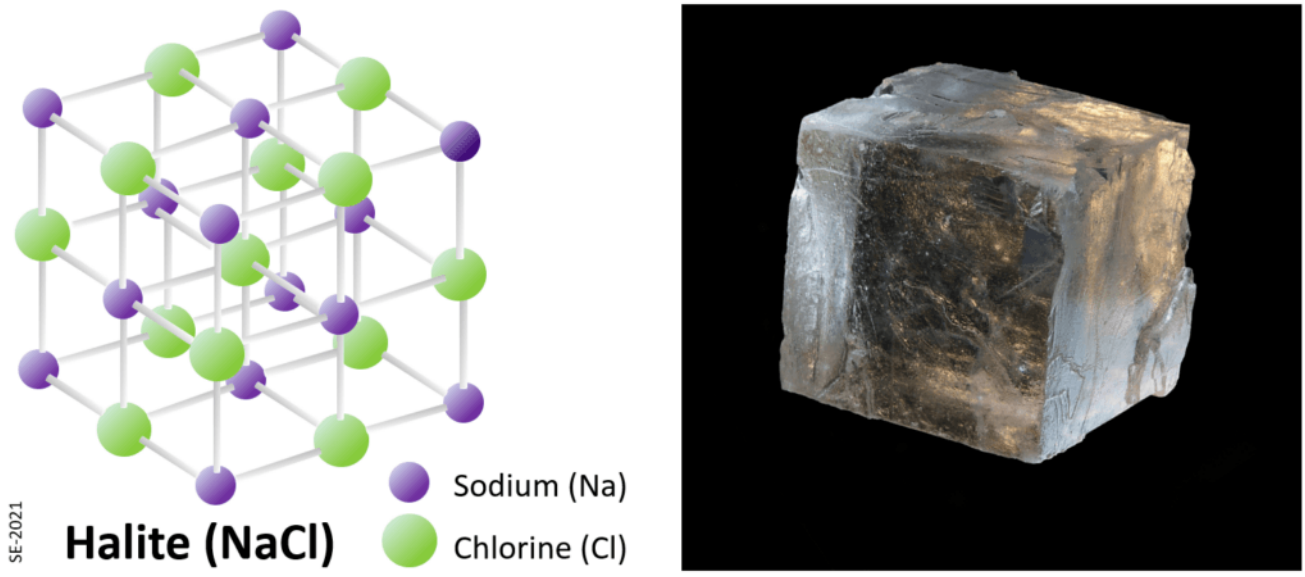


Figure 2.1.3 The Alternating Arrangement of Sodium and Chlorine Atoms in the Mineral Halite (left); and An Example of a Cubic Crystal of Halite (right).

Exercise 2.1 Cations, Anions and Ionic Bonding

Several elements are listed below along with their atomic numbers. Assuming that the first electron shell can hold 2 electrons, and that subsequent electron shells can hold 8 electrons, sketch in the electron configurations for these elements. Predict whether the element is likely to form a cation (+) or an anion (-), and what valency it would have (e.g., +1, +2, -1 etc.) The first one is done

for you.

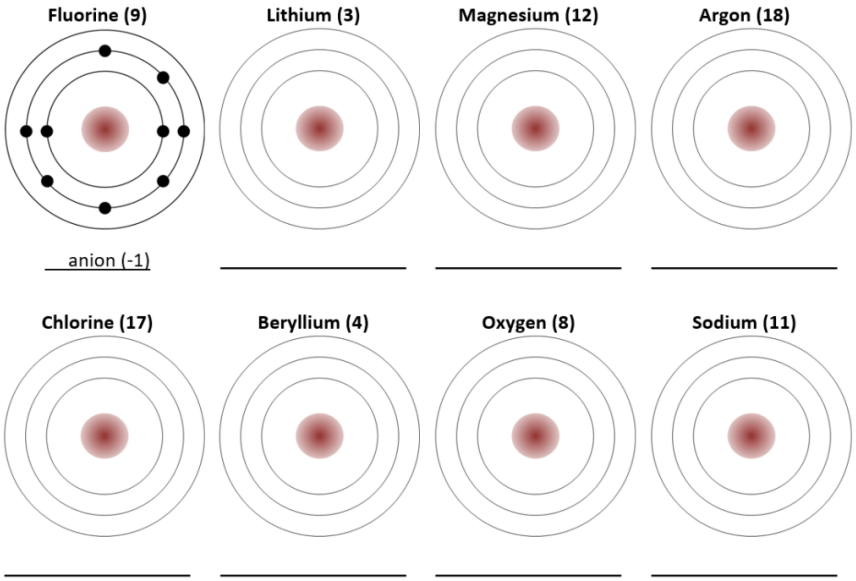


Figure 2.1.4 Predicting Cations, Anions and Ionic Bonding

Exercise answers are provided Appendix 2.

Element number 6 (carbon) has a 6 protons and 6 neutrons in its nucleus, and it also has 6 electrons—two in the first shell and 4 in the second. Carbon atoms would like to have either no electrons in the second shell, or 8, but both of those options are unlikely, so instead of losing or gaining electrons carbon atoms share electrons with other atoms, in many cases with other carbon atoms. This arrangement is depicted as a 2-dimensional structure on Figure 2.1.4, and the bonds between the inner carbon atom is known as a covalent bond. As this arrangement is extended out for millions of atoms (in either two or three dimensions) every carbon atom will be surrounded by 4 others, and each (except the very outermost ones) will have its need for 8 outer electrons fulfilled through sharing.

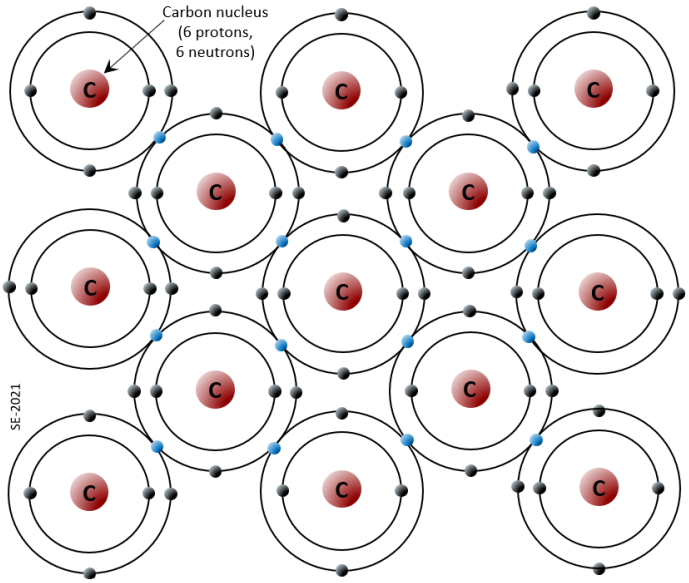


Figure 2.1.5 Electron Sharing in Carbon-Carbon Co-valent Bonds. The light blue circles represent shared electrons.

Covalent bonds are generally stronger than ionic bonds and carbon-carbon covalent bonds are the strongest of all, which is why diamond (which has nothing but covalent C-C bonds) is the hardest mineral and also why some man-made carbon compounds are extremely strong.

The elements silicon and oxygen are both abundant in the Earth's crust and mantle and are present in the minerals that make up

most rocks. Silicon and oxygen bond together to create a four-sided pyramid shape with an oxygen at each corner and a silicon in the middle, known as a silica tetrahedron (Figure 2.1.5). This is the building block of the many important silicate minerals. The bonds in a silica tetrahedron have some of the properties of covalent bonds and some of the properties of ionic bonds. As a result of the ionic character, silicon becomes a cation (with a charge of +4) and oxygen becomes an anion (with a charge of -2). The net charge of a silica tetrahedron (SiO_4) is -4. As we will see later, silica tetrahedra are linked together in a variety of ways to form most of the common minerals of the crust.

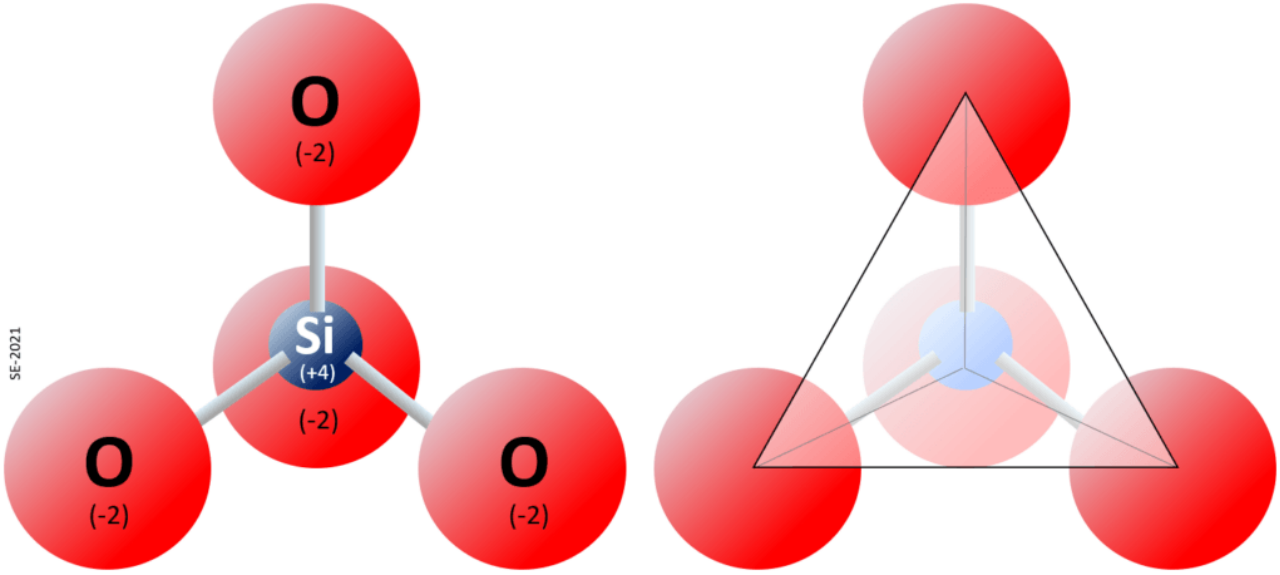


Figure 2.1.6 The Silica Tetrahedron – Building Block of All Silicate Minerals. Because the silicon has a charge of +4 and the four oxygens each have a charge of -2, the silica tetrahedron has a net charge of -4.

Box 2.1 What's With All of These "Sili" Names?

The element silicon is one of the most important geological elements and is the second-most abundant element in the Earth's crust (after oxygen). Silicon bonds readily with oxygen to form a silica tetrahedron (Figure 2.5). Pure silicon crystals are used to make semi-conductive media in electronic devices. A silicate mineral is one in which silicon and oxygen are present as silica tetrahedra (plural of tetrahedron). Silica also refers to a chemical component of a rock, and is expressed as % SiO_2. The mineral quartz is made up entirely of silica tetrahedra, and some forms of quartz are known as silica. Silicone is a synthetic product (e.g., silicone rubber, resin or caulking) made from silicon-oxygen chains and various organic molecules. To help you keep the "sili" names straight, here is a summary table:

Table 2.1.2 "Sili" Names

Sili- Name	**Details**
Silicon	The 14th element
Silicon wafer	A crystal of pure silicon sliced very thinly and used for electronics
Silica tetrahedron	A combination of 1 silicon atom and 4 oxygen atoms that form a tetrahedron
% silica	The proportion of a rock that is comprised of the components Si and O_2
Silica	A form of the mineral quartz (SiO_2)
Silicate mineral	A mineral that has silica tetrahedra in it (e.g., quartz, feldspar, mica, olivine, clay minerals, etc.)
Silicone	A flexible material (but not a mineral) made up of Si-O chains with attached organic molecules

Non-Silicate Minerals and Mineral Groups

Elements bonded together in various configurations form minerals. A mineral is a naturally occurring, solid compound with a specific composition and a regular repeating lattice structure (like the halite in Figure 2.1.3). Most minerals are made up of a

cation (a positively charged ion) or several cations, and an anion (a negatively charged ion) or an anion group. For example, in the mineral hematite (Fe_2O_3) the cation is Fe (iron – Fe^{3+}) and the anion is O (oxygen O^{-2}). (The two +3 iron ions contribute 6 positive charges and the three -2 oxygen ions contribute 6 negative charges, so the charge is balanced, which is a requirement of all minerals.) We group minerals into classes on the basis of their predominant anion or anion group. These include oxides, sulphides, carbonates and silicates, and others. Silicates are by far the predominant group in terms of their abundance within the crust and mantle, and they will be discussed later. Some examples of minerals from the different mineral groups are given in Table 2.1.2.

Table 2.1.3 The Main Mineral Groups and Some Examples of Minerals in Each Group

Group	Examples
Oxides	hematite (iron-oxide – Fe_2O_3), corundum (aluminum-oxide Al_2O_3), water-ice (H_2O)
Sulphides	galena (lead-sulphide – PbS), pyrite (iron-sulphide – FeS_2), chalcopyrite (copper-iron-sulphide – $CuFeS_2$)
Carbonates	calcite (calcium-carbonate – $CaCO_3$), dolomite (calcium-magnesium-carbonate – $(Ca,Mg)CO_3$
Silicates	quartz (SiO_2), feldspar (sodium-aluminum-silicate – $NaAlSi_3O_8$), olivine (iron or magnesium-silicate – $(Mg,Fe)SiO_4$) (Note that in in quartz the anion is oxygen, and while it could be argued, therefore, that quartz is an oxide, it is always classed with the silicates.)
Halides	fluorite (calcium-flouride – CaF_2), halite (sodium-chloride – NaCl) (Halide minerals have halogen elements as their anion – the minerals in the second last column on the right side of the Periodic Table, such as F, Cl, Br etc. (see Figure 2.1.1))
Sulphates	gypsum (calcium-sulphate – $CaSO_4{\cdot}H_2O$), barite (barium-sulphate – $BaSO_4$) (Note that sulphates are different from sulphides. Sulphates have the SO_4^{-2} ion while sulphides have the S^{-2} ion)
Native elements	gold (Au), diamond (C), graphite (C), sulphur (S) (see Figure 2.0.1), copper (Cu)

Oxide minerals have oxygen as their anion, but they exclude those with oxygen complexes such as carbonate (CO_3), sulphate (SO_4), or silicate (SiO_2). If the oxygen is also combined with hydrogen to form the hydroxyl anion (OH^-) the minerals is known as a hydroxide. Some important hydroxides are limonite (FeO(OH)) and gibbsite ($Al(OH)_3$), which are common within ores of iron and aluminum.

Sulphides are minerals with the S^{-2} anion, and they include galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$) and molybdenite (MoS_2), which are the most important ores of lead, zinc, copper and molybdenum respectively. Another important sulphide minerals is pyrite (FeS_2).

Sulphates are minerals with the SO_4^{-2} anion, and these include anhydrite ($CaSO_4$ and its cousin gypsum $CaSO_4.2H_2O$) and the sulphates of barium and strontium: barite ($BaSO_4$) and celestite ($SrSO_4$). In all of these cases the cation has a +2 charge which balances the -2 charge on the sulphate ion.

The halides are so named because the anions include the halogen elements chlorine, fluorine, bromine etc. Examples are halite (NaCl) and fluorite (CaF_2).

The carbonates include minerals in which the anion is the CO_3^{-2} complex. The carbonate combines with +2 cations to form minerals such as calcite ($CaCO_3$), magnesite ($MgCO_3$), dolomite ($(Ca,Mg)CO_3$) and siderite ($FeCO_3$). The copper minerals malachite and azurite are also carbonates.

In phosphate minerals the anion is PO_4^{-4}. An important phosphate mineral is apatite ($Ca_5(PO_4)_3(OH)$), which is what your teeth are made of.

Native minerals include only one element (bonded to itself), such as gold, copper, sulphur or carbon (which could be graphite or diamond).

The silicate minerals include the elements silicon and oxygen in varying proportions ranging from SiO_2 to SiO_4. These are discussed at length below.

> Exercise 2.2 Mineral Groups

We classify minerals according to the anion part of the mineral formula, and mineral formulas are always written with the anion part on the right. For example, for pyrite (FeS_2) Fe^{2+} is the cation and S^- is the anion. This helps us to know that it's a sulphide, but it is not always that obvious. Hematite (Fe_2O_3) is an oxide, that's easy, but anhydrite ($CaSO_4$) is a sulphate because SO_4^{2-} is the anion, not O. Along the same lines, calcite ($CaCO_3$) is a carbonate, and olivine (Mg_2SiO_4) is a silicate. Minerals with only one element (such as S) are called native minerals, while those with an anion from the halogen column of the periodic table (Cl, F, Br, etc.) are halides. Provide group names for the following minerals:

Table 2.1.4 Mineral Groups According to Anion

Name	Formula	Group	Name	Formula	Group
Sphalerite	ZnS		Sylvite	KCl	
Magnetite	Fe_3O_4		Silver	Ag	
Pyroxene	$MgSiO_3$		Fluorite	CaF_2	
Siderite	$FeCO_3$		Feldspar	$KAlSi_3O_8$	

Exercise answers are provided Appendix 2.

Silicate Minerals

The vast majority of the minerals that make up the rocks of the earth's crust are silicate minerals. These include minerals such as quartz, feldspar, mica, amphibole, pyroxene, olivine, and a great variety of clay minerals. The building block of all of these minerals is the silica tetrahedron, a combination of four oxygen atoms and one silicon atom. In silicate minerals these tetrahedra are arranged and linked together in a variety of ways, from single units to complex frameworks (Figure 2.8). The simplest silicate structure, that of the mineral olivine, is composed of isolated tetrahedra bonded to iron and/or magnesium ions. In olivine the -4 charge of each silica tetrahedron is balanced by the addition of two divalent (i.e., +2) iron or magnesium cations. Olivine can be either Mg_2SiO_4 or Fe_2SiO_4, or some combination of the two, which is written like this: $(Mg,Fe)_2SiO_4$, meaning that any proportions of Mg and Fe are possible.

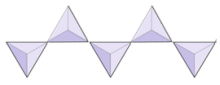
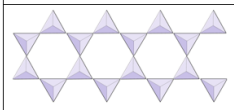
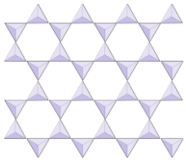
Tetrahedron configuration		Example minerals
	Isolated (nesosilicates)	Olivine, garnet, zircon, kyanite
	Single chains (inosilicates)	Pyroxenes, wollastonite
	Double chains (inosilicates)	Amphiboles
	Sheets (phyllosilicates)	Micas, clay minerals, serpentine, chlorite
3-dimensional structure	Framework (tectosilicates)	Feldspars, quartz

Figure 2.1.7 Silicate Mineral Configurations. The triangles represent silica tetrahedra.

In pyroxene silica tetrahedra are linked together in a single chain, where one oxygen ion from each tetrahedron is shared with the adjacent tetrahedron, and hence there are fewer oxygens in the structure. The result is that the oxygen to silicon ratio is lower than in olivine (3:1 instead of 4:1), the net charge per silicon atom is atom is less (-2 instead of -4), and fewer cations are necessary to balance that charge. Pyroxene compositions are of the type $MgSiO_3$, $FeSiO_3$ and $CaSiO_3$, or some combination of these. In other words, pyroxene has one cation for each silica tetrahedron (e.g., $MgSiO_3$) while olivine has two (e.g., Mg_2SiO_4).

In amphibole structures the silica tetrahedra are linked in a double chain that has an oxygen to silicon ratio lower than that of pyroxene, and hence still fewer cations are necessary to balance the charge. Amphibole is even more permissive than pyroxene and its compositions can be very complex. Hornblende, for example, can include sodium, potassium, calcium, magnesium, iron, aluminum, silicon, oxygen, fluorine and the hydroxyl ion (OH^{-1}).

In mica structures the silica tetrahedra are arranged in continuous sheets. There is even more sharing of oxygens between adjacent tetrahedra and hence fewer charge-balancing cations are needed. Bonding between sheets is relatively weak, and this accounts for the well-developed one-directional cleavage (Figure 2.1.7). Biotite mica can have iron and/or magnesium in it and that makes it a ferromagnesian silicate mineral (like olivine, pyroxene and amphibole). Chlorite is another similar mineral which commonly includes magnesium. In muscovite mica the only cations present are aluminum and potassium, and hence it is not a ferromagnesian silicate mineral.

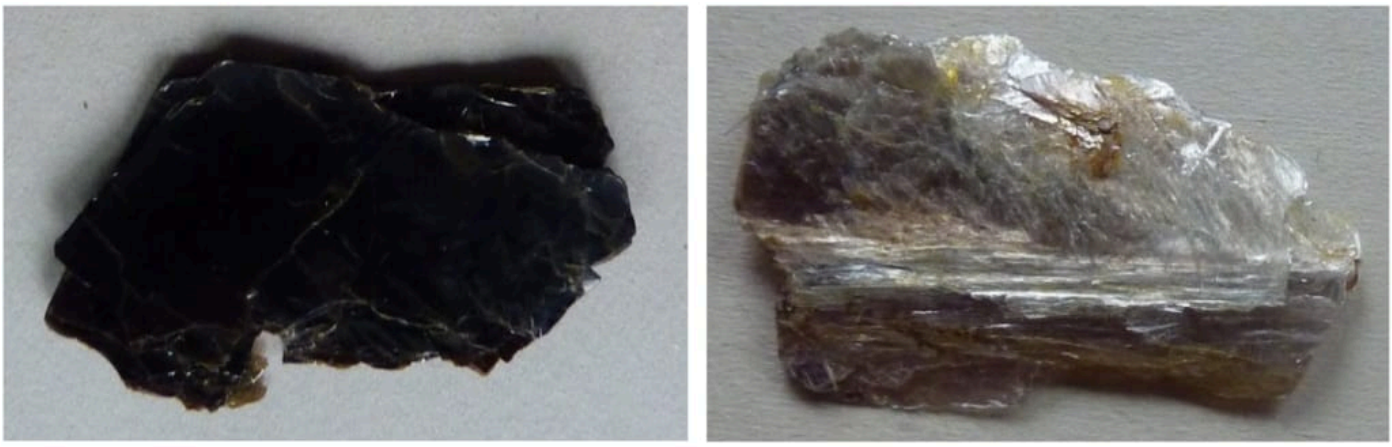


Figure 2.1.8 Biotite Mica (left) and Muscovite Mica (right). Both are sheet silicates and split easily into thin layers along planes parallel to the sheets. Biotite is dark like the other iron- and/or magnesium-bearing silicates (e.g., olivine, pyroxene and amphibole), while muscovite is light coloured. Each sample is about 3 cm across.

Apart from muscovite, biotite and chlorite, there are many other sheet silicates (or phyllosilicates) which usually exist as clay-sized fragments (i.e., less than 0.004 mm). These include the clay minerals kaolinite, illite and smectite, and we will be looking at them more closely in Chapter 10.

Silica tetrahedra are bonded in three-dimensional frameworks in both the feldspars and in quartz. These minerals are non-ferromagnesian—they don't contain any iron or magnesium. In addition to silica tetrahedra, the feldspars include aluminum, potassium, sodium and calcium in various combinations. The three main feldspar minerals are orthoclase (a.k.a., potassium feldspar), and two types of plagioclase: albite (sodium only) and anorthite (calcium only). Quartz contains only silica tetrahedra, so only has silicon and oxygen.

In quartz the silica tetrahedra are bonded in a "perfect" three-dimensional framework. Each tetrahedron is bonded to four other tetrahedra (with oxygen shared at each corner of each tetrahedron), and as a result, the ratio of silicon to oxygen is 1:2 (quartz is SiO_2). Since the one silicon cation has a +4 charge and the two oxygen anions each have a -2 charge, the charge is balanced. There is no need for aluminum or any of the other cations such as sodium or potassium. The hardness, and lack of cleavage in quartz, are related to the fact that all of the bonds are the strong covalent/ionic bonds characteristic of the silica tetrahedron.

Box 2.2 Important Minerals

Before we move on to talk about rocks it may be useful to review some of the important things about minerals. First—and I cannot emphasize this enough—minerals and rocks are not the same. A mineral has a specific chemical composition and structure. Rocks are made up of minerals, just like words are made up of letters. You might be asked on a test to name a specific mineral or rock and it isn't going to make anyone happy if you answer with a rock name for the mineral, or a mineral name for the rock. For

most aspects of Environmental Geology you can get by if you are familiar with a relatively short list of minerals, as follows:

Table 2.1.5 Important Minerals

Types of Minerals	Examples
Silicate minerals of common rocks	plagioclase feldspar, potassium feldspar, quartz, mica, amphibole, pyroxene and olivine
Clay minerals	kaolinite, illite, smectite, and serpentine (all are also silicates and are described in Chapter 10)
Others	hematite, magnetite (oxides), calcite and dolomite (carbonates), gypsum (sulphate), pyrite (sulphide) (plus a few other sulphide minerals that are discussed in Chapter 8)

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1. In fact, for beryllium losing one electron means losing its entire outer shell. ↩

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2.3: Rocks

Just as words are made by combining letters of the alphabet, rocks are generally composed of different combinations of the crystals of one or more minerals, with several notable exceptions. Exceptions include rocks that are aggregates of mineraloids (obsidian) or organic materials (e.g., anthracite coal). There are three main types of rocks: igneous, sedimentary and metamorphic. They form in different ways and have specific properties that help us to distinguish them. The rocks on Earth can be transformed from one type to another through geologic processes, and this concept is illustrated using the rock cycle (Figure 2.2.1). The three types of rock are depicted within rectangles, some of the intermediate forms of rocky materials (magma, outcrop, and loose sediments) are shown as ellipses, and the processes that are important in the transformations are shown as arrows. Those processes (solid black arrows) include:

- Uplift (such as mountain formation) that results in rock that was present at depth in the crust being brought to surface and exposed to weathering,
- Erosion and transportation of weathered products (e.g., sand, clay, and ions in solution) and then deposition as sediments (e.g., within rivers or the ocean),
- Burial of those sediments beneath other sediments, followed by compaction (squeezing) and cementation to make sedimentary rock,
- Further burial which results in heating and more squeezing and then mineral transformations to form metamorphic rock,
- Further heating or other changes in conditions that result in melting to form magma, and
- Movement of magma towards the surface where it can cool slowly to make intrusive igneous rock, or to the surface where it can cool quickly to make extrusive igneous (volcanic) rock.

The rock cycle can be disrupted at any point by a change in conditions brought about by uplift, burial (dashed blue and red arrows), or in rare cases by the nearby presence of magma.

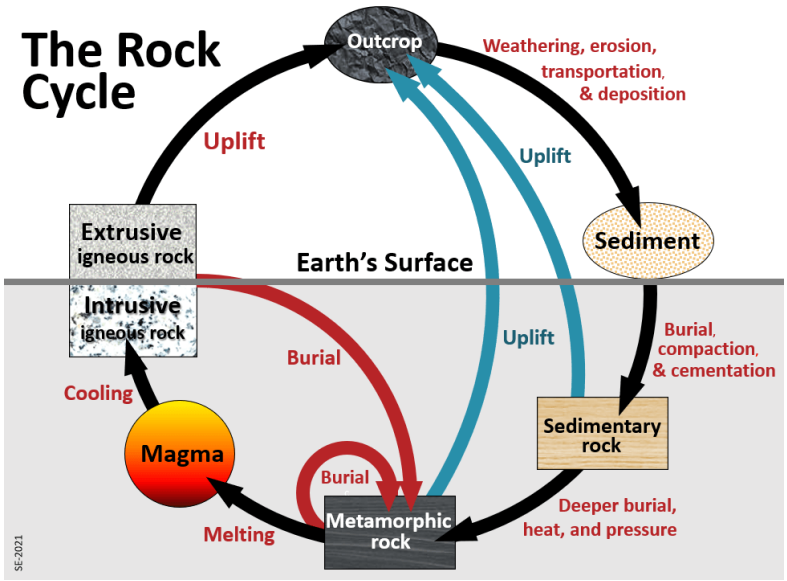


Figure 2.3.1 The Rock Cycle

Igneous Rocks

Igneous rocks form from the cooling of magma (molten rock), either slowly at depth in the crust, or quickly at the surface. In general, the slower the cooling process (up to millions of years), the larger the crystals will be. Volcanic rocks typically have mineral crystals that are less than 0.1 mm across (because they can cool in seconds or minutes), while intrusive igneous rocks have crystals that are typically larger than 1 mm across. Igneous rocks are mainly classified according to rock composition and

rock texture. This is illustrated in Figure 2.2.2.

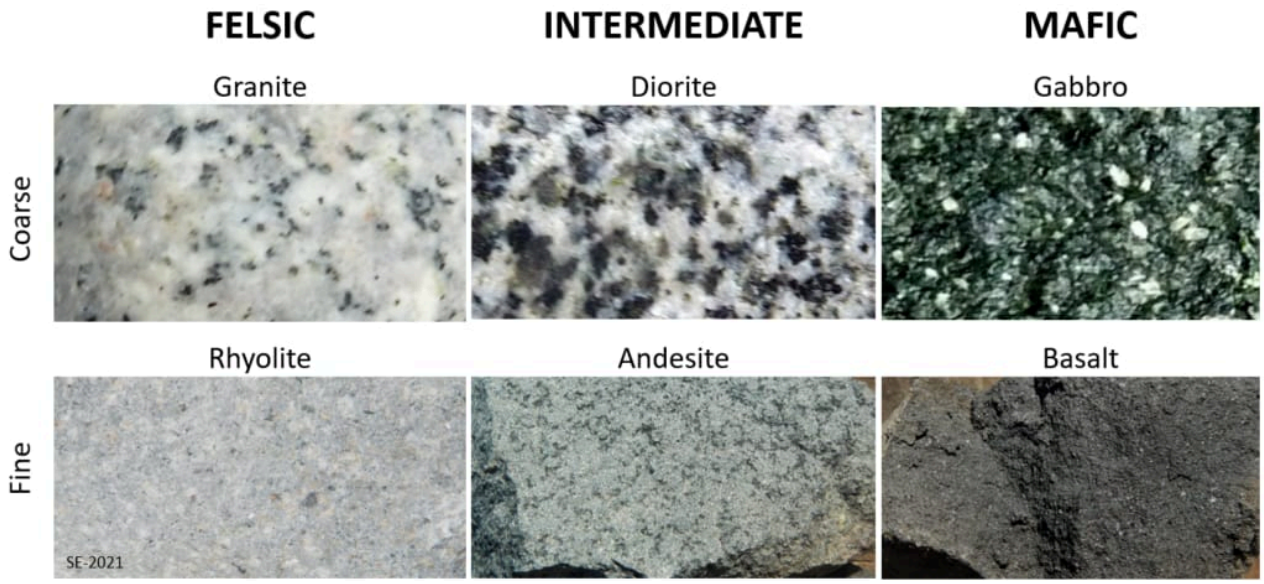


Figure 2.3.2 General Classification of Igneous Rocks

Three broad compositional classes of igneous rocks are shown, namely felsic, intermediate, and mafic, and these are determined by the proportions of the dark silicate minerals (biotite, amphibole, pyroxene and olivine). Felsic rocks are light-coloured, often close to white, with less than 20% dark minerals. Intermediate rocks are medium-dark (typically grey) with 20 to 50% dark minerals, and mafic rocks are close to black (with more than 50% dark minerals). The three main types of intrusive igneous rocks are granite, diorite and gabbro. The equivalent volcanic rocks—which are fine-grained—are rhyolite, andesite and basalt. Igneous rocks with close to 100% dark minerals (not shown on Figure 2.2.2) are known as ultramafic; these are rare on the Earth's surface, but common in the mantle.

Mafic igneous rocks (e.g., basalt or gabbro) are denser than felsic igneous rocks. Basalt has a specific gravity of about 3 g/cm^3, while for granite the value is about 2.6 g/cm^3. This small difference becomes very important in the context of plate tectonics. In comparison, the ultramafic rock of the mantle has a density of about 3.3 g/cm^3.

Sedimentary Rocks

Sedimentary rocks form near to the Earth's surface following the accumulation of fragments of rocks and minerals that have been weathered and eroded from outcrops, transported by gravity, rivers, waves, wind, or glacial ice, and then deposited as sediments (Figure 2.2.3). It is believed that approximatel 75% of all exposed rocks at the Earth's surface are sedimentary rocks. However, they comprise only approximately 5% by volume of all of the rocks in Earth's crust. The sedimentary grains (e.g., grains of sand) are known as clasts, and the resulting sedimentary rocks are called clastic if they are composed mostly of such grains.



Figure 2.3.3 Cross-Bedded River-Deposited Sand on Vancouver Island. This is not sandstone because the deposit is soft and loose, and can be scraped away with fingers.

Clasts can range in size from tiny (invisible) clay fragments to boulders the size of buildings and we classify clastic sedimentary rocks on the basis of the clast sizes. The key piece of information to remember is that a grain of sand ranges in size from 1/16th mm to 2 mm, and that means from about 1/4 the size of the period at the end of this sentence, to about the size of this capital O. (That depends, of course, on the type of device that you are reading this on.) Very fine sand will feel gritty (not slippery) between your fingertips. Clasts smaller than 1/16th mm are classed as silt and clay, and those larger than 2 mm are granules, pebbles, cobbles and boulders (in order of increasing size). Sand grains can be transported by rivers with medium flow, by strong winds, and by waves, and so sand deposits tend to accumulate in rivers and deserts and on beaches. Silt and clay can be transported in similar environments, but they tend not to be deposited unless the medium slows, so they will be deposited in lakes, and the ocean. Granules and larger fragments can typically only be transported and deposited by fast-flowing water, and so they are commonly deposited in high-energy parts of streams. These sediments must then become buried beneath other layers of sediments and compressed and cemented before they can become sedimentary, as illustrated on Figure 2.2.1

The three main types of clastic sedimentary rocks are illustrated on Figure 2.2.4



Figure 2.3.4 Examples of the Elastic Sedimentary Rocks Conglomerate, Sandstone and Mudstone. The pen is 15 cm long, and the coin in the mudstone photo is 2 cm across.

Sedimentary rocks can also form from the crystallization of ions that were transported in water as dissolved ions. These are known as chemical sedimentary rocks. For example, marine organisms extract bicarbonate and calcium ions (HCO_3^- and Ca^{2+}) from ocean-water to make calcite shells ($CaCO_3$) which then accumulate on the sea floor (typically in tropical areas around reefs) to form calcite mud and sand that later gets buried and becomes limestone. Some organisms make their shells out of silica, and those can accumulate on the sea floor to make the rock chert. In some cases, minerals form from the evaporation of water in an inland sea or lake. Examples are rock salt (halite) and gypsum (which is used to make plaster board).

Metamorphic Rocks

Metamorphic rocks form when pre-existing sedimentary or igneous rocks are heated and squeezed in such a way that one or more of the minerals present becomes unstable. The result might be that crystals of those minerals are converted into different minerals or into larger crystals of the same type.
One way to understand this process is to consider the sedimentary rock mudstone, which is mostly made up to clay minerals. Clays are low-temperature minerals; they are not stable at temperatures higher than about 150^0 C. As a clay-rich rock is heated the clay minerals tend to break down and are converted into micas. At even higher temperatures those might be converted to minerals such as quartz, feldspar and amphibole.

Most metamorphism takes place at depth in the crust in areas that have experienced mountain-building (and so crustal thickening) and where there is compression due to plate convergence. That means that the rocks get heated (because of burial) and squeezed (because of the converging plates) at the same time. New minerals that form under these conditions are typically forced to grow perpendicular to the direction of that pressure, and so the metamorphic rock becomes foliated–meaning that it takes on a fabric of aligned minerals or aligned bands of minerals.

Examples of foliated metamorphic rocks are shown on Figure 2.2.5. Slate forms from mudstone at relatively low metamorphic grade, as clay minerals are turned into tiny (invisible) mica crystals. The alignment of these gives slate a layered look and the tendency to split into sheets. Schist forms at higher temperatures that allow the micas to become large enough to see. The mica crystals are generally parallel to each other, but the rock doesn't split into sheets so easily. Gneiss forms at temperatures thar are typically beyond the stability of micas, and so is characterized by minerals like quartz, amphibole and feldspar that have segregated into dark and light bands.



Figure 2.3.5 Examples of Foliated Metamorphic Rocks. (From left to right: slate, schist and gneiss.)

It is very important not to confuse foliation with bedding. The slate of Figure 2.2.5 is not splitting along pre-existing bedding planes in the parent mudstone, and the layers in the gneiss have no relationship to what bedding (if any) might have existed in the parent rock.

Some other metamorphic rocks include quartzite and marble. These form from the metamorphosis of sandstone and limestone respectively, and they tend not to be foliated even if they did form under directional squeezing. Quartzite, for example, is mostly made up of quartz crystals, and they tend not to take on a directional fabric.

Exercise 2.3 Rock Groups

For each of the rocks illustrated in Figure 2.2.6 indicate (a) the major rock type (e.g., igneous, sedimentary or metamorphic), (b) a sub-type (e.g., intrusive igneous, clastic sedimentary), (c) a rock name (e.g., sandstone, andesite), and (d) the likely geological environment and processes that led to the formation of this rock.



Figure 2.3.6 What Kinds of Rocks are These?

Exercise answers are provided Appendix 2.

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2.4: Layers of the Earth

In order to understand plate tectonics, which are covered in the next section, it is essential to first understand the layers of the earth. Firsthand information about what is below the surface is very limited; most of what we know is pieced together from hypothetical models, and analyzing seismic wave data and meteorite materials. In general, the Earth can be divided into layers based on chemical composition and physical characteristics.

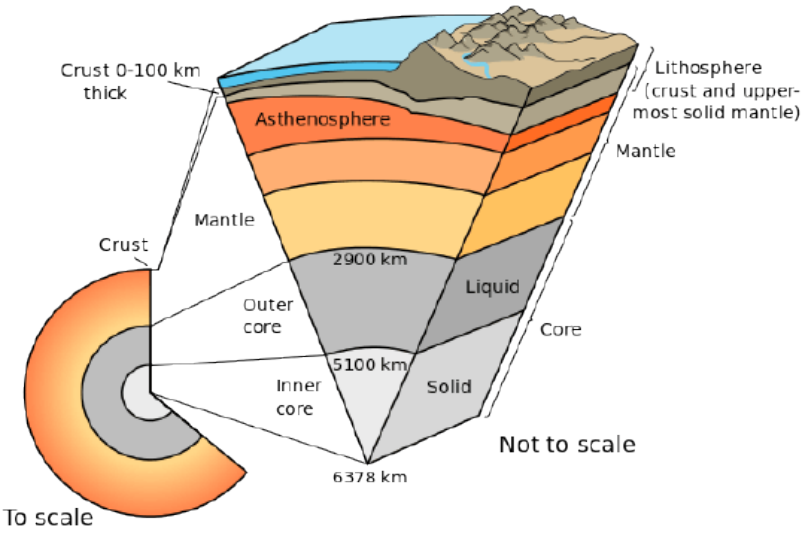


Figure 2.4.1: The layers of the Earth. Physical layers include the lithosphere and asthenosphere; chemical layers are crust, mantle, and core.

Chemical Layers

Certainly, the earth is composed of countless combinations of elements. Regardless of what elements are involved, several major factors—density, temperature and pressure—are responsible for creating three distinct chemical layers.

Crust

The outermost chemical layer and the one we currently reside on is the crust. There are two types of crust. Continental crust has a relatively low density and composition similar to granite. Oceanic crust has a relatively high density, especially when cold and old, and composition similar to basalt. The surface levels of crust are relatively brittle. The deeper parts of the crust are subjected to higher temperatures and pressure, which makes them more ductile. Ductile materials are like soft plastics or putty, they move under force. Brittle materials are like solid glass or pottery, they break under force, especially when it is applied quickly. Earthquakes, generally occur in the upper crust and are caused by the rapid movement of relatively brittle materials.

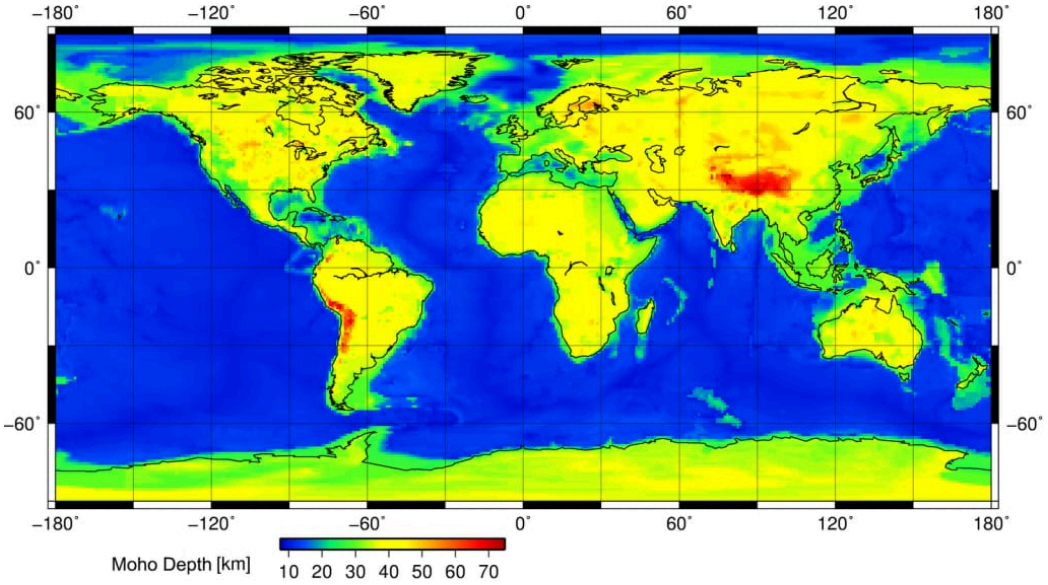


Figure 2.4.2: The global map of the depth of the moho.

The base of the crust is characterized by a large increase in seismic velocity, which measures how fast earthquake waves travel through solid matter. Called the Mohorovičić Discontinuity, or Moho for short, this zone was discovered by Andrija Mohorovičić (pronounced mo-ho-ro-vee-cheech; audio pronunciation) in 1909 after studying earthquake wave paths in his native Croatia [27]. The change in wave direction and speed is caused by dramatic chemical differences between the crust and mantle. Underneath the oceans, the Moho is found roughly 5 km below the ocean floor. Under the continents, it is located about 30-40 km below the surface. Near certain large mountain-building events known as orogenies, the continental Moho depth is doubled [28].

Mantle



Figure 2.4.3: This mantle peridotite xenolith containing olivine (green) is chemically weathering by hydrolysis and oxidation into the brown pseudo-mineral iddingsite, which is a complex of water, clay, and iron oxides. The more altered side of the rock has been exposed to the environment longer.

The mantle sits below the crust and above the core. It is the largest chemical layer by volume, extending from the base of the crust to a depth of about 2900 km [29]. Most of what we know about the mantle comes from seismic wave analysis, though the information is gathered by studying ophiolites and xenoliths. Ophiolites are pieces of the mantle that have risen through the crust until they are exposed as part of the ocean floor. Xenoliths are carried within magma and brought to the Earth's surface by volcanic eruptions. Most xenoliths are made of peridotite, an ultramafic class of igneous rock (see Chapter 4 for explanation). Because of this, scientists hypothesize most of the mantle is made of peridotite [30].

Core

The meteorite is polished showing the Widmanstätten Pattern.
GFDL or CC-BY-SA-3.0], via Wikimedia Commons" width="335px" height="251px" src="/@api/deki/files/8034/02.2_TolucaMeteorite-300x225.jpg">

Figure 2.4.4: A polished fragment of the iron-rich Toluca Meteorite, with octahedral Widmanstätten Pattern.

The core of the Earth, which has both liquid and solid layers, and consists mostly of iron, nickel, and possibly some oxygen [31]. Scientists looking at seismic data first discovered this innermost chemical layer in 1906 [32]. Through a union of hypothetical modeling, astronomical insight, and hard seismic data, they concluded the core is mostly metallic iron [33]. Scientists studying meteorites, which typically contain more iron than surface rocks, have proposed the earth was formed from meteoric material. They believe the liquid component of the core was created as the iron and nickel sank into the center of the planet, where it was liquefied by intense pressure [34].

Physical Layers

The Earth can also be broken down into five distinct physical layers based on how each layer responds to stress. While there is some overlap in the chemical and physical designations of layers, specifically the core-mantle boundary, there are significant differences between the two systems.

Lithosphere

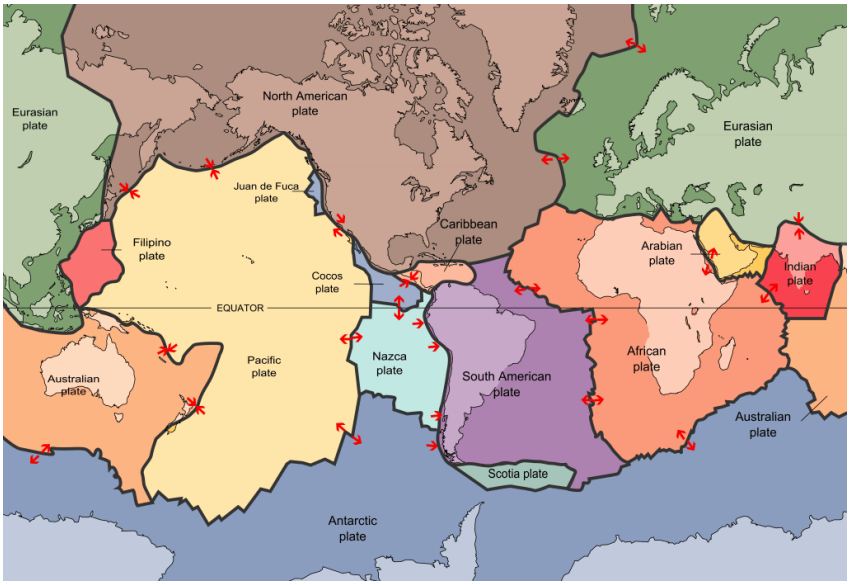


Figure 2.4.5: Map of the major plates and their motions along boundaries.

Lithos is Greek for stone, and the lithosphere is the outermost physical layer of the Earth. It is grouped into two types: oceanic and continental. Oceanic lithosphere is thin and relatively rigid. It ranges in thickness from nearly zero in new plates found around mid-ocean ridges, to an average of 140 km in most other locations. Continental lithosphere is generally thicker and considerably more plastic, especially at the deeper levels. Its thickness ranges from 40 to 280 km [35]. The lithosphere is not continuous. It is broken into segments called tectonic plates. The subsequent section on Plate Tectonics provides a detailed explanation. In brief, a plate boundary is where two plates meet and move relative to each other. Plate boundaries are where we see plate tectonics in action—mountain building, triggering earthquakes, and generating volcanic activity.

Asthenosphere

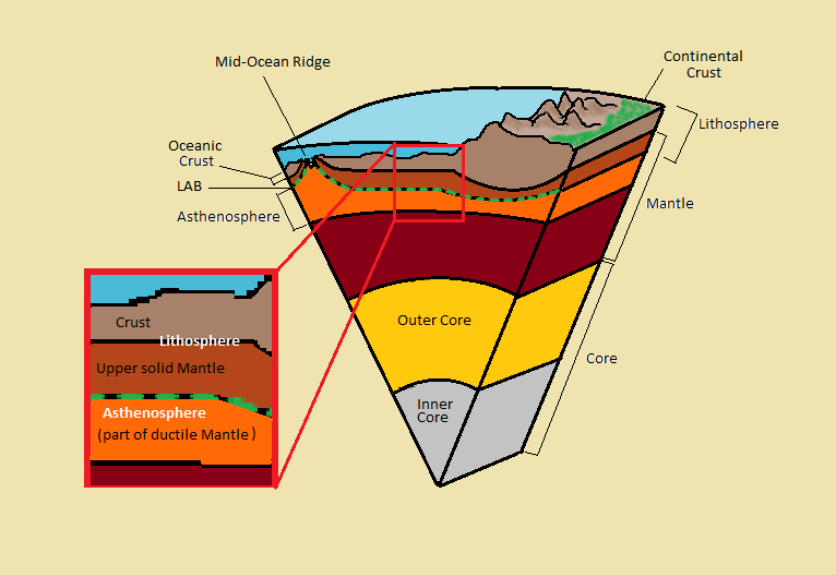


Figure 2.4.5: The lithosphere-asthenosphere boundary changes with certain tectonic situations.

The asthenosphere is the layer below the lithosphere. *Astheno-* means lacking strength, and the most distinctive property of the asthenosphere is movement. Because it is mechanically weak, this layer moves and flows due to convection currents created by heat coming from the earth's core cause [33]. Unlike the lithosphere that consists of multiple plates, the asthenosphere is relatively unbroken. Scientists have determined this by analyzing seismic waves that pass through the layer. The depth at which the asthenosphere is found is temperature-dependent [36]. It tends to lie closer to the earth's surface around mid-ocean ridges and much deeper underneath mountains and the centers of lithospheric plates.

Lower Mantel

The atoms are arranged.
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Figure 2.4.6: General perovskite structure. Perovskite silicates (e.g. Bridgmenite, $(Mg, Fe)SiO_3$) are thought to be the main component of the lower mantle, making it the most common mineral in or on Earth.

The lower mantle is more rigid and immobile than the asthenosphere. Beginning at a depth of approximately 410 to 660 km below the earth's surface, the lower mantle is subjected to very high pressures and temperatures. These extreme conditions create a transition zone in the upper portion of the lower mantle where minerals continuously change into various forms or pseudomorphs [37]. Scientists identify this zone by changes in seismic velocity and sometimes physical barriers to movement [38]. Below this transitional zone, the lower mantle is relatively uniform until it reaches the core.

Inner and Outer Core



Figure 2.4.7: Lehmann in 1932

The outer core is the only entirely liquid layer within the Earth. It starts at a depth of 2,890 km and extends to 5,150 km, making it about 2,300 km thick. In 1936, the Danish geophysicist Inge Lehmann analyzed seismic data and was the first to prove a solid inner core existed within a liquid outer core [39]. The solid inner core is about 1,220 km thick, and the outer core is about 2,300 km thick [40].

It seems like a contradiction that the hottest part of the Earth is solid, as the minerals making up the core should be liquified or vaporized at this temperature. Immense pressure keeps the minerals of the inner core in a solid phase [41]. The inner core grows slowly from the lower outer core solidifying as heat escapes the interior of the Earth and is dispersed to the outer layers [42].

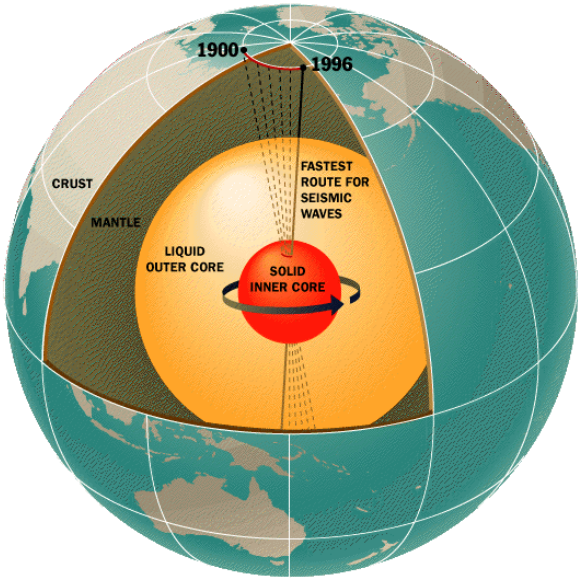


Figure 2.4.8: The outer core's spin most likely causes our protective magnetic field.

The earth's liquid outer core is critically important in maintaining a breathable atmosphere and other environmental conditions favorable for life. Scientists believe the earth's magnetic field is generated by the circulation of molten iron and nickel within the outer core [43]. If the outer core were to stop circulating or become solid, the loss of the magnetic field would result in Earth getting stripped of life-supporting gases and water. This is what happened, and continues to happen, on Mars [44].

Plate Tectonic Boundaries

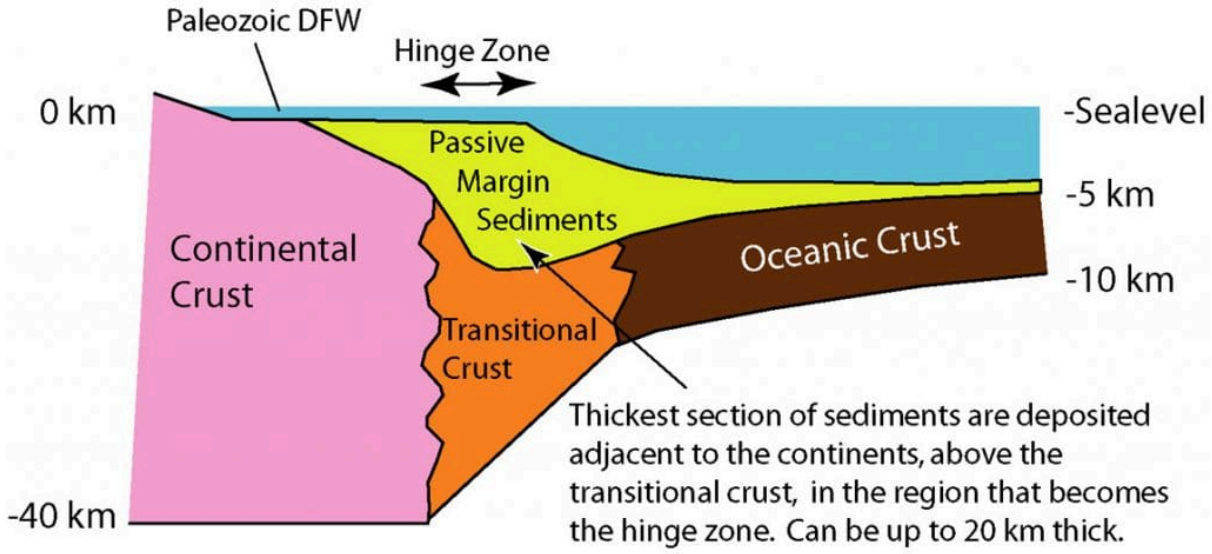


Figure 2.4.9: Passive Margin

At passive margins, the plates don't move—the continental lithosphere transitions into the oceanic lithosphere and forms plates made of both types. A tectonic plate may be made of both oceanic and continental lithosphere connected by a passive margin. North and South America's eastern coastlines are examples of passive margins. Active margins are places where the oceanic and continental lithospheric tectonic plates meet and move relative to each other, such as the western coasts of North and South America. This movement is caused by frictional drag created between the plates and differences in plate densities. The majority of mountain-building events, earthquake activity and active volcanism on the Earth's surface can be attributed to tectonic plate movement at active margins.

It shows all the types
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Figure 2.4.10: Schematic of plate boundary types.

In a simplified model, there are three categories of tectonic plate boundaries. Convergent boundaries are places where plates move toward each other. At divergent boundaries, the plates move apart. At transform boundaries, the plates slide past each other.

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2.5: Plate Tectonics- Continental Drift

INTRODUCTION

The continental drift hypothesis was developed in the early part of the 20th century, mostly by Alfred Wegener. Wegener said that continents move around on Earth's surface and that they were once joined together as a single supercontinent. While Wegener was alive, scientists did not believe that the continents could move.

THE CONTINENTAL DRIFT IDEA

Find a map of the continents and cut each one out. Better yet, use a map where the edges of the continents show the continental shelf. That's the true size and shape of a continent. Can you fit the pieces together? The easiest link is between the eastern Americas and western Africa and Europe, but the rest can fit together too (figure 1).



Figure 2.5.1. The continents fit together like pieces of a puzzle. This is how they looked 250 million years ago.

Alfred Wegener proposed that the continents were once united into a single supercontinent named Pangaea, meaning *all earth* in ancient Greek. He suggested that Pangaea broke up long ago and that the continents then moved to their current positions. He called his hypothesis **continental drift.**

EVIDENCE FOR CONTINENTAL DRIFT

Besides the way the continents fit together, Wegener and his supporters collected a great deal of evidence for the continental drift hypothesis.

- Identical rocks, of the same type and age, are found on both sides of the Atlantic Ocean. Wegener said the rocks had formed side-by-side and that the land had since moved apart.
- Mountain ranges with the same rock types, structures, and ages are now on opposite sides of the Atlantic Ocean. The Appalachians of the eastern United States and Canada, for example, are just like mountain ranges in eastern Greenland, Ireland, Great Britain, and Norway (figure 2). Wegener concluded that they formed as a single mountain range that was separated as the continents drifted.



Figure 2.5.2. The similarities between the Appalachian and the eastern Greenland mountain ranges are evidences for the continental drift hypothesis.

- Ancient fossils of the same species of extinct plants and animals are found in rocks of the same age but are on continents that are now widely separated (figure 3). Wegener proposed that the organisms had lived side by side, but that the lands had moved apart after they were dead and fossilized. He suggested that the organisms would not have been able to travel across the oceans.
  - Fossils of the seed fern *Glossopteris* were too heavy to be carried so far by wind.
  - *Mesosaurus* was a swimming reptile but could only swim in fresh water.
  - *Cynognathus* and *Lystrosaurus* were land reptiles and were unable to swim

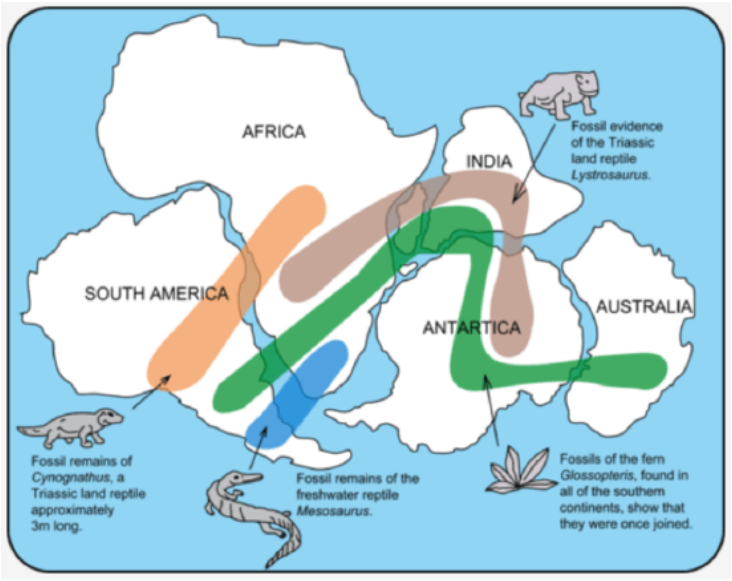


Figure 2.5.3. Wegener used fossil evidence to support his continental drift hypothesis. The fossils of these organisms are found on lands that are now far apart.

- Grooves and rock deposits left by ancient glaciers are found today on different continents very close to the equator. This would indicate that the glaciers either formed in the middle of the ocean and/or covered most of the Earth. Today glaciers only form on land and nearer the poles. Wegener thought that the glaciers were centered over the southern land mass close to the South Pole and the continents moved to their present positions later on.
- Coral reefs and coal-forming swamps are found in tropical and subtropical environments, but ancient coal seams and coral reefs are found in locations where it is much too cold today. Wegener suggested that these creatures were alive in warm climate zones and that the fossils and coal later had drifted to new locations on the continents.

Take a look at this animation showing that Earth's climate belts remain in roughly the same position while the continents move and this animation showing how the continents split up.

Although Wegener's evidence was sound, most geologists at the time rejected his hypothesis of continental drift. Why do you think they did not accept continental drift?

Scientists argued that there was no way to explain how solid continents could plow through solid oceanic crust. Wegener's idea was nearly forgotten until technological advances presented even more evidence that the continents moved and gave scientists the tools to develop a mechanism for Wegener's drifting continents.

MAGNETIC POLARITY EVIDENCE

Puzzling new evidence came in the 1950s from studies on the Earth's magnetic history (figure 4). Scientists used **magnetometers**, devices capable of measuring the magnetic field intensity, to look at the magnetic properties of rocks in many locations.

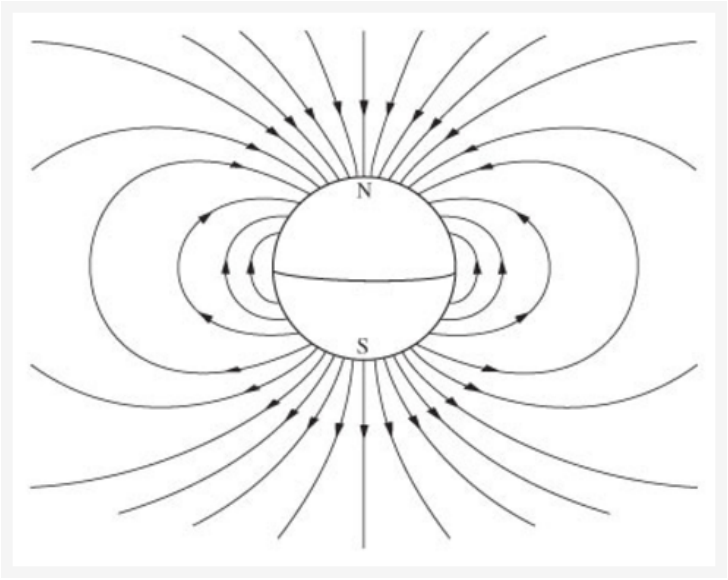


Figure 2.5.4. Earth's magnetic field is like a magnet with its north pole near the geographic North Pole and the south pole near the geographic South Pole.

Magnetite crystals are like tiny magnets that point to the north magnetic pole as they crystallize from magma. The crystals record both the direction and strength of the **magnetic field** at the time. The direction is known as the field's **magnetic polarity.**

Magnetic Polarity on the Same Continent with Rocks of Different Ages

Geologists noted important things about the magnetic polarity of different aged rocks on the same continent:

- Magnetite crystals in fresh volcanic rocks point to the current magnetic north pole (figure 5) no matter what continent or where on the continent the rocks are located.

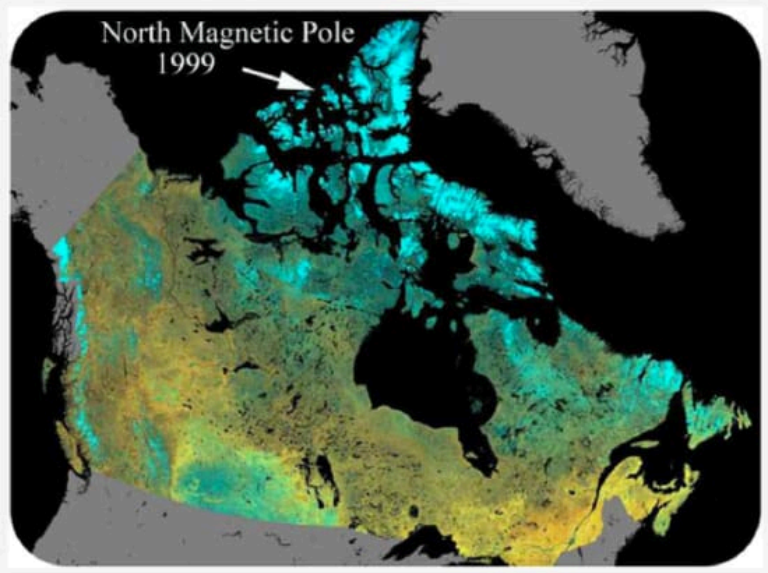


Figure 2.5.5. Earth's current north magnetic pole is in northern Canada.

- Older rocks that are the same age and are located on the same continent point to the same location, but that location is not the current north magnetic pole.
- Older rock that are of different ages do not point to the same locations or to the current magnetic north pole.

In other words, although the magnetite crystals were pointing to the magnetic north pole, the location of the pole seemed to wander. Scientists were amazed to find that the north magnetic pole changed location through time (figure 6).

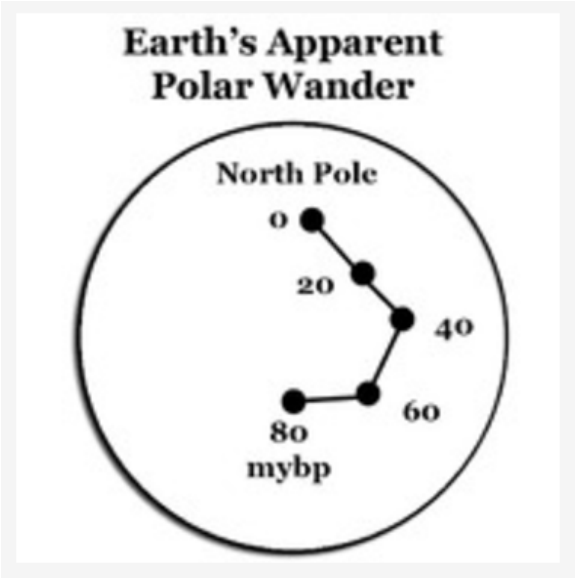


Figure 2.5.6. The location of the north magnetic north pole 80 million years before present (mybp), then 60, 40, 20, and now.

There are three possible explanations for this:

1. The continents remained fixed and the north magnetic pole moved.
2. The north magnetic pole stood still and the continents moved.
3. Both the continents and the north pole moved.

Magnetic Polarity on Different Continents with Rocks of the Same Age

Geologists noted that for rocks of the same age but on different continents, the little magnets pointed to different magnetic north

poles.

- 400-million-year-old magnetite in Europe pointed to a different north magnetic pole than the same-aged magnetite in North America.
- 250 million years ago, the north poles were also different for the two continents.

The scientists looked again at the three possible explanations. Only one can be correct. If the continents had remained fixed while the north magnetic pole moved, there must have been two separate north poles. Since there is only one north pole today, the only reasonable explanation is that the north magnetic pole has remained fixed but that the continents have moved.

To test this, geologists fitted the continents together as Wegener had done. It worked! There has only been one magnetic north pole and the continents have drifted (figure 7). They named the phenomenon of the magnetic pole that seemed to move but actually did not **apparent polar wander.**

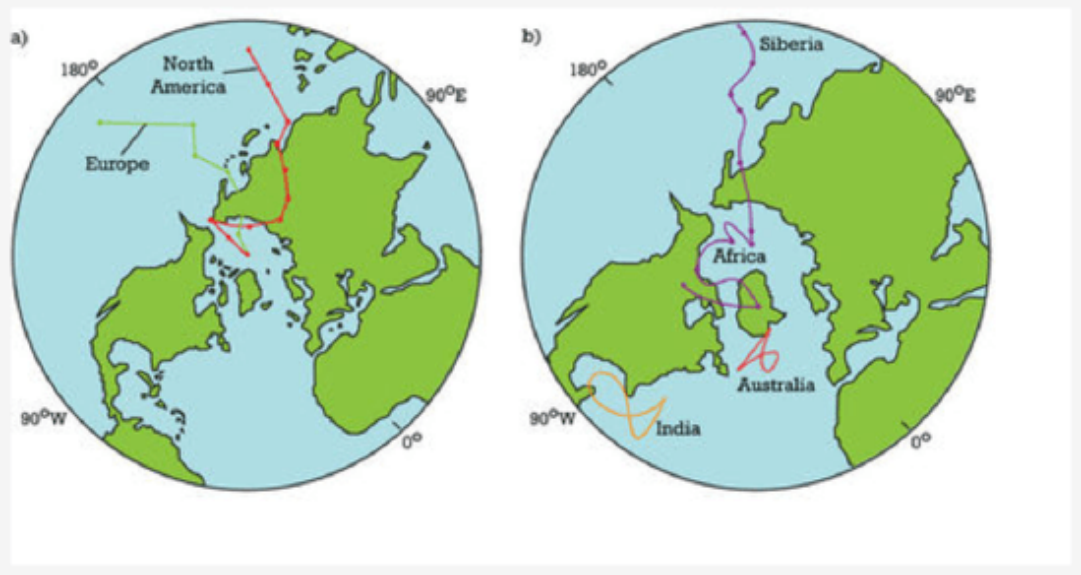


Figure 2.5.7. On the left: The apparent north pole for Europe and North America if the continents were always in their current locations. The two paths merge into one if the continents are allowed to drift.

This evidence for continental drift gave geologists renewed interest in understanding how continents could move about on the planet's surface.

LESSON SUMMARY

- In the early part of the 20th century, scientists began to put together evidence that the continents could move around on Earth's surface.
- The evidence for continental drift included the fit of the continents; the distribution of ancient fossils, rocks, and mountain ranges; and the locations of ancient climatic zones.
- Although the evidence for continental drift was extremely strong, scientists rejected the idea because no mechanism for how solid continents could move around on the solid earth was developed.
- The discovery of apparent polar wander renewed scientists interest in continental drift.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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2.6: Plate Tectonics- Convergent Boundaries

Convergent boundaries, also called destructive boundaries, are places where two or more plates move toward each other. Convergent boundary movement is divided into two types, subduction and collision, depending on the density of the involved plates. Continental lithosphere is of lower density and thus more buoyant than the underlying asthenosphere. Oceanic lithosphere is denser than continental lithosphere, and, when old and cold, may even be denser than asthenosphere.

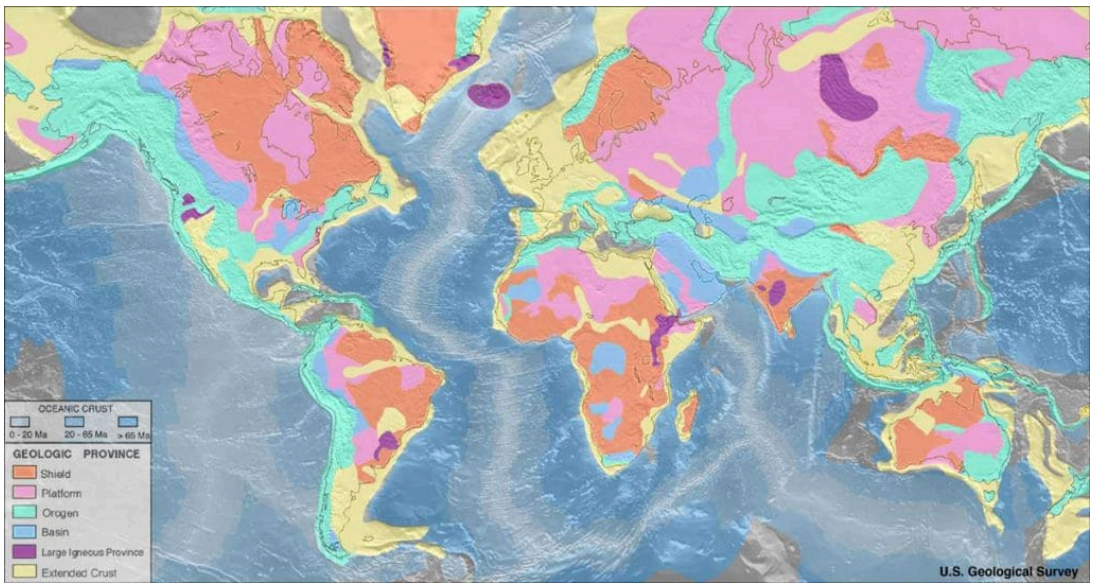


Figure 2.6.1: Geologic provinces of Earth. Orogenies are labeled light blue.

When plates of different densities converge, the higher density plate is pushed beneath the more buoyant plate in a process called subduction. When continental plates converge without subduction occurring, this process is called collision.

Subduction

Video showing continental-oceanic subduction, causing volcanism. By Tanya Atwater and John Iwerks.

Subduction occurs when a dense oceanic plate meets a more buoyant plate, like a continental plate or warmer/younger oceanic plate, and descends into the mantle [45]. The worldwide average rate of oceanic plate subduction is 25 miles per million years, about a half-inch per year [46]. As an oceanic plate descends, it pulls the ocean floor down into a trench. These trenches can be more than twice as deep as the average depth of the adjacent ocean basin, which is usually three to four km. The Mariana Trench, for example, approaches a staggering 11 km [47].

diagram of ocean continent subduction
CC BY-SA 4.0], via Wikimedia Commons" width="534px" height="261px" src="/@api/deki/files/8044/Subduction-en.svg_.png">

Figure 2.6.2: Diagram of ocean-continent subduction.

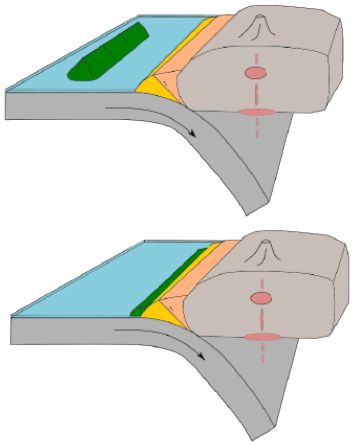


Figure 2.6.3: Microcontinents can become part of the accretionary prism of a subduction zone.

Within the trench, ocean floor sediments are scraped together and compressed between the subducting and overriding plates. This feature is called the accretionary wedge, mélange, or accretionary prism. Fragments of continental material, including microcontinents, riding atop the subducting plate may become sutured to the accretionary wedge and accumulate into a large area of land called a terrane [48]. Vast portions of California are comprised of accreted terranes [49].

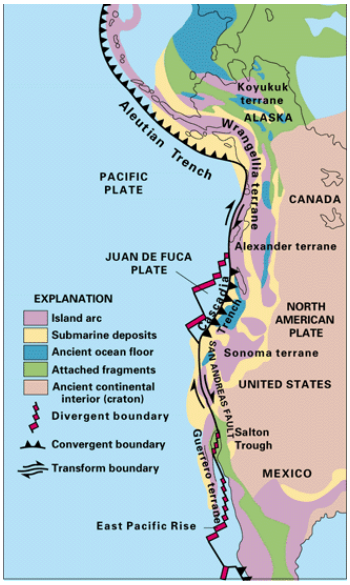


Figure 2.6.4: Accreted terranes of western North America. Everything that is not the “Ancient continental interior (craton)” has been smeared onto the side of the continent by accretion from subduction.

When the subducting oceanic plate, or slab, sinks into the mantle, the immense heat and pressure push volatile materials like water and carbon dioxide into an area below the continental plate and above the descending plate called the mantle wedge. The volatiles are released mostly by hydrated minerals that revert to non-hydrated minerals in these higher temperatures and pressure conditions. When mixed with asthenospheric material above the plate, the volatile lower the melting point of the mantle wedge, and through a process called flux melting it becomes liquid magma. The molten magma is more buoyant than the lithospheric plate above it and migrates to the Earth’s surface where it emerges as volcanism. The resulting volcanoes frequently appear as curved mountain chains, volcanic arcs, due to the curvature of the earth. Both oceanic and continental plates can contain volcanic arcs.

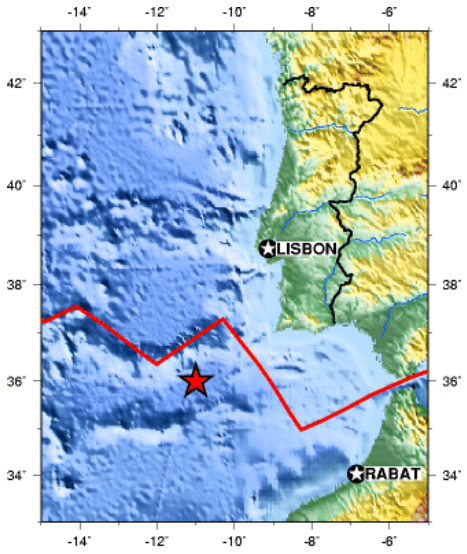


Figure 2.6.5: Location of the large (Mw 8.5-9.0) 1755 Lisbon Earthquake.

How subduction is initiated is still a matter of scientific debate [50]. It is generally accepted that subduction zones start as passive margins, where oceanic and continental plates come together, and then gravity initiates subduction and converts the passive margin into an active one [51]. One hypothesis is gravity pulls the denser oceanic plate down [52] or the plate can start to flow ductility at a low angle [53]. Scientists seeking to answer this question have collected evidence that suggests a new subduction zone is forming off the coast of Portugal [54]. Some scientists have proposed large earthquakes like the 1755 Lisbon earthquake may even have something to do with this process of creating a subduction zone [55], although the evidence is not definitive. Another hypothesis proposes subduction happens at transform boundaries involving plates of different densities [56].

Some plate boundaries look like they should be active, but show no evidence of subduction. The oceanic lithospheric plates on either side of the Atlantic Ocean for example, are denser than the underlying asthenosphere and are not subducting beneath the continental plates.

One hypothesis is the bond holding the oceanic and continental plates together is stronger than the downward force created by the difference in plate densities.

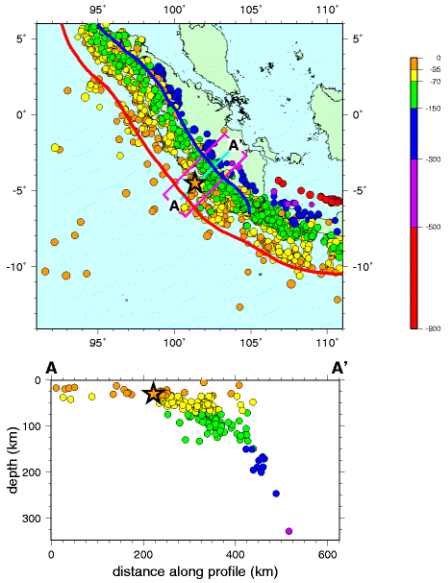


Figure 2.6.6: Earthquakes along the Sunda megathrust subduction zone, along the island of Sumatra, showing the 2006 Mw 9.1-9.3 Indian Ocean Earthquake as a star.

Subduction zones are known for having the largest earthquakes and tsunamis; they are the only places with fault surfaces large

enough to create magnitude-9 earthquakes. These subduction-zone earthquakes not only are very large but also are very deep. When a subducting slab becomes stuck and cannot descend, a massive amount of energy builds up between the stuck plates. If this energy is not gradually dispersed, it may force the plates to suddenly release along several hundred kilometers of the subduction zone [57]. Because subduction-zone faults are located on the ocean floor, this massive amount of movement can generate giant tsunamis such as those that followed the 2004 Indian Ocean Earthquake and 2011 Tōhoku Earthquake in Japan.

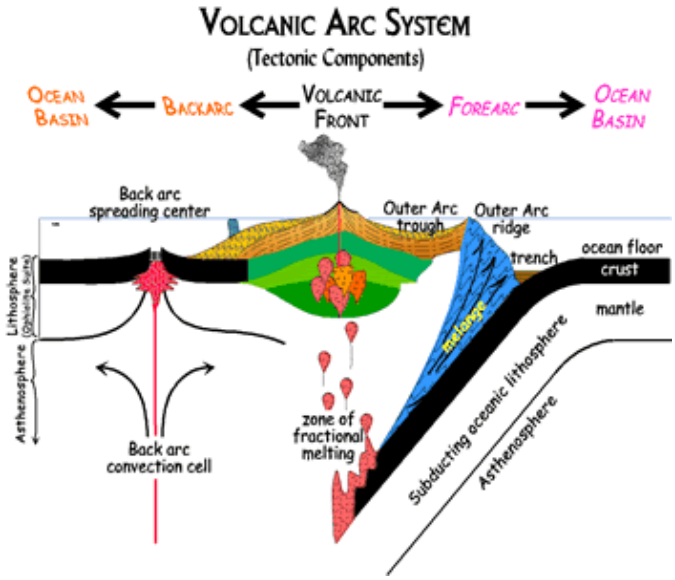


Figure 2.6.7: Various parts of a subduction zone. This subduction zone is ocean-ocean subduction, though the same features can apply to continent-ocean subduction.

All subduction zones have a forearc basin, a feature of the overriding plate found between the volcanic arc and oceanic trench. The forearc basin experiences a lot of faulting and deformation activity, particularly within the accretionary wedge [58].

In some subduction zones, tensional forces working on the continental plate create a backarc basin on the interior side of the volcanic arc. Some scientists have proposed a subduction mechanism called oceanic slab rollback creates extension faults in the overriding plates [59]. In this model, the descending oceanic slab does not slide directly under the overriding plate but instead rolls back, pulling the overlying plate seaward. The continental plate behind the volcanic arc gets stretched like pizza dough until the surface cracks and collapses to form a backarc basin. If the extension activity is extensive and deep enough, a backarc basin can develop into a continental rifting zone. These continental divergent boundaries may be less symmetrical than their mid-ocean ridge counterparts [60].

In places where numerous young buoyant oceanic plates are converging and subducting at a relatively high velocity, they may force the overlying continental plate to buckle and crack [61]. This is called back-arc faulting. Extensional back-arc faults pull rocks and chunks of plates apart. Compressional back-arc faults, also known as thrust faults, push them together.

The dual spines of the Andes Mountain range include a example of compressional thrust faulting. The western spine is part of a volcanic arc. Thrust faults have deformed the non-volcanic eastern spine, pushing rocks and pieces of a continental plate on top of each other.

There are two styles of thrust fault deformation: thin-skinned faults that occur in superficial rocks lying on top of the continental plate and thick-skinned faults that reach deeper into the crust. The Sevier Orogeny in the western U.S. is a notable thin-skinned type of deformation created during the Cretaceous Period. The Laramide Orogeny, a thick-skinned type of deformation, occurred near the end of and slightly after the Sevier Orogeny in the same region.

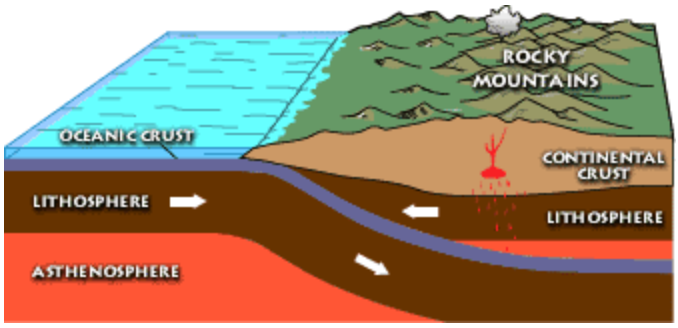


Figure 2.6.8: Shallow subduction during the Laramide Orogeny.

Flat-slab, or shallow, subduction caused the Laramide Orogeny. When the descending slab subducts at a low angle, there is more contact between the slab and the overlying continental plate than in a typical subduction zone. The shallowly-subducting slab pushes against the overriding plate and creates an area of deformation on the overriding plate many kilometers away from the subduction zone [62].

Oceanic-Continental Subduction

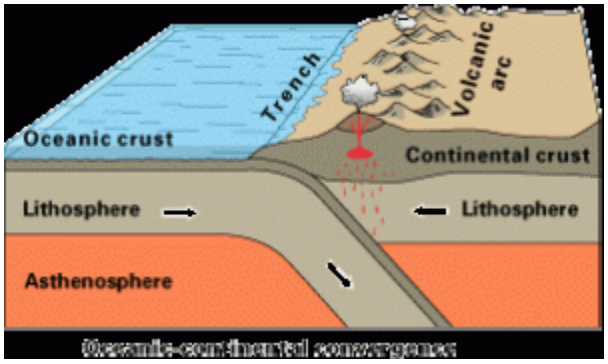


Figure 2.6.9: Subduction of an oceanic plate beneath a continental plate, forming a trench and volcanic arc.

Oceanic-continental subduction occurs when an oceanic plate dives below a continental plate. This convergent boundary has a trench and mantle wedge and frequently, a volcanic arc. Well-known examples of continental volcanic arcs are the Cascade Mountains in the Pacific Northwest [63] and the Western Andes Mountains in South America [64].

Oceanic-Oceanic Subduction

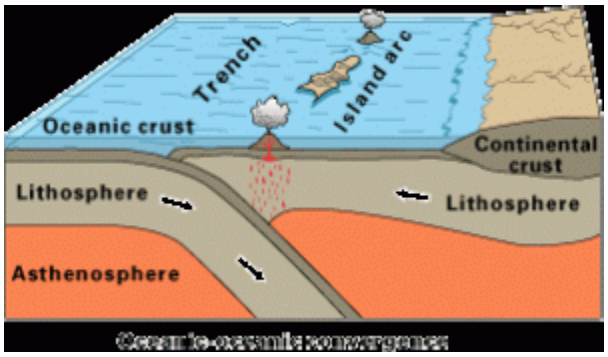


Figure 2.6.10: Subduction of an oceanic plate beneath another oceanic plate, forming a trench and an island arc.

The boundaries of oceanic-oceanic subduction zones show very different activity from those involving oceanic-continental plates. Since both plates are made of oceanic lithosphere, it is usually the older plate that subducts because it is colder and denser. The volcanism on the overlying oceanic plate may remain hidden underwater.. If the volcanoes rise high enough the reach the ocean surface, the chain of volcanism forms an island arc. Examples of these island arcs include the Aleutian Islands in the northern Pacific Ocean, Lesser Antilles in the Caribbean Sea, and numerous island chains scattered throughout the western Pacific Ocean [65].

Collisions

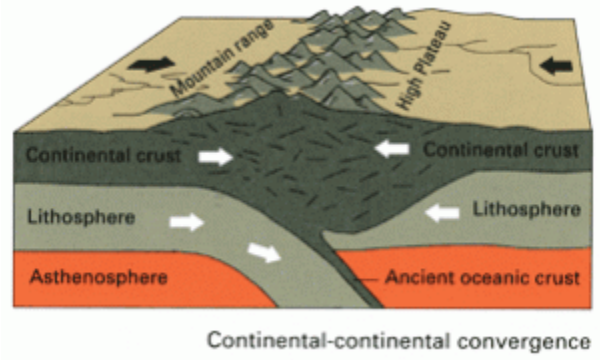


Figure 2.6.11: Two continental plates colliding.

When continental plates converge, during the closing of an ocean basin, for example, subduction is not possible between the equally buoyant plates. Instead of one plate descending beneath another, the two masses of continental lithosphere slam together in a process known as collision [66]. Without subduction, there is no magma formation and no volcanism. Collision zones are characterized by tall, non-volcanic mountains; a broad zone of frequent, large earthquakes; and very little volcanism.

When oceanic crust connected by a passive margin to continental crust completely subducts beneath a continent, an ocean basin closes, and continental collision begins. Eventually, as ocean basins close, continents join together to form a massive accumulation of continents called a supercontinent, a process that has taken place in ~500 million-year-old cycles over earth's history.



Figure 2.6.12: A reconstruction of the supercontinent Pangaea, showing approximate positions of modern continents.

The process of collision created Pangea, the supercontinent envisioned by Wegener as the key component of his continental drift hypothesis. Geologists now have evidence that continental plates have been continuously converging into supercontinents and splitting into smaller basin-separated continents throughout Earth's existence, calling this process the supercontinent cycle, a process that takes place in approximately 500 million years. For example, they estimate Pangea began separating 200 million years ago. Pangea was preceded by an earlier supercontinents, one of which being Rodinia, which existed 1.1 billion years ago and started breaking apart 800 million to 600 million years ago.



Figure 2.6.13: The tectonics of the Zagros Mountains. Note the Persian Gulf foreland basin.

A foreland basin is a feature that develops near mountain belts, as the combined mass of the mountains forms a depression in the lithospheric plate. While foreland basins may occur at subduction zones, they are most commonly found at collision boundaries. The Persian Gulf is possibly the best modern example, created entirely by the weight of the nearby Zagros Mountains.



Figure 2.6.14: Pillow lavas, which only form underwater, from an ophiolite in the Apennine Mountains of central Italy.

If continental and oceanic lithosphere are fused on the same plate, it can partially subduct but its buoyancy prevents it from fully descending. In very rare cases, part of a continental plate may become trapped beneath a descending oceanic plate in a process called obduction [67]. When a portion of the continental crust is driven down into the subduction zone, due to its buoyancy it returns to the surface relatively quickly.

As pieces of the continental lithosphere break loose and migrate upward through the obduction zone, they bring along bits of the mantle and ocean floor and amend them on top of the continental plate. Rocks composed of this mantle and ocean-floor material are called ophiolites and they provide valuable information about the composition of the mantle.

The area of collision-zone deformation and seismic activity usually covers a broader area because the continental lithosphere is plastic and malleable. Unlike subduction-zone earthquakes, which tend to be located along a narrow swath near the convergent boundary, collision-zone earthquakes may occur hundreds of kilometers from the boundary between the plates.

The Eurasian continent has many examples of collision-zone deformations covering vast areas. The Pyrenees mountains begin in the Iberian Peninsula and cross into France. Also, there are the Alps stretching from Italy to central Europe; the Zagros mountains from Arabia to Iran; and Himalaya mountains from the Indian subcontinent to central Asia.

Video Animation of India crashing into Asia, by Tanya Atwater.

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2.7: Plate Tectonics- Divergent Boundaries

At divergent boundaries, sometimes called constructive boundaries, lithospheric plates move away from each other. There are two types of divergent boundaries, categorized by where they occur: continental rift zones and mid-ocean ridges. Continental rift zones occur in weak spots in the continental lithospheric plate. A mid-ocean ridge usually originates in a continental plate as a rift zone that expands to the point of splitting the plate apart, with seawater filling in the gap. The separate pieces continue to drift apart and become individual continents. This process is known as rift-to-drift.

Continental Rifting

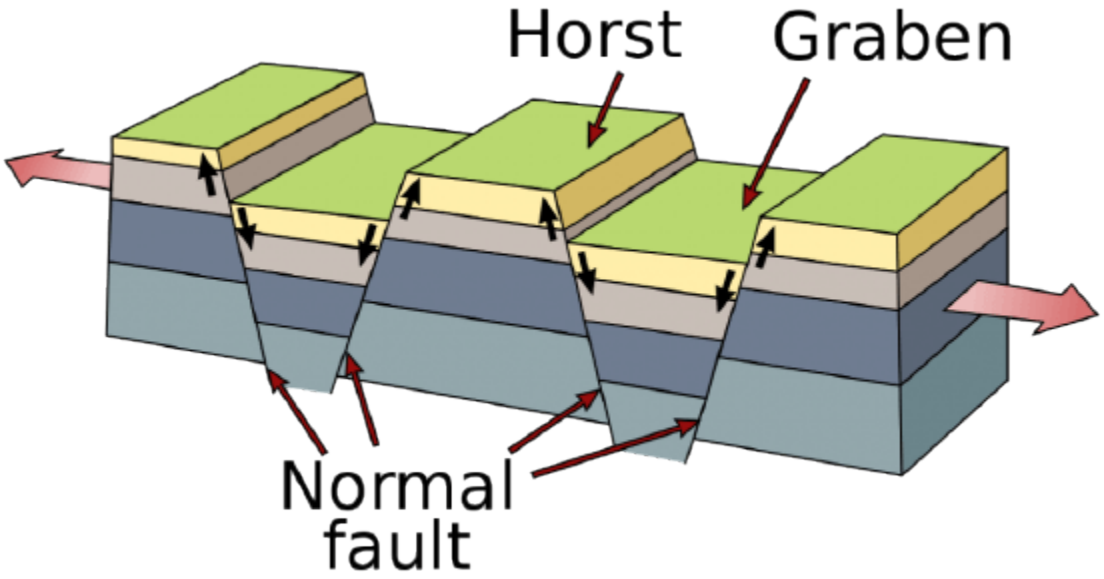


Figure 2.7.1: Faulting that occurs in divergent boundaries.

In places where the continental plates are very thick, they reflect so much heat back into the mantle it develops strong convection currents that push super-heated mantle material up against the overlying plate, softening it. Tensional forces created by this convective upwelling begin to pull the weakened plate apart. As it stretches, it becomes thinner and develops deep cracks called extension or normal faults. Eventually, plate sections located between large faults drop into deep depressions known as rift valleys, which often contain keystone-shaped blocks of down-dropped crust known as grabens. The shoulders of these grabens are called horsts. If only one side of a section drops, it is called a half-graben. Depending on the conditions, rifts can grow into very large lakes and even oceans.



Figure 2.7.2: The Afar Triangle (center) has the Red Sea ridge (center to upper left), Gulf of Aden ridge (center to right), and East African Rift (center to lower left) form a triple junction that are about 120° apart.

While seemingly occurring at random, rifting is dictated by two factors. Rifting does not occur in continents with older and more stable interiors, known as cratons. When continental rifting does occur, the break-up pattern resembles the seams of a soccer ball, also called a truncated icosahedron. This is the most common surface-fracture pattern to develop on an evenly expanding sphere because it uses the least amount of energy [68].

Using the soccer ball model, rifting tends to lengthen and expand along a particular seam while fizzling out in the other directions. These seams with little or no tectonic activity are called failed rift arms. A failed rift arm is still a weak spot in the continental plate; even without the presence of active extension faults, it may develop into a called an aulacogen. One example of a failed rift arm is the Mississippi Valley Embayment, a depression through which the upper end of the Mississippi River flows. Occasionally connected rift arms do develop concurrently, creating multiple boundaries of active rifting. In places where the rift arms do not fail, for example the Afar Triangle, three divergent boundaries can develop near each other forming a triple junction.



Figure 2.7.3: NASA image of the Basin and Range horsts and grabens across central Nevada.

Rifts come in two types: narrow and broad. Narrow rifts are characterized by a high density of highly active divergent boundaries. The East African Rift Zone, where the horn of Africa is pulling away from the mainland, is an excellent example of an active narrow rift. Lake Baikal in Russia is another. Broad rifts also have numerous fault zones, but they are distributed over wide areas of deformation. The Basin and Range region located in the western United States is a type of broad rift. The Wasatch Fault, which also created the Wasatch Mountain Range in the state of Utah, forms the eastern divergent boundary of this broad rift (Animation 1 and Animation 2).

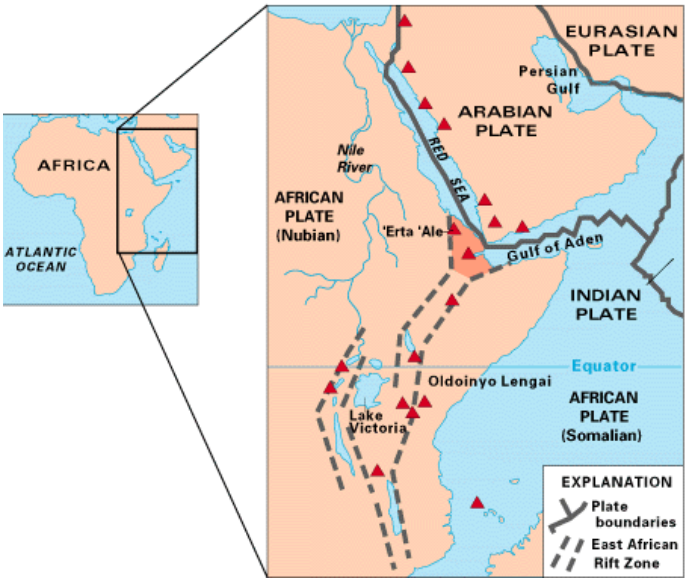


Figure 2.7.4: The narrow East African Rift.

Rifts have earthquakes, although not of the magnitude and frequency of other boundaries. They may also exhibit volcanism. Unlike the flux-melted magma found in subduction zones, rift-zone magma is created by decompression melting. As the continental plates are pulled apart, they create a region of low pressure that melts the lithosphere and draws it upwards. When this molten magma reaches the weakened and fault-riddled rift zone, it migrates to the surface by breaking through the plate or escaping via an open fault. Examples of young rift volcanoes dot the Basin and Range region in the United States. Rift-zone activity is responsible for generating some unique volcanism, such as the Ol Doinyo Lengai in Tanzania. This volcano erupts lava consisting largely of carbonatite, a relatively cold, liquid carbonate mineral [69].

South America and Africa rift, forming the Atlantic. Video by Tanya Atwater.

Mid-Ocean Ridges

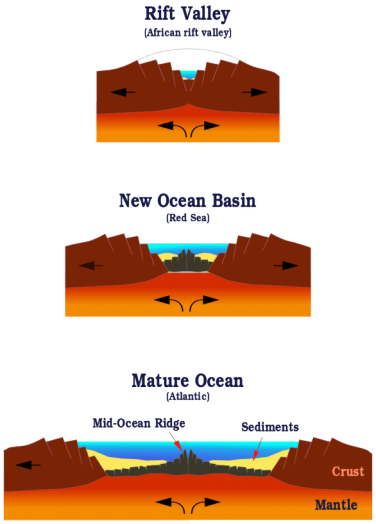


Figure 2.7.5: Progression from rift to mid-ocean ridge.

As rifting and volcanic activity progress, the continental lithosphere becomes more mafic (see Chapter 4) and thinner, with the eventual result transforming the plate under the rifting area into the oceanic lithosphere. This is the process that gives birth to a new ocean, much like the narrow Red Sea emerged with the movement of Arabia away from Africa. As the oceanic lithosphere continues to diverge, a mid-ocean ridge is formed.

Mid-ocean ridges, also known as spreading centers, have several distinctive features. They are the only places on earth that create new oceanic lithosphere. Decompression melting in the rift zone changes asthenosphere material into the new lithosphere, which oozes up through cracks in the oceanic plate. The amount of new lithosphere being created at mid-ocean ridges is highly significant. These undersea rift volcanoes produce more lava than all other types of volcanism combined. Despite this, most mid-oceanic ridge volcanism remains unmapped because the volcanoes are located deep on the ocean floor.

In rare cases, such as a few locations in Iceland, rift zones display the type of volcanism, spreading, and ridge formation found on the ocean floor.

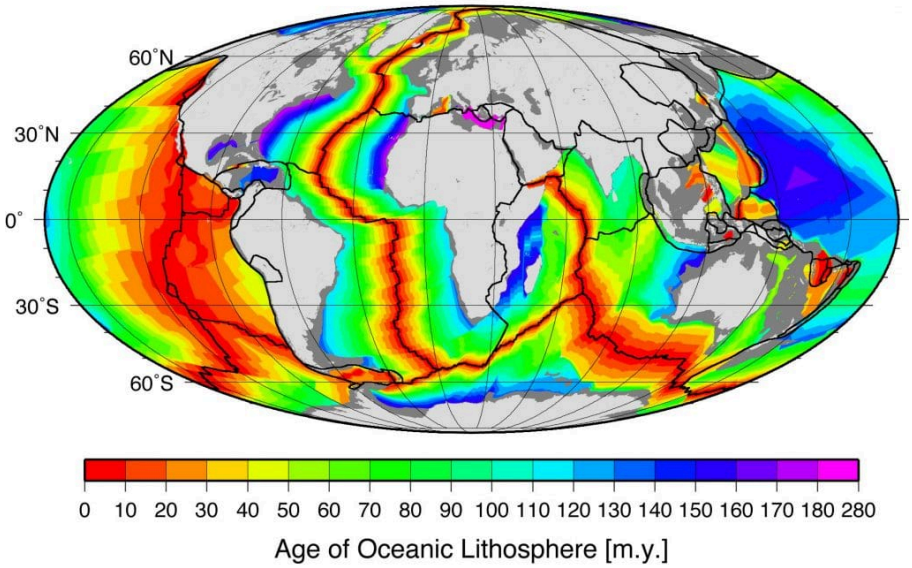


Figure 2.7.6: Age of oceanic lithosphere, in millions of years. Notice the differences in the Atlantic Ocean along the coasts of the continents.

The ridge feature is created by the accumulation of hot lithosphere material, which is lighter than the dense underlying asthenosphere. This chunk of isostatically buoyant lithosphere sits partially submerged and partially exposed to the asthenosphere, like an ice cube floating in a glass of water.

As the ridge continues to spread, the lithosphere material is pulled away from the area of volcanism and becomes colder and denser. As it continues to spread and cool, the lithosphere settles into wide swathes of relatively featureless topography called abyssal plains with lower topography [70].

This model of ridge formation suggests the sections of the lithosphere furthest away from the mid-ocean ridges will be the oldest. Scientists have tested this idea by comparing the age of rocks located in various locations on the ocean floor. Rocks found near ridges are younger than those found far away from any ridges. Sediment accumulation patterns also confirm the idea of sea-floor spreading. Sediment layers tend to be thinner near mid-ocean ridges, indicating it has had less time to build up.

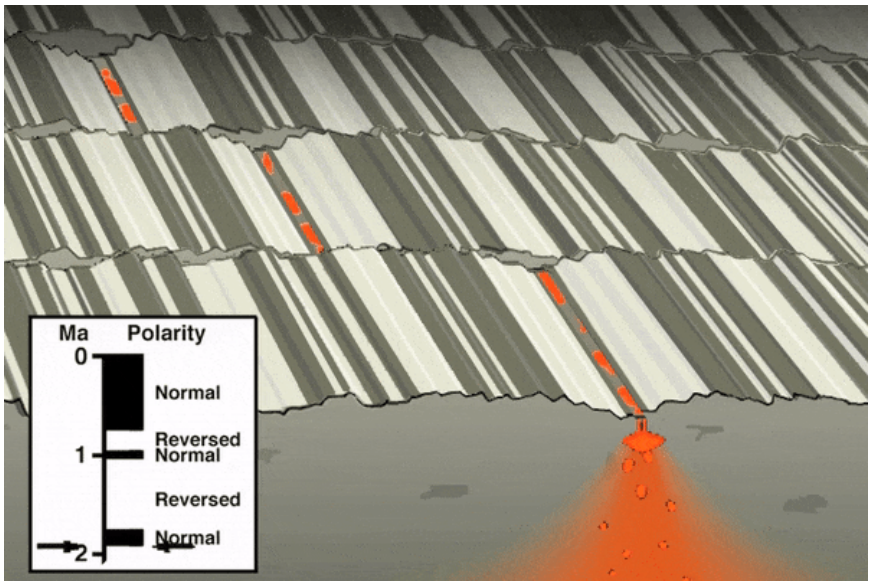


Figure 2.7.8: Spreading along several mid-ocean ridges, showing magnetic striping symmetry. By Tanya Atwater.

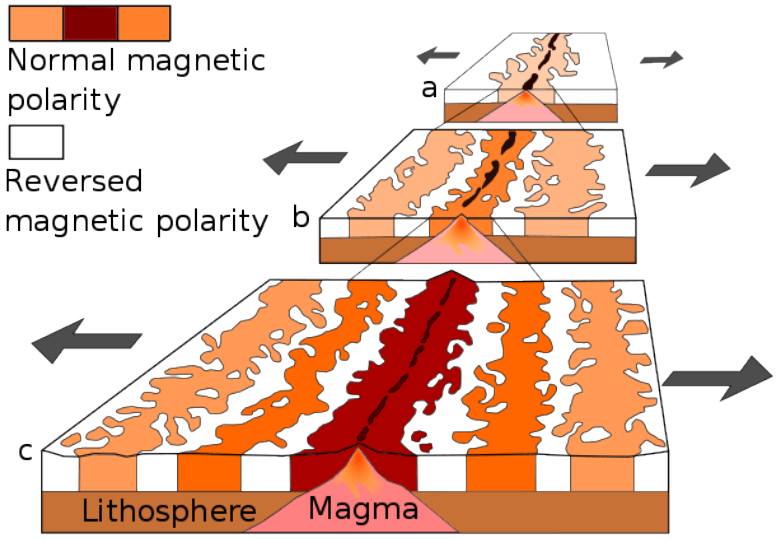


Figure 2.7.9: A time progression (with “a” being first and “c” being last) showing a spreading center getting wider while recording changes in the magnetic field of the Earth.

As mentioned in the section on paleomagnetism and the development of plate tectonic theory, scientists noticed mid-ocean ridges contained unique magnetic anomalies that show up as symmetrical striping on both sides of the ridge. The Vine-Matthews-Morley hypothesis [20] proposes these alternating reversals are created by the earth’s magnetic field being imprinted into magma after it emerges from the ridge [71]. Very hot magma has no magnetic field. As the oceanic plates get pulled apart, the magma cools below the Curie point, the temperature below which a magnetic field gets locked into magnetic minerals. The alternating magnetic reversals in the rocks reflect the periodic swapping of earth’s magnetic north and south poles. This paleomagnetic pattern provides a great historical record of ocean-floor movement, and is used to reconstruct past tectonic activity and determine rates of ridge spreading [72].

Video of the breakup of Pangea and formation of the northern Atlantic Ocean. By Tanya Atwater.

There is a large build up of minerals around the vent
CC BY 2.0 or Public domain], via Wikimedia Commons" width="268px" height="345px" src="/@api/deki/files/8071/BlackSmoker-233x300.jpg">

Figure 2.7.10: Black smoker hydrothermal vent with a colony of giant (6’+) tube worms.

Thanks to their distinctive geology, mid-ocean ridges are home to some of the most unique ecosystems ever discovered. The ridges are often studded with hydrothermal vents, deep fissures that allow seawater to circulate through the upper portions of the oceanic plate and interact with hot rock. The super-heated seawater rises back up to the surface of the plate, carrying dissolved gasses and minerals, and small particulates. The resulting emitted hydrothermal water looks like black underwater smoke.

Scientists had known about these geothermal areas on the ocean floor for some time. However, it was not until 1977, when scientists piloting a deep submergence vehicle, the Alvin, discovered a thriving community of organisms clustered around these hydrothermal vents [73]. These unique organisms, which include 10-foot-long tube worms taller than people, live in the complete darkness of the ocean floor deprived of oxygen and sunlight. They use the geothermal energy provided by the vents and a process called bacterial chemosynthesis to feed on sulfur compounds. Before this discovery, scientists believed life on earth could not exist without photosynthesis, a process that requires sunlight. Some scientists suggest this type of environment could have been the origin of life on Earth [74], and perhaps even extraterrestrial life elsewhere in the galaxy, such as on Jupiter's moon Europa [75].

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2.8: Plate Tectonics- Transform Boundaries

A transform boundary, sometimes called a strike-slip or conservative boundary, is where the lithospheric plates slide past each other in the horizontal plane. This movement is described based on the perspective of an observer standing on one of the plates, looking across the boundary at the opposing plate. Dextral, also known as right-lateral, movement describes the opposing plate moving to the right. Sinistral, also known as left lateral, movement describes the opposing plate moving to the left.

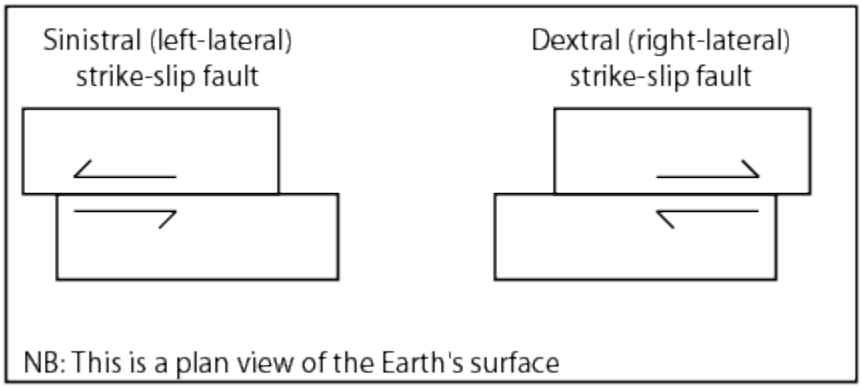


Figure 2.8.1: The two types of transform/strike-slip faults.

Most transform boundaries are found on the ocean floor, around mid-ocean ridges. These boundaries form aseismic fracture zones, filled with earthquake-free transform faults, to accommodate different rates of spreading occurring at the ridge.

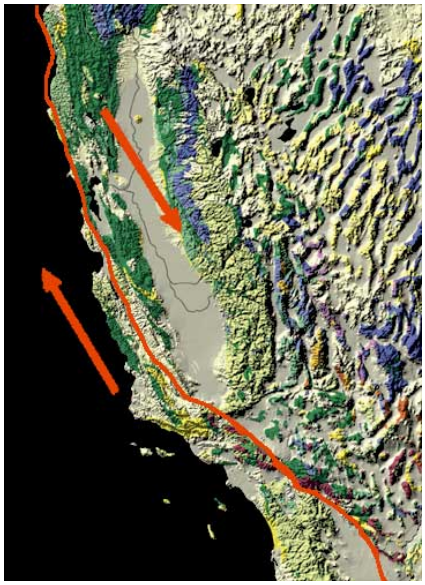


Figure 2.8.2: Map of the San Andreas fault, showing relative motion.

Some transform boundaries produce significant seismic activity, primarily as earthquakes, with very little mountain-building or volcanism. This type of transform boundary may contain a single fault or series of faults, which develop in places where plate tectonic stresses are transferred to the surface. As with other types of active boundaries, if the plates are unable to shear past each other the tectonic forces will continue to build up. If the built-up energy between the plates is suddenly released, the result is an earthquake.

In the eyes of humanity, the most significant transform faults occur within continental plates and have a shearing motion that frequently produces moderate-to-large magnitude earthquakes. Notable examples include the San Andreas Fault in California, Northern and Eastern Anatolian Faults in Turkey, Altyn Tagh Fault in Central Asia, and Alpine Fault in New Zealand.

Transpression and Transtension

Bends along transform faults may create compressional or extensional forces that cause secondary faulting zones. Transpression occurs where there is a component of compression in addition to the shearing motion. These forces build up around the area of the bend, where the opposing plates are restricted from sliding past each other. As the forces continue to build up, they create mountains in the restraining bend around the fault. The Big Bend area, located in the southern part of the San Andreas Fault includes a large area of transpression where many mountains have been built, moved, and even rotated [76].

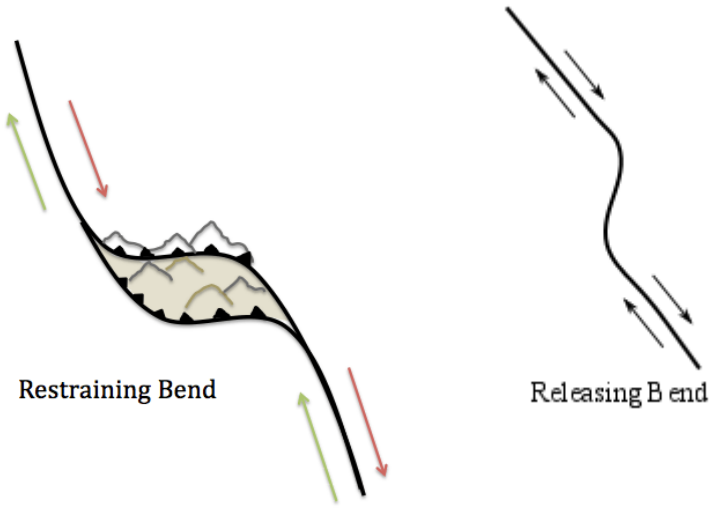


Figure 2.8.3: A transpressional strike-slip fault, causing uplift called a restraining bend. A transtensional strike-slip fault, resulting in a releasing bend.

Transtension zones require a fault that includes a releasing bend, where the plates are being pulled apart by extensional forces. Depressions and sometimes volcanism develop in the releasing bend, along the fault. The Dead Sea found between Israel and Jordan, and the Salton Sea of California are examples of basins formed by transtensional forces.

Piercing Points

The offset is to the left.
via Wikimedia Commons" width="406px" height="277px" src="/@api/deki/files/8067/Wallace_Creek_offset_across_the_San_Andreas_Fault-300x205.png">

Figure 2.8.4: Wallace (dry) Creek on the Carrizo Plain, California. Note as the creek flows from the northern mountainous part of the image, it takes a sharp right (as viewed from the flow of water), then a sharp left. This is caused by the San Andreas Fault cutting roughly perpendicular to the creek, and shifting the location of the creek over time. The fault can be seen about halfway down, trending left to right, as a change in the topography.

When a geological feature is cut by a fault, it is called a piercing point. Piercing points are very useful for recreating past fault movement, especially along transform boundaries. Transform faults are unique because their horizontal motion keeps a geological feature relatively intact, preserving the record of what happened. Other types of faults—normal and reverse —tend to be more destructive, obscuring or destroying these features. The best type of piercing point includes unique patterns that are used to match the parts of a geological feature separated by fault movement. Detailed studies of piercing points show the San Andreas Fault has experienced over 225 km of movement in the last 20 million years, and this movement occurred at three different fault traces.

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2.9: Plate Tectonics- The Wilson Cycle

The Wilson Cycle is named for J. Tuzo Wilson who first described it in 1966 [24], and it outlines the ongoing origin and breakup of supercontinents, such as Pangea and Rodinia [77]. Scientists have determined this cycle has been operating for at least three billion years and possibly earlier.

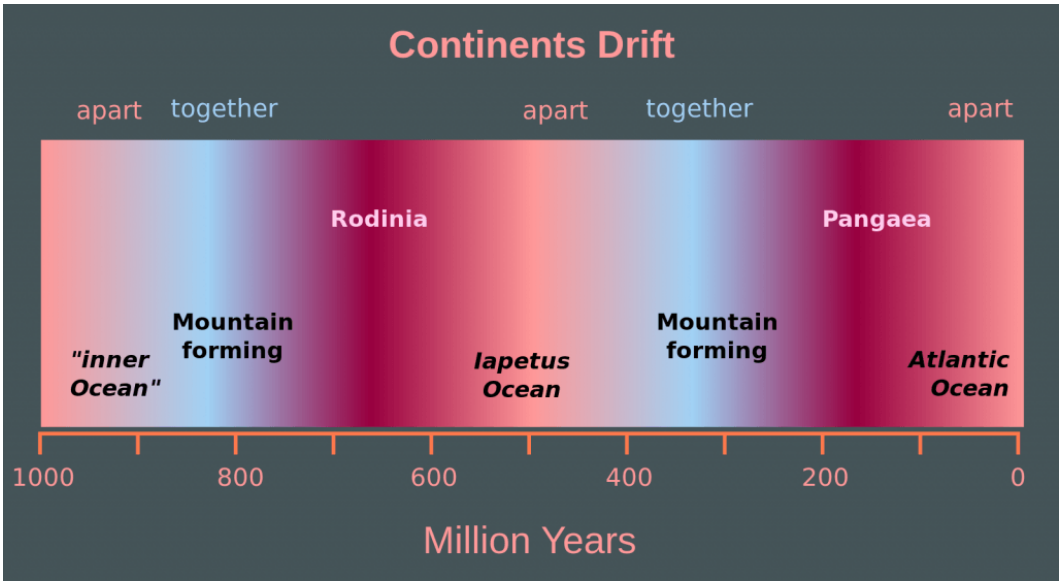


Figure 2.9.1: Diagram of the Wilson Cycle, showing rifting and collision phases.

There are a number of hypotheses about how the Wilson Cycle works. One mechanism proposes that rifting happens because continental plates reflect the heat much better than oceanic plates [78]. When continents congregate together, they reflect more of the Earth's heat back into the mantle, generating more vigorous convection currents that then start the continental rifting process [79].

Some geologists believe mantle plumes are remnants of these periods of increased mantle temperature and convection upwelling and study them for clues about the origin of continental rifting. The mechanism behind how supercontinents are created is still largely a mystery. There are three schools of thought about what continues to drive the continents further apart and eventually bring them together. The ridge-push hypothesis suggests after the initial rifting event, plates continue to be pushed apart by mid-ocean spreading centers and their underlying convection currents. Slab-pull proposes the plates are pulled apart by descending slabs in the subduction zones of the oceanic-continental margins [80]. A third idea, gravitational sliding, attributes the movement to gravitational forces pulling the lithospheric plates down from the elevated mid-ocean ridges and across the underlying asthenosphere [81]. Current evidence seems to support slab pull more than ridge push or gravitational sliding.

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2.10: Plate Tectonics- Hotspots

The Wilson Cycle provides a broad overview of the tectonic plate movement. To analyze plate movement more precisely, scientists study hotspots. First postulated by J. Tuzo Wilson in 1963, a hotspot is an area in the lithospheric plate where molten magma breaks through and creates a volcanic center, islands in the ocean and mountains on land [82]. As the plate moves across the hotspot, the volcano center becomes extinct because it is no longer over an active magma source. Instead, the magma emerges through another area in the plate to create a new active volcano. Over time, the combination of a moving plate and a stationary hotspot creates a chain of islands or mountains. The classic definition of hotspots states they do not move, although recent evidence suggests that there may be exceptions [83].

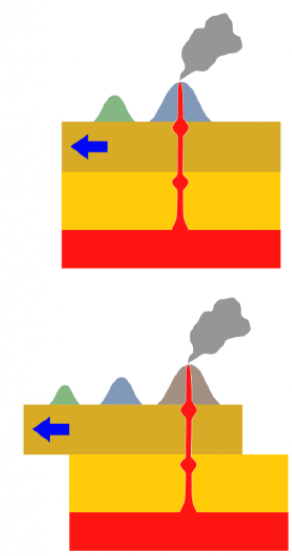


Figure 2.10.1: Diagram showing a non-moving source of magma (mantle plume) and a moving overriding plate.

Hotspots are the only types of volcanism not associated with subduction or rifting zones at plate boundaries; they seem totally disconnected from any plate tectonics processes, such as earthquakes. However, there are relationships between hotspots and plate tectonics. There are several hotspots, current and former, that are believed to have begun at the time of rifting. Also, scientists use the age of volcanic eruptions and shape of the chain to quantify the rate and direction of plate movements relative to the hotspot.

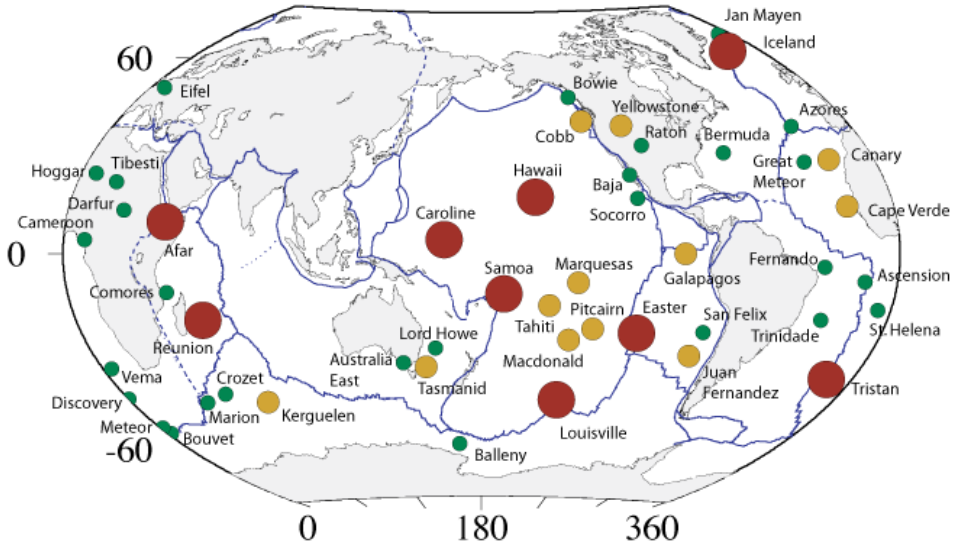


Figure 2.10.2: Map of world hotspots. Larger circles indicate more active hotspots.

Scientists are divided over how magma is generated in hotspots. Some suggest that hotspots originate from super-heated material from as deep as the core that reaches the Earth's crust as a mantle plume [84]. Others argue the molten material that feeds hotspots is sourced from the mantle [85]. Of course, it is difficult to collect data from these deep-Earth features due to the extremely high pressure and temperature [86].

How hotspots are initiated is another highly debated subject. The prevailing mechanism has hotspots starting in divergent boundaries during supercontinent rifting [87]. Scientists have identified a number of current and past hotspots believed to have begun this way. Subducting slabs have also been named as causing mantle plumes and hot-spot volcanism [88]. Some geologists have suggested another geological process not involving plate tectonics may be involved, such as large space objects crashing into the earth [89]. Regardless of how they are formed, dozens are on the Earth. Some well-known examples include the Tahiti Islands, Afar Triangle, Easter Island, Iceland, Galapagos Islands, and the Samoan Islands. The United States is home to two of the largest and best-studied hotspots: Hawaii and Yellowstone.

Hawaiian Hotspot

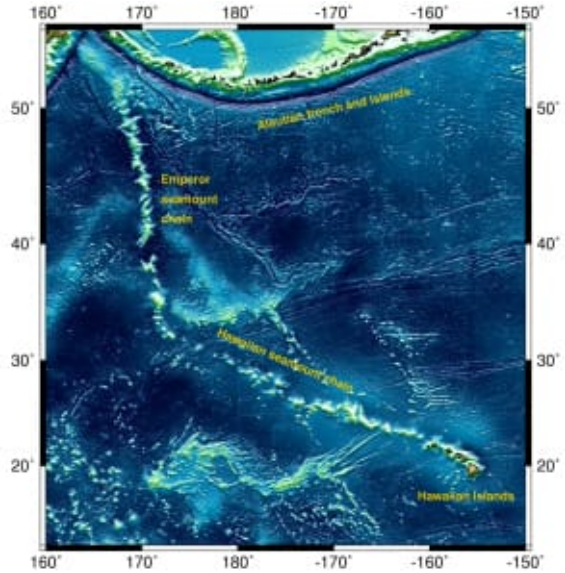


Figure 2.10.3: The Hawaii-Emperor seamount and island chain.

The active volcanoes at the end of the represent one of the most active hotspot sites on earth. Scientific evidence indicates the

Hawaiian hotspot is at least 80 million years old [90]. Geologists believe it is actually much older. However, any rocks with proof of this have been subducted under the ocean floor. The big island of Hawaii sits atop a large mantle plume that marks the active hotspot. The Kilauea volcano is the main vent for this hotspot and has been actively erupting since 1983.

This enormous volcanic island chain, much of which is underwater, stretches across the Pacific for almost 6,000 km. The seamount chain's most striking feature is a sharp 60-degree bend located at the midpoint, which marks a significant change in plate movement direction that occurred 50 million years ago. The change in direction has been more often linked to a plate reconfiguration [91], but also to other things like plume migration [83].

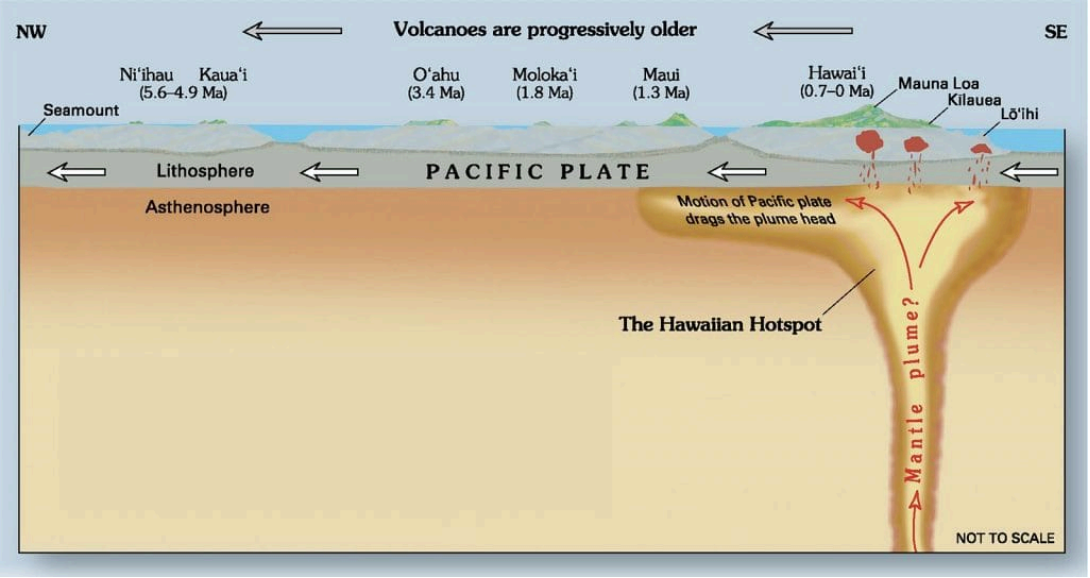


Figure 2.10.4:: Diagram of the Hawaiian hotspot and islands that it formed.

In an attempt to map the Hawaiian mantle plume as far down as the lower mantle [92], scientists have used tomography, a type of three-dimensional seismic imaging. This information—along with other evidence gathered from rock ages, vegetation types, and island size—indicates the oldest islands in the chain are located the furthest away from the active hotspot.

Yellowstone Hotspot

Like the Hawaiian version, the Yellowstone hotspot is formed by magma rising through the lithosphere. What makes it different is this hotspot is located under a thick, continental plate. Hawaii sits on a thin oceanic plate, which is easily breached by magma coming to the surface. At Yellowstone, the thick continental plate presents a much more difficult barrier for magma to penetrate. When it does emerge, the eruptions are generally much more violent. Thankfully they are also less frequent.

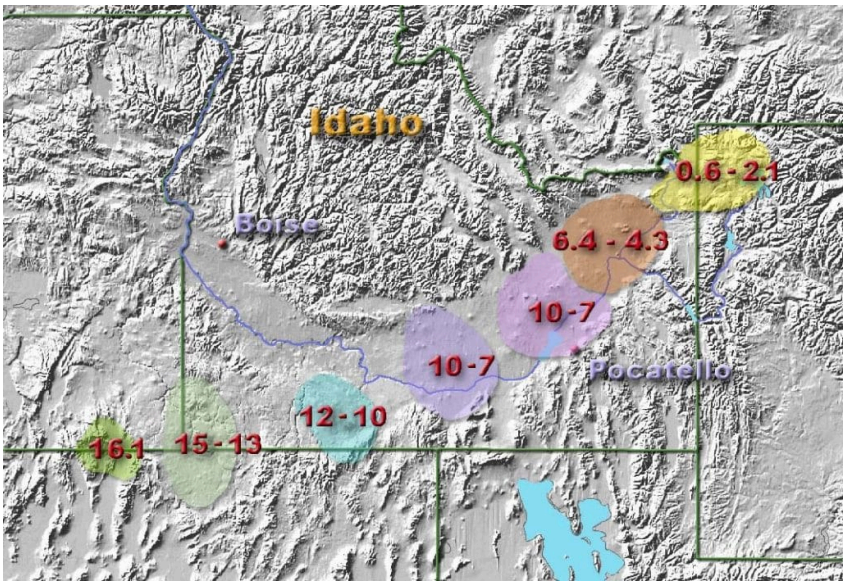


Figure 2.10.5:: The track of the Yellowstone hotspot which shows the age of different eruptions millions of years ago.

Over 15 million years of eruptions by this hotspot have carved a curved path across the western United States. It has been suggested the Yellowstone hotspot is connected to the much older Columbia River flood basalts [93] and even to 70 million-year-old volcanism found in the Yukon region of Canada [94].

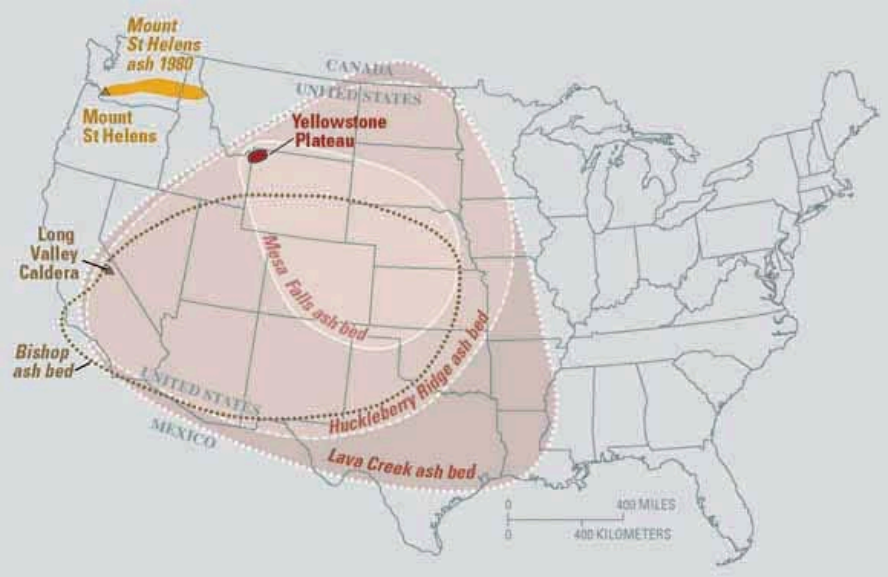


Figure 2.10.6:: Several prominent ash beds found in North America, including three Yellowstone eruptions which are shaded pink (Mesa Falls, Huckleberry Ridge, and Lava Creek), the Bisho Tuff ash bed (brown dashed line), and the modern May 18th, 1980 ash fall (yellow).

The most recent major eruption of this hotspot created the Yellowstone Caldera and Lava Creek tuff formation approximately 631,000 years ago [95]. The eruption threw 1,000 cubic kilometers of ash and magma into the atmosphere, some of which was found as far away as Mississippi. Should the hotspot erupt again, scientists predict it will be another massive event. This would be a calamity reaching far beyond the western United States. These super volcanic eruptions fill the earth's atmosphere with so much gas and ash, they block sunlight from reaching the earth. Not only would this drastically alter climates and environments around the globe, but it could also affect worldwide food production.

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2.11: Plate Tectonics- Continental Margins

Continental margins refer to the region of transition from the land to the deep seafloor, i.e. between continental and oceanic crust. In an **active continental margin**, the boundary between the continent and the ocean is also a tectonic plate boundary, so there is a lot of geological activity around the margin. The west coast of the United States is an example of an active margin, where the coastline corresponds with the boundary between the Pacific and North America Plates. A **passive continental margin** occurs where the transition from land to sea is not associated with a plate boundary. The east coast of the United States is a good example; the plate boundary is located along the mid Atlantic ridge, far from the coast. Passive margins are less geologically active. Figure 2.11.1 shows an idealized passive margin. When examining this figure, and others like it, note that there is significant vertical exaggeration; the depth scale covers approximately 5000 m, while the horizontal scale extends around 300 km. This makes the features look much steeper than they actually are. The bar at the bottom of Figure 2.11.1 shows what a passive margin would look like without this exaggeration; there is a much more gradual transition to depth.

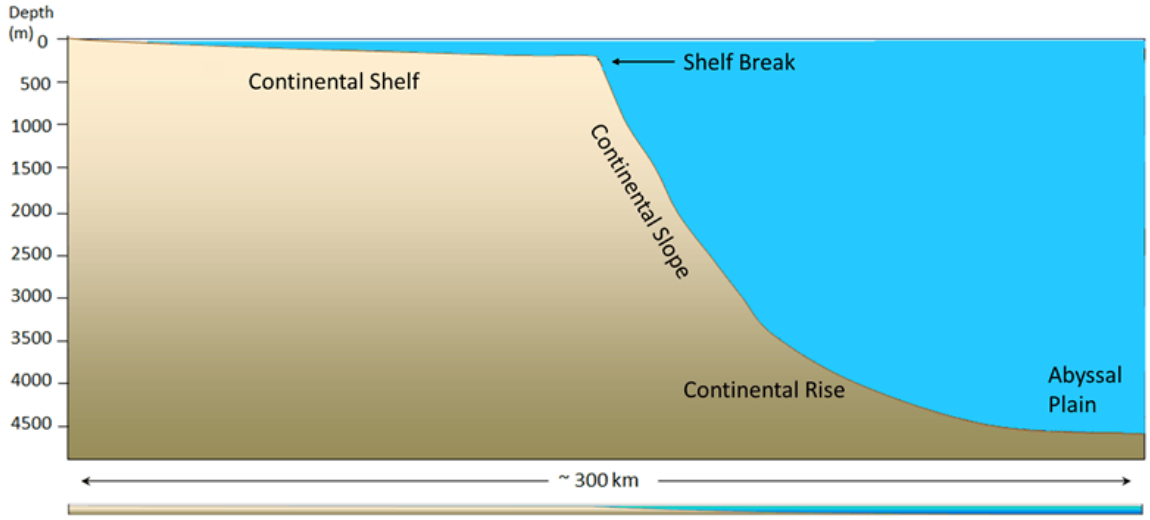


Figure 2.11.1 Features of a passive continental margin (modified by PW from Steven Earle, "Physical Geology").

The **continental shelf** is the shallow, flooded edge of the continent. Geologically the shelf is still part of the continental crust, but it is often overlaid with marine sediments. On average, the shelf extends about 80 km from the coast; some margins have very little shelf, while the Siberian Shelf in the Arctic extends roughly 1500 km. The depth of the shelf generally remains below about 150 m, and the floor of the shelf is fairly flat. The flat topography is the result of changes in sea level; throughout history the shelves have been both submerged and exposed, and as sea level rose and fell, wave action, ice sheets, and other erosional processes smoothed out the shelf surface. Wave action and the movement of sediments over the shelf have continued this smoothing process. Continental shelves only make up about 6% of the ocean's surface area, but they are biologically one of the richest parts of the ocean; their shallow depth prevents nutrients from sinking out, and their proximity to the coast provides significant nutrient input. The continental shelf ends at the **shelf break**, which is the point where the angle of the seafloor begins to get steeper. The shelf break averages about 135 m deep.

After the shelf break, the seafloor takes on a steeper angle (about 4°) as it descends to the deep ocean. This steeper portion of the margin is the **continental slope**, and it extends from the shelf break down to 3000-5000m. In some parts of the ocean, large submarine canyons have been carved into the continental slope; for example, Monterey Canyon in Monterey Bay, California, is a submarine canyon similar in size to the Grand Canyon! These canyons may be carved out by **turbidity currents**, which are essentially landslides of sediment, rocks, and other debris down the face of the slope.

At the bottom of the slope is the **continental rise**. This area represents where the continental crust meets the oceanic crust, as the slope begins to level off to become the deep ocean floor. The rise consists of a thick layer of accumulated sediment coming from the continent, so it is difficult to tell where the slope ends and the rise begins.

After the rise comes the **abyssal plain**, or the deep ocean floor, lying between 4500 – 6000 m. The abyssal plain includes most

of the ocean floor, and is the flattest region on Earth. It is flat due to millions of years of sediment accumulation on the bottom, which buries many bottom features (Figure 2.11.2).

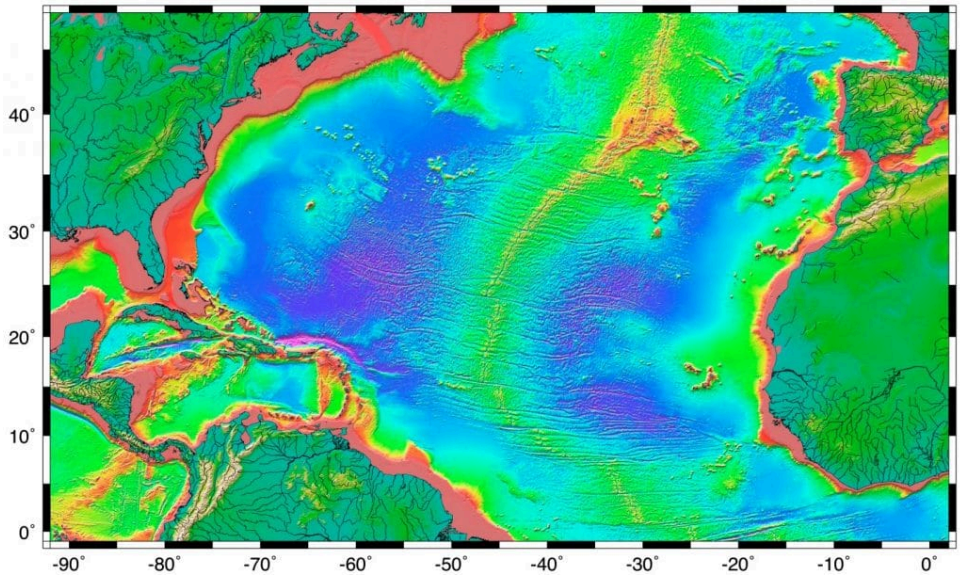


Figure 2.11.2 Topography of the North Atlantic. Shallow continental shelf regions are shown in red, and the abyssal plain is shown in blue. Along the east coast of the United States the continental slope can be seen in green (Steven Earle, "Physical Geology").

Passive margins, as described above, have wide shelves, gentle slopes, and a well-developed rise. Since passive margins are not plate boundaries, they experience long periods of relative stability which can lead to the development of these features. Active margins have similar features to passive margins, but the plate boundary affects the properties of the features. Active margins, like the Pacific coast of North America, have narrower shelves, steeper slopes, and little to no rise, particularly in convergent boundaries. Trenches associated with subduction zones act as sediment traps, preventing the accumulation of a continental rise, and keeping sediments off of the abyssal plains.

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2.12: Measuring Geological Time- The Geological Time Scale

William Smith worked as a surveyor in the coal-mining and canal-building industries in southwestern England in the late 1700s and early 1800s. While doing his work, he had many opportunities to look at the Paleozoic and Mesozoic sedimentary rocks of the region, and he did so in a way that few had done before. Smith noticed the textural similarities and differences between rocks in different locations, and more importantly, he discovered that fossils could be used to correlate rocks of the same age. Smith is credited with formulating the **principle of faunal succession** (the concept that specific types of organisms lived during different time intervals), and he used it to great effect in his monumental project to create a geological map of England and Wales, published in 1815. For more on William Smith, including a large-scale digital copy of the famous map, see the William Smith Wikipedia page.

Inset into Smith's great geological map is a small diagram showing a schematic geological cross-section extending from the Thames estuary of eastern England all the way to the west coast of Wales. Smith shows the sequence of rocks, from the Paleozoic rocks of Wales and western England, through the Mesozoic rocks of central England, to the Cenozoic rocks of the area around London (Figure 2.12.1). Although Smith did not put any dates on these—because he didn't know them—he was aware of the **principle of superposition** (the idea, developed much earlier by the Danish theologian and scientist Nicholas Steno, that young sedimentary rocks form on top of older ones), and so he knew that this diagram represented a stratigraphic column. And because almost every period of the Phanerozoic is represented along that section through Wales and England, it is a primitive geological time scale.

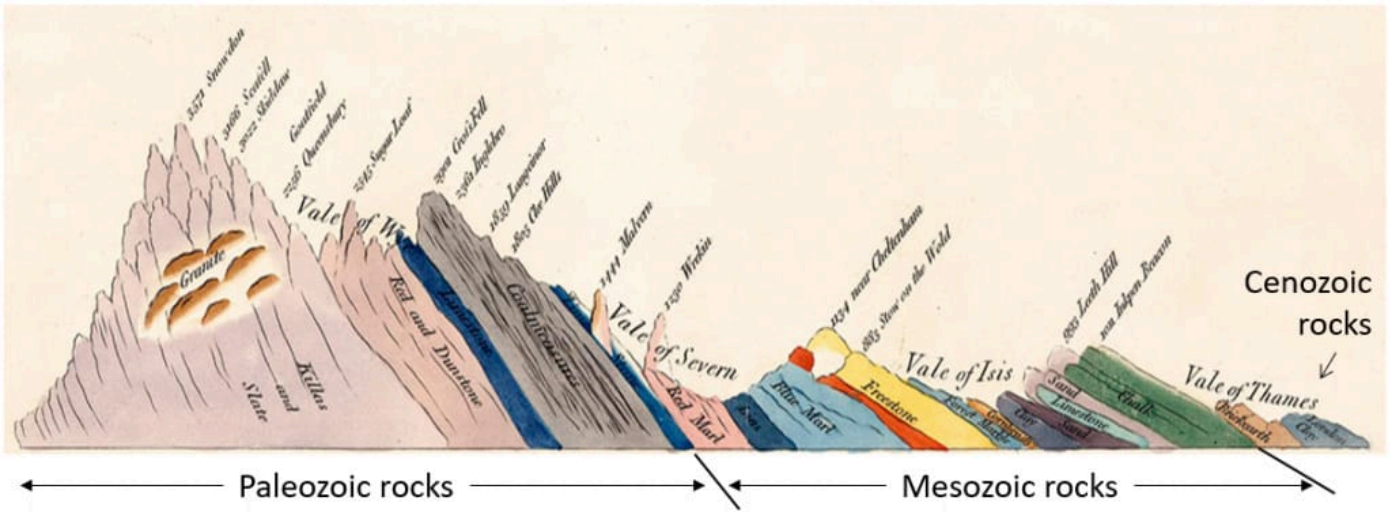


Figure 2.12.1 William Smith's "Sketch of the succession of strata and their relative altitudes," an inset on his geological map of England and Wales (with era names added).

Smith's work set the stage for the naming and ordering of the geological periods, which was initiated around 1820, first by British geologists, and later by other European geologists. Many of the periods are named for places where rocks of that age are found in Europe, such as Cambrian for Cambria (Wales), Devonian for Devon in England, Jurassic for the Jura Mountains in France and Switzerland, and Permian for the Perm region of Russia. Some are named for the type of rock that is common during that age, such as Carboniferous for the coal- and carbonate-bearing rocks of England, and Cretaceous for the chalks of England and France.

The early time scales were only relative because 19th century geologists did not know the ages of the rocks. That information was not available until the development of isotopic dating techniques early in the 20th century.

The geological time scale is currently maintained by the International Commission on Stratigraphy (ICS), which is part of the International Union of Geological Sciences. The time scale is continuously being updated as we learn more about the timing and nature of past geological events. You can view the ICS time scale online. It would be a good idea to print a copy (in color) to put on your wall while you are studying geology.

Geological time has been divided into four eons: Hadean (4570 to 4850 Ma), Archean (3850 to 2500 Ma), Proterozoic (2500 to 540 Ma), and Phanerozoic (540 Ma to present). As shown in Figure 2.12.2, the first three of these represent almost 90% of Earth's

history. The last one, the Phanerozoic (meaning “visible life”), is the time that we are most familiar with because Phanerozoic rocks are the most common on Earth, and they contain evidence of the life forms that we are familiar with to varying degrees.

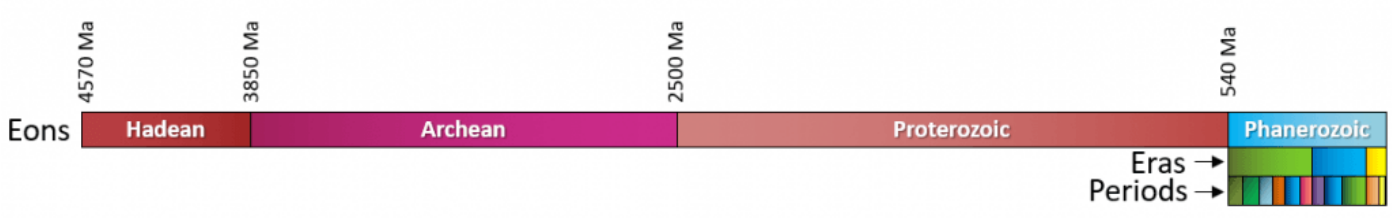


Figure 2.12.2 The four eons of Earth’s history.

The Phanerozoic eon—the past 540 Ma of Earth’s history—is divided into three eras: the Paleozoic (“early life”), the Mesozoic (“middle life”), and the Cenozoic (“new life”), and each of these is divided into a number of periods (Figure 2.12.3). Most of the organisms that we share Earth with evolved at various times during the Phanerozoic.

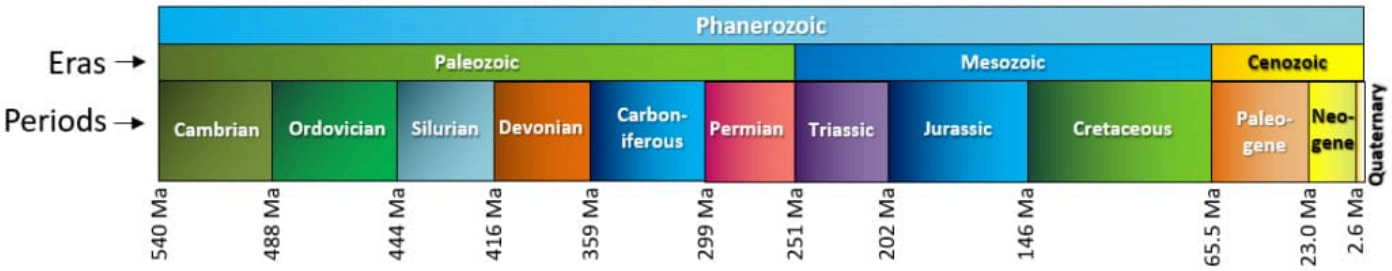


Figure 2.12.3 The eras (middle row) and periods (bottom row) of the Phanerozoic eon.

The Cenozoic era, which represents the past 65.5 Ma, is divided into three periods: Paleogene, Neogene, and Quaternary, and seven epochs (Figure 2.12.4). Dinosaurs became extinct at the start of the Cenozoic, after which birds and mammals radiated to fill the available habitats. Earth was very warm during the early Eocene and has steadily cooled ever since. Glaciers first appeared on Antarctica in the Oligocene and then on Greenland in the Miocene, and covered much of North America and Europe by the Pleistocene. The most recent of the Pleistocene glaciations ended around 11,700 years ago. The current epoch is known as the Holocene. Epochs are further divided into ages (a.k.a. stages), but we won’t be going into that level of detail here.

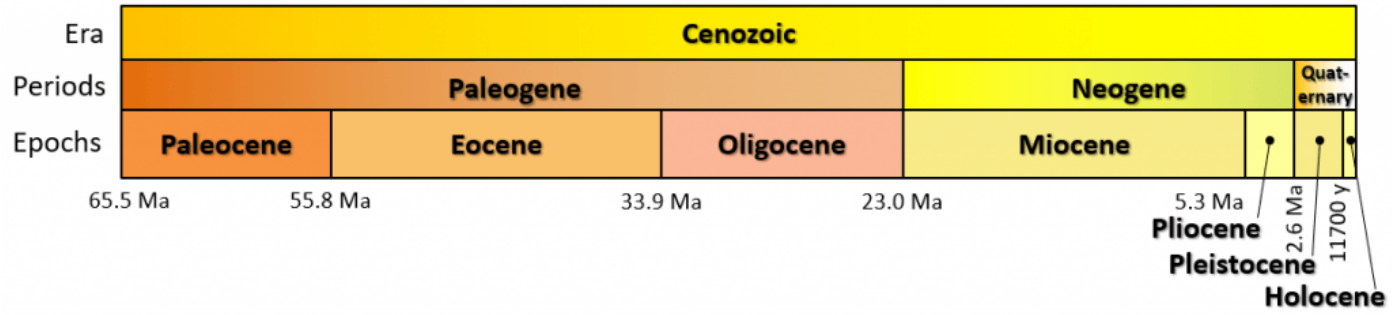


Figure 2.12.4 The periods (middle row) and epochs (bottom row) of the Cenozoic era.

Most of the boundaries between the periods and epochs of the geological time scale have been fixed on the basis of significant changes in the fossil record. For example, as already noted, the boundary between the Cretaceous and the Paleogene coincides exactly with a devastating mass extinction. That’s not a coincidence. The dinosaurs and many other types of organisms went extinct at this time, and the boundary between the two periods marks the division between sedimentary rocks with Cretaceous organisms (including dinosaurs) below, and Paleogene organisms above.

Image Descriptions

Figure 2.12.3 image description: The eras and periods that make up the Phanerozoic Eon.

Era	Period	Time span
Paleozoic	Cambrian	488 to 540 Ma
Paleozoic	Ordovician	488 to 444 Ma
Paleozoic	Silurian	444 to 416 Ma
Paleozoic	Devonian	416 to 359 Ma
Paleozoic	Carboniferous	359 to 299 Ma
Paleozoic	Permian	299 to 251 Ma
Mesozoic	Triassic	251 to 202 Ma
Mesozoic	Jurassic	202 to 146 Ma
Mesozoic	Cretaceous	146 to 65.5 Ma
Cenozoic	Paleogene	65.5 to 23 Ma
Cenozoic	Neogene	23 to 2.6 Ma
Cenozoic	Quaternary	2.6 Ma to present

[Return to Figure 2.12.3]

Figure 2.12.4 image description: The periods and epochs that make up the Cenozoic era.

Period	Epoch	Time span
Paleogene	Paleocene	65.5 to 55.8 Ma
Paleogene	Eocene	55.8 to 33.9 Ma
Paleogene	Oligocene	33.9 to 23.0 Ma
Neogene	Miocene	23.0 to 5.3 Ma
Neogene	Pliocene	5.3 to 2.6 Ma
Quaternary	Pleistocene	2.6 Ma to 11,700 years ago
Quaternary	Holocene	11,700 years ago to the present

[Return to Figure 2.12.4]

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2.13: Measuring Geological Time- Relative Dating Methods

The simplest and most intuitive way of dating geological features is to look at the relationships between them. There are a few simple rules for doing this, some of which we've already looked at in Chapter 6. For example, the principle of superposition states that sedimentary layers are deposited in sequence, and, unless the entire sequence has been turned over by tectonic processes or disrupted by faulting, the layers at the bottom are older than those at the top. The **principle of inclusions** states that any rock fragments that are included in rock must be older than the rock in which they are included. For example, a **xenolith** in an igneous rock or a clast in sedimentary rock must be older than the rock that includes it (Figure 2.13.1).



Figure 2.13.1a A xenolith of diorite incorporated into a basalt lava flow, Mauna Kea volcano, Hawaii. The lava flow took place some time after the diorite cooled, was uplifted, and then eroded. (geological rock hammer head for scale).



Figure 2.13.1b Rip-up clasts of shale embedded in Gabriola Formation sandstone, Gabriola Island, B.C. The pieces of shale were eroded as the sandstone was deposited, so the shale is older than the sandstone.

The **principle of cross-cutting relationships** states that any geological feature that cuts across, or disrupts another feature must be younger than the feature that is disrupted. An example of this is given in Figure 2.13.2, which shows three different sedimentary layers. The lower sandstone layer is disrupted by two **faults**, so we can conclude that the faults are younger than that layer. But the faults do not appear to continue into the coal seam, and they certainly do not continue into the upper sandstone. So

we can infer that coal seam is younger than the faults (because it cuts them off), and of course the upper sandstone is youngest of all, because it lies on top of the coal seam.

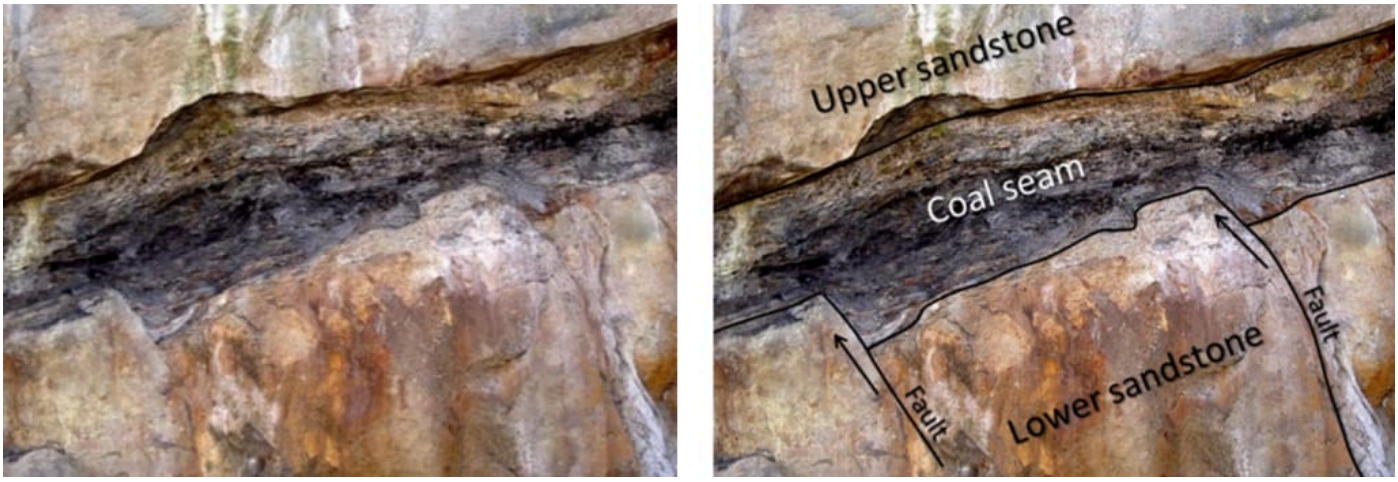


Figure 2.13.2 Superposition and cross-cutting relationships in Cretaceous Nanaimo Group rocks in Nanaimo, B.C. The coal seam is about 50 centimeters thick. The sequence of events is as follows: a) deposition of lower sandstone, b) faulting of lower sandstone, c) deposition of coal seam and d) deposition of upper sandstone.

Exercise 8.1 Cross-Cutting Relationships



Figure 2.13.3

The outcrop shown here (at Horseshoe Bay, B.C.) has three main rock types:

1. Buff/pink felsic intrusive igneous rock present as somewhat irregular masses trending from lower right to upper left
2. Dark grey metamorphosed basalt
3. A 50 centimeters wide light-grey felsic intrusive igneous dyke extending from the lower left to the middle right – offset in several places

Using the principle of cross-cutting relationships outlined above, determine the relative ages of these three rock types.

(The near-vertical stripes are blasting drill holes. The image is about 7 meters across.)

See Appendix 3 for Exercise 8.1 answers.

An **unconformity** represents an interruption in the process of deposition of sedimentary rocks. Recognizing unconformities is important for understanding time relationships in sedimentary sequences. An example of an unconformity is shown in Figure 2.13.4. The Proterozoic rocks of the Grand Canyon Group have been tilted and then eroded to a flat surface prior to deposition of the younger Paleozoic rocks. The difference in time between the youngest of the Proterozoic rocks and the oldest of the Paleozoic rocks is close to 300 million years. Tilting and erosion of the older rocks took place during this time, and if there was any deposition going on in this area, the evidence of it is now gone.



Figure 2.13.4 The great angular unconformity in the Grand Canyon, Arizona. The tilted rocks at the bottom are part of the Proterozoic Grand Canyon Group (aged 825 to 1,250 Ma). The flat-lying rocks at the top are Paleozoic (540 to 250 Ma). The boundary between the two represents a time gap of nearly 300 million years.

There are four types of unconformities, as summarized in Table 8.1, and illustrated in Figure 2.13.5.

Table 8.1 The characteristics of the four types of unconformities

Unconformity Type	Description
Nonconformity	A boundary between non-sedimentary rocks (below) and sedimentary rocks (above)
Angular unconformity	A boundary between two sequences of sedimentary rocks where the underlying ones have been tilted (or folded) and eroded prior to the deposition of the younger ones (as in Figure 2.13.4)
Disconformity	A boundary between two sequences of sedimentary rocks where the underlying ones have been eroded (but not tilted) prior to the deposition of the younger ones (as in Figure 2.13.2)
Paraconformity	A time gap in a sequence of sedimentary rocks that does not show up as an angular unconformity or a disconformity

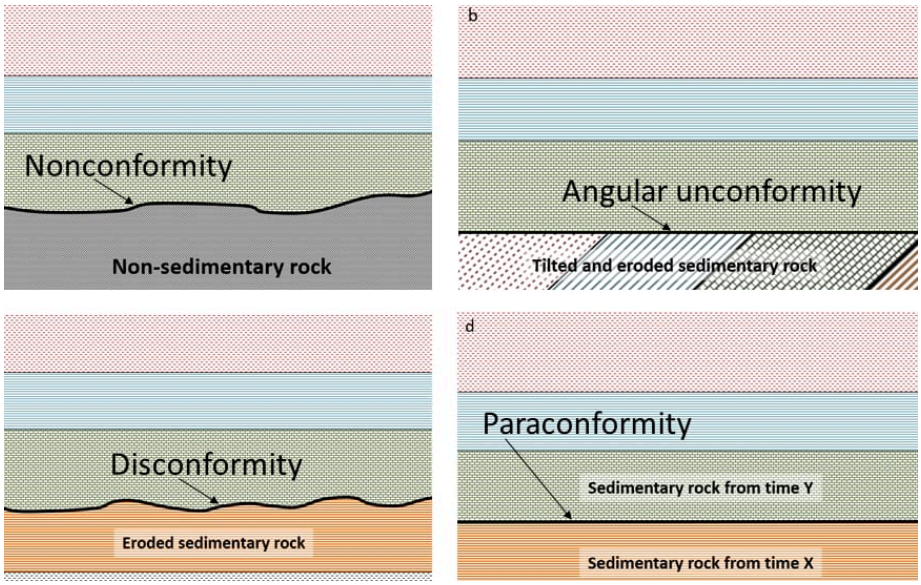


Figure 2.13.5 The four types of unconformities: (a) a nonconformity between older non-sedimentary rock and sedimentary rock, (b) an angular unconformity, (c) a disconformity between layers of sedimentary rock, where the older rock has been eroded but not tilted, and (d) a paraconformity where there is a long period (typically millions of years) of non-deposition between two parallel layers.

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2.14: Measuring Geological Time- Fossils and Evolution



Figure 2.14.1: Archaeopteryx lithographica, specimen displayed at the Museum für Naturkunde in Berlin.

Fossils are any evidence of past life preserved in rocks. They may be actual remains of body parts (rare), impressions of soft body parts, casts and molds of body parts (more common), body parts replaced by mineral (common) or evidence of animal behavior such as footprints and burrows. The body parts of living organisms range from the hard bones and shells of animals, soft cellulose of plants, soft bodies of jellyfish, down to single cells of bacteria and algae. Which body parts can be preserved? The vast majority of life today consists of soft-bodied and/or single-celled organisms, and will not likely be preserved in the geologic record except under unusual conditions. The best environment for preservation is the ocean, yet marine processes can dissolve hard parts and scavenging can reduce or eliminate remains. Thus, even under ideal conditions in the ocean, the likelihood of preservation is quite limited. For terrestrial life, the possibility of remains being buried and preserved is even more limited. In other words, the fossil record is incomplete and records only a small percentage of life that existed. Although incomplete, fossil records are used for stratigraphic correlation, using the Principle of Faunal Succession, and provide a method used for establishing the age of a formation on the Geologic Time Scale.

Types of Preservation

Image of three lobes of an external skeleton like an insect has today.
via Wikimedia Commons" width="204px" height="252px" src="/@api/deki/files/7565/ElrathiakingiUtahWheelerCambrian-243x300.jpg">

Figure 2.14.1: Trilobites had a hard exoskeleton and are often preserved by permineralization.

Remnants or impressions of hard parts, such as a marine clamshell or dinosaur bone, are the most common types of fossils [24]. The original material has almost always been replaced with new minerals that preserve much of the shape of the original shell, bone, or cell. The common types of fossil preservation are actual preservation, permineralization, molds and casts, carbonization, and trace fossils.

Actual preservation is a rare form of fossilization where the original materials or hard parts of the organism are preserved. Preservation of soft-tissue is very rare since these organic materials easily disappear because of bacterial decay [24]. Examples of actual preservation are unaltered biological materials like insects in amber or original minerals like mother-of-pearl on the interior of a shell. Another example is mammoth skin and hair preserved in post-glacial deposits in the Arctic regions [25]. Rare mummification [26] have left fragments of soft tissue, skin, and sometimes even blood vessels of dinosaurs, from which proteins have been isolated and evidence for DNA fragments have been discovered [27].

Mosquito trapped in amber in actal preservation
via Wikimedia Commons" width="388px" height="266px" src="/@api/deki/files/7566/07.19_mosquito_in_amber-300x206.jpg">

Figure 2.14.1: Mosquito preserved in amber

Photo of log of petrified wood showing structures of the original wood
CC BY-SA 2.5], via Wikimedia Commons" width="250px" height="250px" src="/@api/deki/files/7567/07.20_Petrified_forest_log_2_md-300x300.jpg">

Figure 2.14.1: Permineralization in petrified wood

Permineralization occurs when an organism is buried, and then elements in groundwater completely impregnate all spaces within the body, even cells. Soft body structures can be preserved in great detail, but stronger materials like bone and teeth are the most likely to be preserved. Petrified wood is an example of detailed cellulose structures in the wood being preserved. The University of California Berkeley website has more information on permineralization.

Molds and **casts** form when the original material of the organism dissolves and leaves a cavity in the surrounding rock. The shape of this cavity is an external mold. If the mold is subsequently filled with sediments or a mineral precipitate, the organism's external shape is preserved as a cast. Sometimes internal cavities of organisms, such internal casts of clams, snails, and even skulls are preserved as internal casts showing details of soft structures. If the chemistry is right, and burial is rapid, mineral nodules form around soft structures preserving the three-dimensional detail. This is called **authigenic mineralization**.

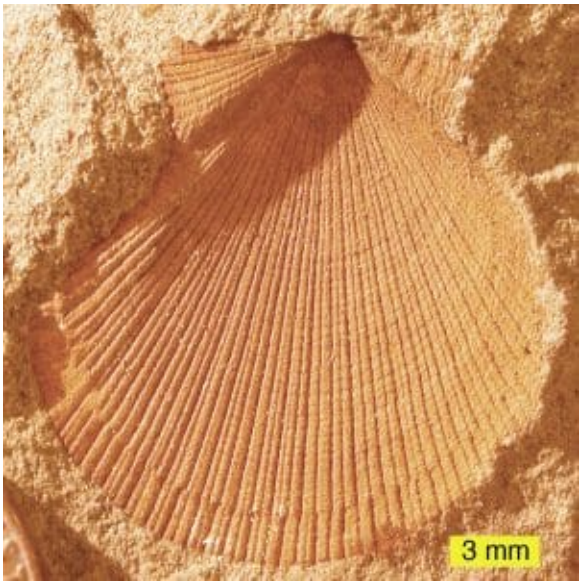


Figure 2.14.1: External mold of a clam

carbonized leaf fossil showing insect damage and vein structure
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Figure 2.14.1: Carbonized leaf

Carbonization occurs when the organic tissues of an organism are compressed, the volatiles are driven out, and everything but the carbon disappears leaving a carbon silhouette of the original organism. Leaf and fern fossils are examples of carbonization [28].

Trace fossils are indirect evidence left behind by an organism, such as burrows and footprints, as it lived its life. **Ichnology** is specifically the study of prehistoric animal tracks. Dinosaur tracks testify to their presence and movement over an area and even provide information about their size, gait, speed, and behavior [29; 30]. Burrows dug by tunneling organisms tell of their presence and mode of life [31; 32; 33]. Other trace fossils include fossilized feces called **coprolites** [34] and stomach stones called **gastroliths** [35] that provide information about diet and habitat.

Tracks of an ancient 5-toed animal
Ballista at the English language Wikipedia [GFDL or CC-BY-SA-3.0], via Wikimedia Commons" width="218px" height="346px" src="/@api/deki/files/7569/07.24_Cheirotherium_prints_possibly_Ticinosuchus-189x300.jpg">

Figure 2.14.1: Footprints of the early crocodile Chirotherium



Figure 2.14.1: Fossil animal droppings (coprolite)

Evolution

Evolution has created a variety of ancient fossils that are important to stratigraphic correlation. (see chapter 7 and Chapter 5) This section is a brief discussion of the process of evolution. The British naturalist Charles Darwin (1809-1882) recognized that life forms evolve into progeny life forms. He proposed **natural selection**—which operated on organisms living under environmental conditions that posed challenges to survival—was the mechanism driving the process of evolution forward.

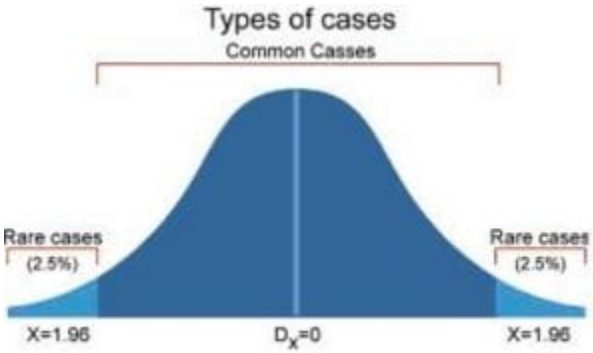


Figure 2.14.1: Variation within a population

The basic classification unit of life is the **species**: a population of organisms that exhibit shared characteristics and are capable of reproducing fertile offspring. For a species to survive, each individual within a particular population is faced with challenges posed by the environment and must survive them long enough to reproduce. Within the natural variations present in the population, there may be individuals possessing characteristics that give them some advantage in facing environmental challenges. These individuals are more likely to reproduce and pass these favored characteristics on to successive generations. If sufficient individuals in a population fail to surmount the challenges of the environment and the population cannot produce enough viable offspring, the species becomes extinct. The average lifespan of a species in the fossil record is around a million years. That life still exists on Earth shows the role and importance of evolution as a natural process in meeting the continual challenges posed by our dynamic Earth. If the inheritance of certain distinctive characteristics is sufficiently favored over time, populations may become genetically isolated from one another, eventually resulting in the evolution of separate species. This genetic isolation may also be caused by a geographic barrier, such as an island surrounded by ocean. This theory of evolution by natural selection was elaborated by Darwin in his book *On the Origin of Species* (see Chapter 1) [36]. Since Darwin's original ideas, technology has provided many tools and mechanisms to study how evolution and speciation take place and this arsenal of tools is growing. Evolution is well beyond the hypothesis stage and is a well-established theory of modern science.

Variation within populations occurs by the natural mixing of genes through sexual reproduction or from naturally occurring mutations. Some of this genetic variation can introduce advantageous characteristics that increase the individual's chances of survival. While some species in the fossil record show little morphological change over time, others show gradual or punctuated changes, within which intermediate forms can be seen.

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2.15: Measuring Geological Time- Fossils and Evolution- Dating Rocks Using Fossils

Geologists get a wide range of information from fossils. They help us to understand evolution and life in general; they provide critical information for understanding depositional environments and changes in Earth's climate; and, of course, they can be used to provide a relative date for rocks and rock formations.

Although the recognition of fossils goes back hundreds of years, the systematic cataloguing and assignment of relative ages to different organisms from the distant past—paleontology—only dates back to the earliest part of the 19th century. The oldest undisputed fossils are from rocks dated around 3.5 Ga, and although fossils this old are tiny, typically poorly preserved and are not useful for dating rocks, they can still provide important information about conditions at the time. The oldest well-understood fossils are from rocks dating back to around 600 Ma, and the sedimentary record from that time forward is rich in fossil remains that provide a detailed record of the history and evolution of life on Earth. However, as anyone who has gone hunting for fossils knows, that does not mean that all sedimentary rocks have visible fossils, or that they are easy to find. Fossils alone cannot provide us with numerical ages of rocks, but over the past century geologists have acquired enough isotopic dates from rocks associated with fossil-bearing rocks (such as igneous dykes cutting through sedimentary layers, or volcanic layers between sedimentary layers) to be able to put specific time limits on most fossils.

A very selective history of life on Earth over the past 600 million years is provided in Figure 2.15.1. The major groups of organisms that we are familiar with evolved between the late Proterozoic and the Cambrian (approximately 600 to 520 Ma). Plants, which evolved in the oceans as green algae, came onto land during the Ordovician (approximately 450 Ma). Insects, which evolved from marine arthropods, came onto land during the Devonian (400 Ma), and amphibians (i.e., vertebrates) came onto land about 50 million years later. By the late Carboniferous, trees had evolved from earlier plants, and reptiles had evolved from amphibians. By the mid-Triassic, dinosaurs and mammals had evolved from very different branches of the reptiles; birds evolved from dinosaurs during the Jurassic. Flowering plants evolved in the late Jurassic or early Cretaceous. The earliest primates evolved from other mammals in the early Paleogene, and the genus *Homo* evolved during the late Neogene (roughly 2.8 Ma).

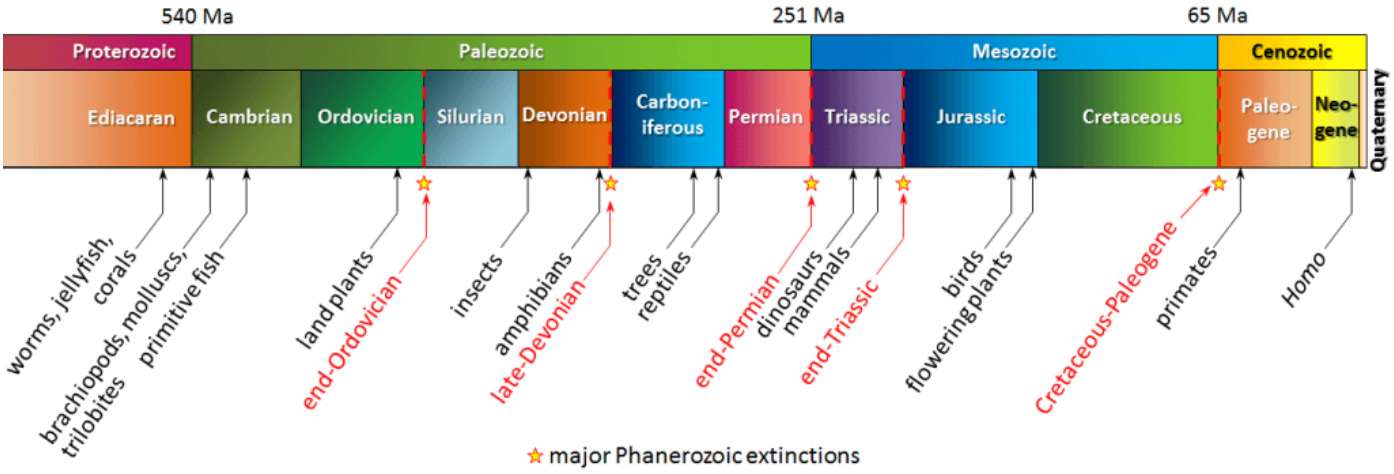


Figure 2.15.1 A summary of life on Earth during the late Proterozoic and the Phanerozoic. The top row shows geological eras, and the lower row shows the periods.

If we understand the sequence of evolution on Earth, we can apply knowledge to determining the relative ages of rocks. This is William Smith's principle of faunal succession, although of course it doesn't just apply to "fauna" (animals); it can also apply to fossils of plants and those of simple organisms.

The Phanerozoic has seen five major extinctions, as indicated in Figure 2.15.1. The most significant of these was at the end of the Permian, which saw the extinction of over 80% of all species and over 90% of all marine species. Most well-known types of organisms were decimated by this event, but only a few became completely extinct, including trilobites. The second most significant extinction was at the Cretaceous-Paleogene boundary (K-Pg, a.k.a. the K-T extinction). At that time, about 75% of marine species disappeared. Again, a few well-known types of organisms disappeared altogether, including the dinosaurs (but not birds) and the pterosaurs. Many other types were badly decimated by that event but survived, and then flourished in the

Paleogene. The K-Pg extinction is thought to have been caused by the impact of a large extraterrestrial body (10 to 15 kilometers across), but it is generally agreed that the other four Phanerozoic extinctions had other causes, although their exact nature is not clearly understood.

As already stated, it is no coincidence that the major extinctions all coincide with boundaries of geological periods and even eras. Geologists have placed most of the divisions of the geological time scale at points in the fossil record where there are major changes in the type of organisms observed, and most of these correspond with minor or major extinctions.

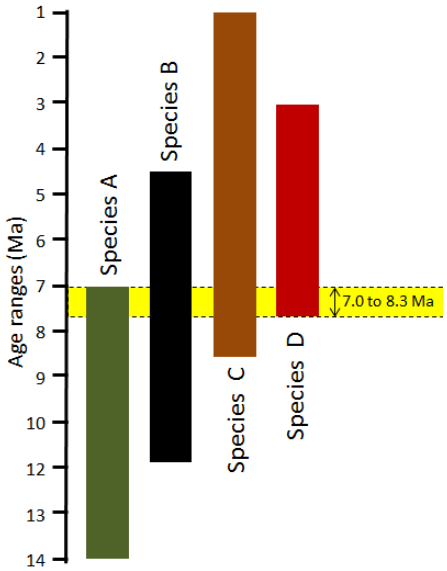


Figure 2.15.2 The application of bracketing to constrain the age of a rock based on several fossils. In this diagram, the colored bars represent the time range during which each of the four species (A, B, C, D) existed on Earth. Although each species lived for several million years, we can narrow down the likely age of the rock to just 700,000 years during which all four species coexisted.

If we can identify a fossil to the species level, or at least to the genus level, and we know the time period when the organism lived, we can assign a range of time to the rock. That range might be several million years because some organisms survived for a very long time. If the rock we are studying has several types of fossils in it, and we can assign time ranges to several of them, we might be able to narrow the time range for the age of the rock considerably. An example of this is given in Figure 2.15.2.

Some organisms survived for a very long time, and are not particularly useful for dating rocks. Sharks, for example, have been around for over 400 million years, and the great white shark has survived for 16 million years, so far. Organisms that lived for relatively short time periods are particularly useful for dating rocks, especially if they were distributed over a wide geographic area and so can be used to compare rocks from different regions. These are known as **index fossils**. There is no specific limit on how short the time span has to be to qualify as an index fossil. Some lived for millions of years, and others for much less than a million years.

Some well-studied groups of organisms qualify as **biozone** fossils because, although the genera and families lived over a long time, each species lived for a relatively short time and can be easily distinguished from others on the basis of specific features. For example, ammonites have a distinctive feature known as the **suture** line—where the internal shell layers that separate the individual chambers (**septae**) meet the outer shell wall, as shown in Figure 2.15.3. These suture lines are sufficiently variable to identify species that can be used to estimate the relative or absolute ages of the rocks in which they are found.



Figure 2.15.3 The septum of an ammonite (white part, left), and the suture lines where the septae meet the outer shell (right).

Foraminifera (small, carbonate-shelled marine organisms that originated during the Triassic and are still around today) are also useful biozone fossils. As shown in Figure 2.15.4, numerous different foraminifera lived during the Cretaceous. Some lasted for over 10 million years, but others for less than 1 million years. If the foraminifera in a rock can be identified to the species level, we can get a good idea of its age.

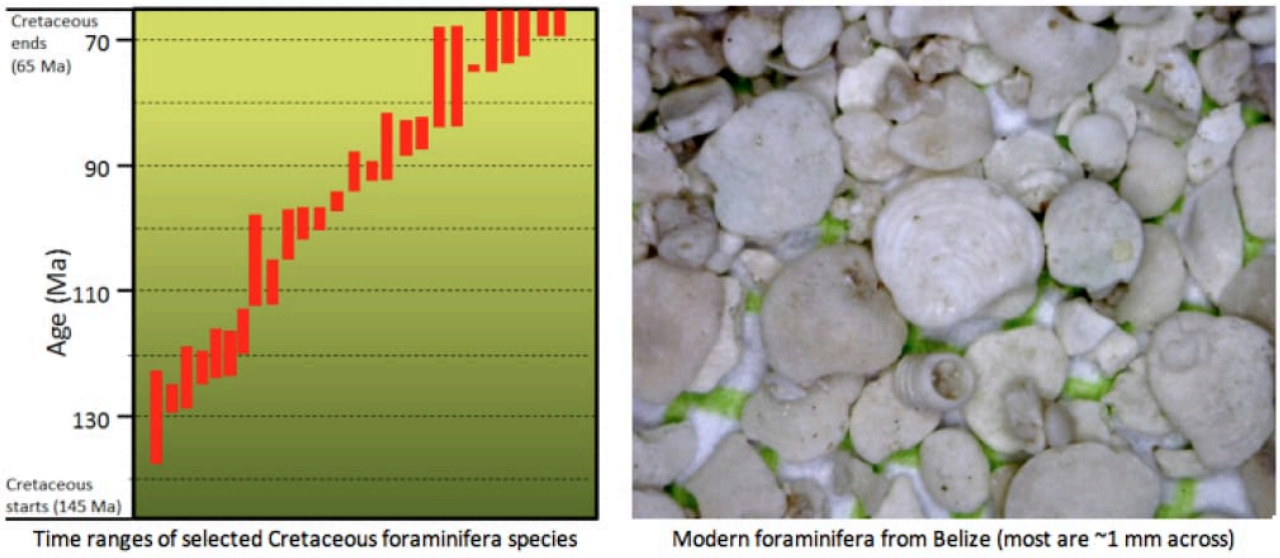


Figure 2.15.4 Time ranges for Cretaceous foraminifera (left). Modern foraminifera from the Ambergris area of Belize (right).

Exercise 8.2 Dating rocks using index fossils

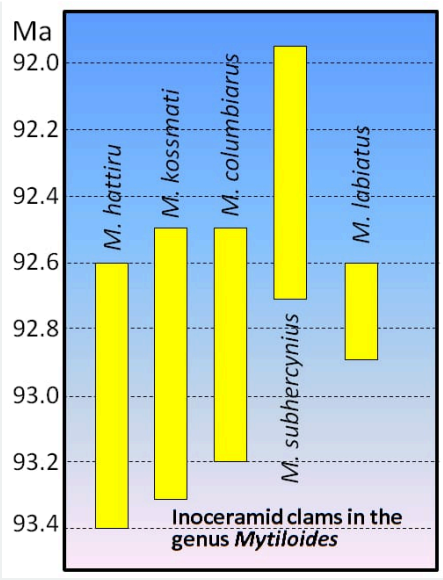


Figure 2.15.5 shows the age ranges for some late Cretaceous inoceramid clams in the genus Mytiloides:

Figure 2.15.5 shows the age ranges for some late Cretaceous inoceramid clams in the genus *Mytiloides:*

- *M. hattiru*, 93.4 to 92.6 Ma
- *M. kossmati*, 93.3 to 92.5 Ma
- *M. columbiarus*, 93.2 to 92.5 Ma
- *M. subhercynius*, 92.7 to 91.9 Ma
- *M. labiatus*, 92.9 to 92.6 Ma

Using the bracketing method described above, determine the possible age range of the rock that these five organisms were found in.

How would that change if *M. subhercynius* was not present in these rocks?

See Appendix 3 for Exercise 8.2 answers.

Image Descriptions

Figure 2.15.1 image description: Life on earth during the late Proterozoic and the Phanerozoic.

Eon	Ero	Period	Life on Earth
Proterozoic		Ediacaran	Worms, jellyfish, corals
Phanerozoic	Paleozoic (540 to 251 Ma)	Cambrian	Brachiopods, molluscs, trilobites, primitive fish
Phanerozoic	Paleozoic (540 to 251 Ma)	Ordovician	Land plants, the period ends with a major extinction
Phanerozoic	Paleozoic (540 to 251 Ma)	Silurian	
Phanerozoic	Paleozoic (540 to 251 Ma)	Devonian	Insects, amphibians, the period ends with a major extinction
Phanerozoic	Paleozoic (540 to 251 Ma)	Carboniferous	Trees, reptiles
Phanerozoic	Paleozoic (540 to 251 Ma)	Permian	The period ends with a major extinction
Phanerozoic	Mesozoic (251 to 65 Ma)	Triassic	Dinosaurs, mammals, the period ends with a major extinction
Phanerozoic	Mesozoic (251 to 65 Ma)	Jurrassic	Birds, flowering plants

Eon	Ero	Period	Life on Earth
Phanerozoic	Mesozoic (251 to 65 Ma)	Cretaceous	The period ends with a major extinction
Phanerozoic	Cenozoic, (65 Ma to present)	Paleogene	Primates
Phanerozoic	Cenozoic, (65 Ma to present)	Neogene	*Homo*
Phanerozoic	Cenozoic, (65 Ma to present)	Quaternary	

[Return to Figure 2.15.1]

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2.16: Measuring Geological Time- Isotopic Dating Methods

Originally fossils only provided us with relative ages because, although early paleontologists understood biological succession, they did not know the absolute ages of the different organisms. It was only in the early part of the 20th century, when isotopic dating methods were first applied, that it became possible to discover the absolute ages of the rocks containing fossils. In most cases, we cannot use isotopic techniques to directly date fossils or the sedimentary rocks they are found in, but we can constrain their ages by dating igneous rocks that cut across sedimentary rocks, or volcanic layers that lie within sedimentary layers.

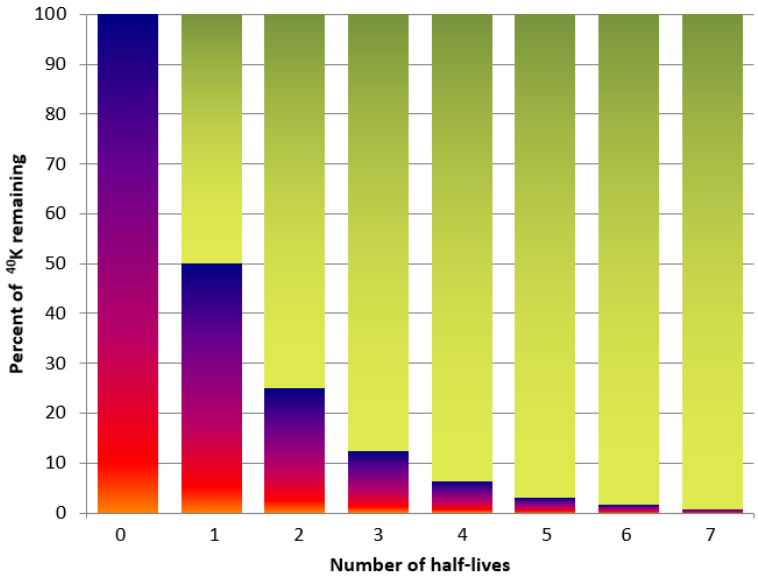


Figure 2.16.1 The decay of ^{40}K over time. Each half-life is 1.3 billion years, so after 3.9 billion years (three half-lives) 12.5% of the original ^{40}K will remain. The red-blue bars represent ^{40}K and the green-yellow bars represent ^{40}Ar.

Isotopic dating of rocks, or the minerals in them, is based on the fact that we know the decay rates of certain unstable **isotopes** of elements and that these rates have been constant over geological time. It is also based on the premise that when the atoms of an element decay within a mineral or a rock, they stay there and don't escape to the surrounding rock, water, or air. One of the isotope pairs widely used in geology is the decay of ^{40}K to ^{40}Ar (potassium-40 to argon-40). ^{40}K is a radioactive isotope of potassium that is present in very small amounts in all minerals that have potassium in them. It has a half-life of 1.3 billion years, meaning that over a period of 1.3 Ga one-half of the ^{40}K atoms in a mineral or rock will decay to ^{40}Ar, and over the next 1.3 Ga one-half of the remaining atoms will decay, and so on (Figure 2.16.1).

In order to use the K-Ar dating technique, we need to have an igneous or metamorphic rock that includes a potassium-bearing mineral. One good example is granite, which normally has some potassium feldspar (Figure 2.16.2). Feldspar does not have any argon in it when it forms. Over time, the ^{40}K in the feldspar decays to ^{40}Ar. Argon is a gas and the atoms of ^{40}Ar remain embedded within the crystal, unless the rock is subjected to high temperatures after it forms. The sample must be analyzed using a very sensitive mass-spectrometer, which can detect the differences between the masses of atoms, and can therefore distinguish between ^{40}K and the much more abundant ^{39}K. Biotite and hornblende are also commonly used for K-Ar dating.

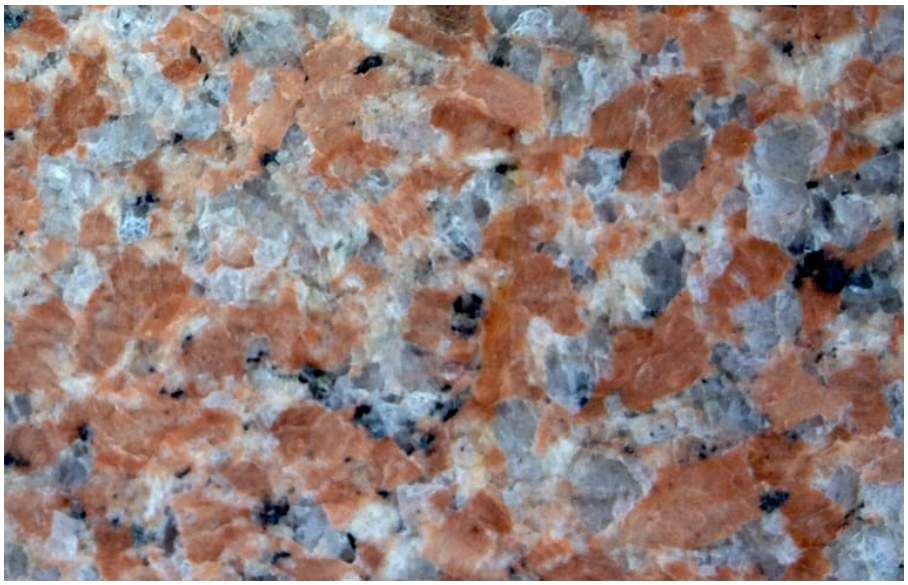


Figure 2.16.2 Crystals of potassium feldspar (pink) in a granitic rock are candidates for isotopic dating using the K-Ar method because they contained potassium and no argon when they formed.

Why can't we use isotopic dating techniques to accurately date sedimentary rocks?



Figure 2.16.3

An important assumption that we have to be able to make when using isotopic dating is that when the rock formed none of the daughter isotope was present (e.g., ^{40}Ar in the case of the K-Ar method). A clastic sedimentary rock is made up of older rock and mineral fragments, and when the rock forms it is almost certain that all of the fragments already have daughter isotopes in them. Furthermore, in almost all cases, the fragments have come from a range of source rocks that all formed at different times. If we dated a number of individual grains in the sedimentary rock, we would likely get a range of different dates, all older than the age of the rock. That could be useful information, but it would not provide an accurate date for the rock in question.

It might be possible to directly date some chemical sedimentary rocks isotopically, but there are no useful isotopes that can be used on old chemical sedimentary rocks. Radiocarbon dating can be used on sediments or sedimentary rocks that contain carbon, but it cannot be used on materials older than about 60 ka.

K-Ar is just one of many isotope-pairs that are useful for dating geological materials. Some of the other important pairs are listed in Table 8.2, along with the age ranges that they apply to and some comments on their applications. When radiometric techniques are applied to metamorphic rocks, the results normally tell us the date of metamorphism, not the date when the parent rock

formed.

Table 8.2 A few of the isotope systems that are widely used for dating geological materials

[Skip Table]

Isotope System	Half-Life	Useful Range	Comments
Potassium-argon	1.3 Ga	10 Ka to 4.57 Ga	Widely applicable because most rocks have some potassium
Uranium-lead	4.5 Ga	1 Ma to 4.57 Ga	The rock must have uranium-bearing minerals, but most have enough.
Rubidium-strontium	47 Ga	10 Ma to 4.57 Ga	Less precision than other methods at old dates
Carbon-nitrogen (a.k.a. radiocarbon dating)	5,730 years	100 to 60,000 years	Sample must contain wood, bone, or carbonate minerals; can be applied to young sediments

Exercise 8.3 Isotopic dating

Assume that a feldspar crystal from the granite shown in Figure 2.16.2 was analyzed for ^{40}K and ^{40}Ar. The proportion of ^{40}K remaining is 0.91. Using the decay curve shown on the graph below, estimate the age of the rock.

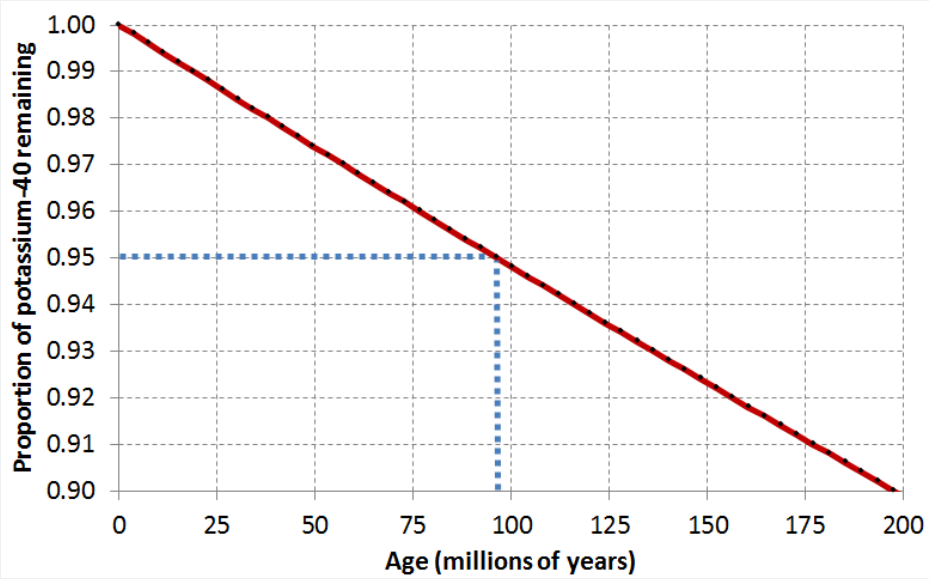


Figure 2.16.4

An example is provided (in blue) for a ^{40}K proportion of 0.95, which is equivalent to an age of approximately 96 Ma. This is determined by drawing a horizontal line from 0.95 to the decay curve line, and then a vertical line from there to the time axis.

See Appendix 3 for Exercise 8.3 answers.

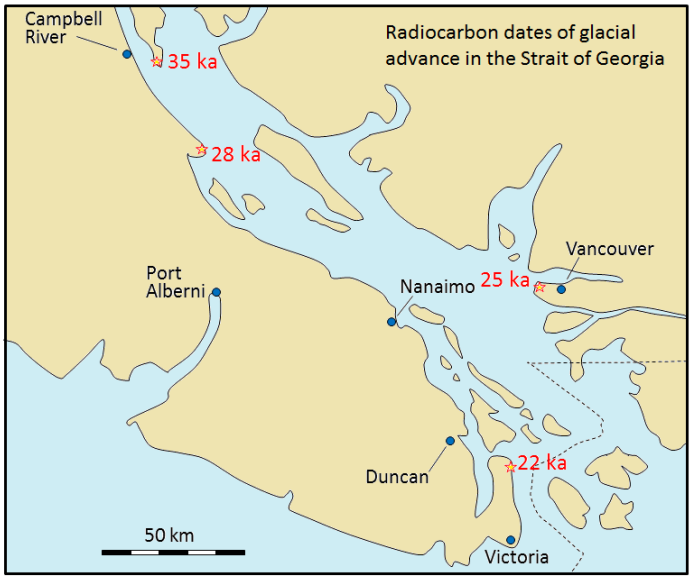


Figure 2.16.5 Radiocarbon dates on wood fragments in glacial sediments in the Strait of Georgia.

Radiocarbon dating (using ^{14}C) can be applied to many geological materials, including sediments and sedimentary rocks, but the materials in question must be younger than 60 ka. Fragments of wood incorporated into young sediments are good candidates for carbon dating, and this technique has been used widely in studies involving late Pleistocene glaciers and glacial sediments. An example is shown in Figure 2.16.5; radiocarbon dates from wood fragments in glacial sediments have been used to estimate the timing of the last glacial advance along the Strait of Georgia. It is evident that the ice-front of the major glacier that occupied the Strait of Georgia was near to Campbell River at around 35 ka, near to Nanaimo and Vancouver at about 25 ka, and had reached the Victoria area by around 22 ka.

Over the past decade there has been increasing use of U-Pb dating to study sedimentary rocks, not necessarily to find out the age of the rock, but to discover something about its history and origins. All clastic sedimentary rocks contain some tiny clasts of the silicate mineral zircon ($ZrSiO_4$), derived from the weathering of the sediment parent rocks. Zircon always has some uranium in it (but no lead) so it is a good candidate for U-Pb dating, and it isn't too difficult to separate the grains of zircon from the other grains in a sandstone. The procedure is to isolate a few hundred tiny zircons from a rock sample, and then carry out U-Pb dating on each one of them. An example of the types of results obtained are shown on Figure 2.16.6. All of the samples are from Nanaimo Gp. rocks on Vancouver Island and nearby Salt Spring Island.

The three samples from Vancouver Island have zircons aged around 90 Ma, 118 Ma and 150 Ma. The Salt Spring Island sample has some zircons aged around 150 Ma, but most are much older, at 200 Ma and 340 to 360 Ma. It is interpreted that the younger zircons (90 to 150 Ma) are mostly derived from granitic rocks in the Coast Range, while the older ones (>200 Ma) are from older rocks on Vancouver Island (Huang, 2018).

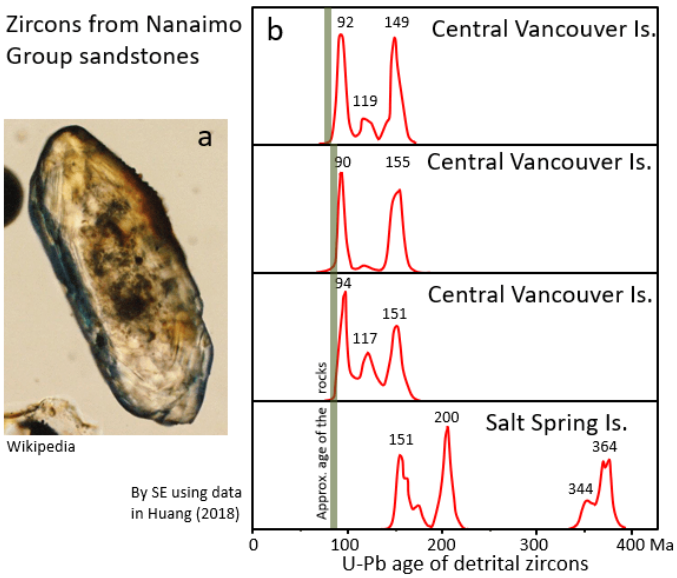


Figure 2.16.6 U-Pb dates for zircon samples from the Nanaimo Gp. (after Krause, 2018) a: a typical zircon clast (this one is about 1/4 mm long). b: plots of zircon ages for 4 sandstone samples.

Image Descriptions

Figure 2.16.1 image description: Decay of 40K over time.

Number of half-lives	Percent of 40K remaining	Percent of 40Ar
0	100	0
1	50	50
2	25	75
3	12.5	87.5
4	6.25	93.75
5	3.125	96.875
6	1.5625	98.4375
7	0.78125	99.21875

[Return to Figure 2.16.1]

Figure 2.16.4 image description: isotopic dating graph

Proportion of Potassium-40 remaining	Age (in millions of Years)
1.00	0
0.99	19
0.98	37
0.97	55
0.96	75
0.95	96
0.94	114
0.93	134

Proportion of Potassium-40 remaining	Age (in millions of Years)
0.92	156
0.91	175
0.90	194

[Return to Figure 2.16.4]

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- Figure 2.16.5: © Steven Earle. CC BY. From J. Clague, 1976, Quadra Sand and its relation to late Wisconsin glaciation of southeast British Columbia, Can. J. Earth Sciences, V. 13, p. 803-815.
- Figure 2.16.6 (left): "Zircon microscope" © Chd. CC BY-SA.
- Figure 2.16.6b: © Steven Earle. CC BY. From data in Huang, C, 2018, Refining the chronostratigraphy of the lower Nanaimo Group, Vancouver Island, Canada, using Detrital Zircon Geochronology, MSc thesis, Department of Earth Science, Simon Fraser University, 74 p.

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2.17: Measuring Geological Time- Other Dating Methods

There are numerous other techniques for dating geological materials, but we will examine just two of them here: tree-ring dating (i.e., dendrochronology) and dating based on the record of reversals of Earth's magnetic field.

Dendrochronology can be applied to dating very young geological materials based on reference records of tree-ring growth going back many millennia. The longest such records can take us back to 25 ka, to the height of the last glaciation. One of the advantages of dendrochronology is that, providing reliable reference records are available, the technique can be used to date events to the nearest year.

Dendrochronology has been used to date the last major subduction-zone earthquake on the coast of B.C., Washington, and Oregon. When large earthquakes strike in this setting, there is a tendency for some coastal areas to subside by one or two meters. Seawater then rushes in, flooding coastal flats and killing trees and other vegetation within a few months. There are at least four locations along the coast of Washington that have such dead trees (and probably many more in other areas). Wood samples from these trees have been studied and the ring patterns have been compared with patterns from old living trees in the region (Figure 2.17.1).

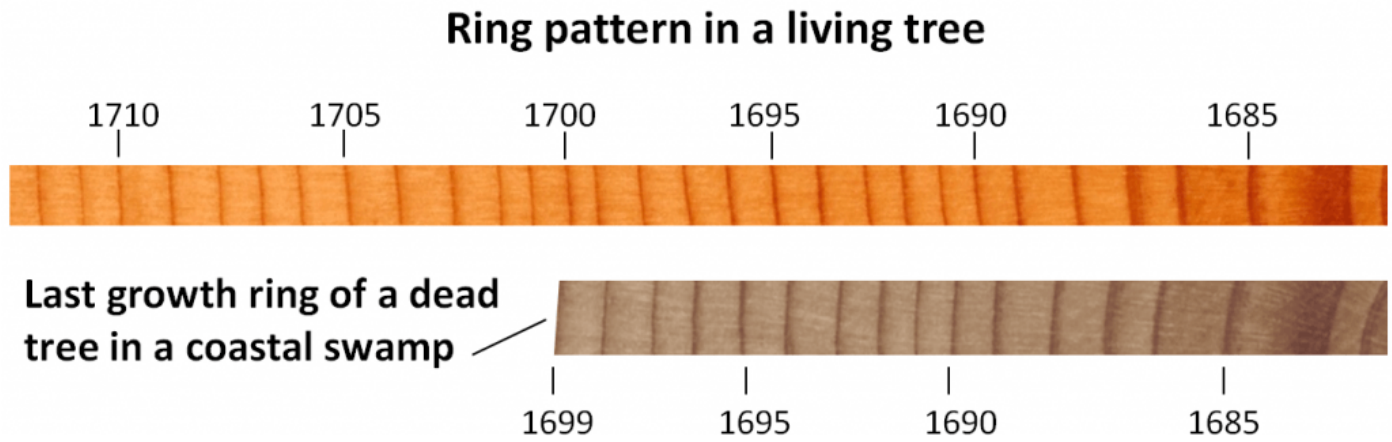


Figure 2.17.1 Example of tree-ring dating of dead trees.

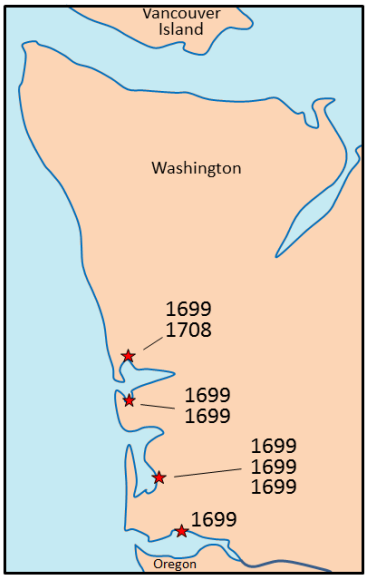


Figure 2.17.2 Sites in Washington where dead trees are present in coastal flats. The outermost wood of eight trees was dated using dendrochronology, and of these, seven died during the year 1699, suggesting that the land near to the coast was inundated by water at that time.

At all of the locations studied, the trees were found to have died either in the year 1699, or very shortly thereafter (Figure 2.17.2). On the basis of these results, it was concluded that a major earthquake took place in this region sometime between the end of growing season in 1699 and the beginning of the growing season in 1700. Evidence from a major tsunami that struck Japan on January 27, 1700, narrowed the timing of the earthquake to sometime in the evening of January 26, 1700. For more information, see The 1700 Juan de Fuca Earthquake.

Changes in Earth's magnetic field can also be used to date events in geologic history. The magnetic field makes compasses point toward the North Pole, but, as we'll see in Chapter 10, this hasn't always been the case. At various times in the past, Earth's magnetic field has reversed itself completely, and during those times a compass would have pointed to the South Pole. By studying magnetism in volcanic rocks that have been dated isotopically, geologists have been able to delineate the chronology of magnetic field reversals going back to 250 Ma. About 5 million years of this record is shown in Figure 2.17.3, where the black bands represent periods of normal magnetism ("normal" meaning similar to the current magnetic field) and the white bands represent periods of reversed magnetism. These periods of consistent magnetic polarity are given names to make them easier to reference. The current normal magnetic field, known as Brunhes, has lasted for the past 780,000 years. Prior to that there was a short reversed period and then a short normal period known as Jaramillo.

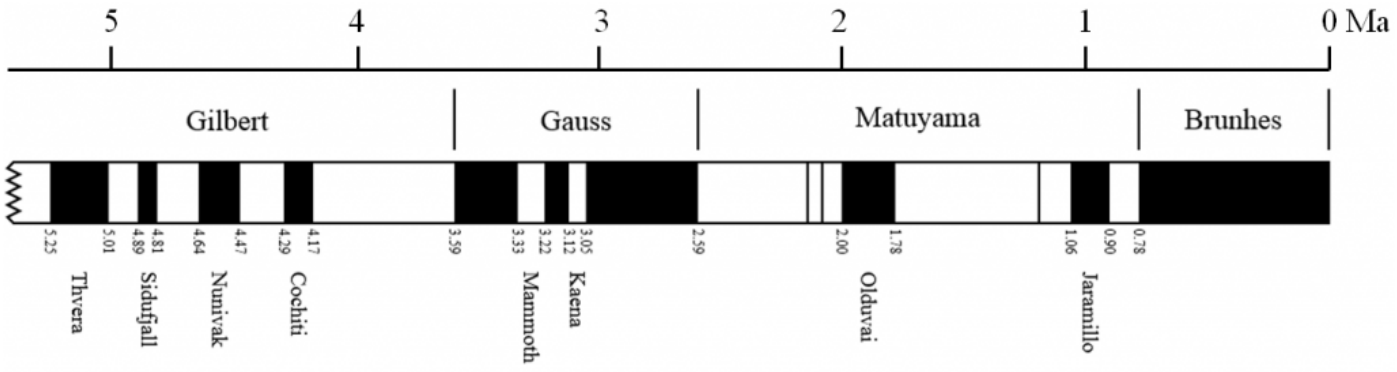


Figure 2.17.3 The last 5 Ma of magnetic field reversals.

Oceanic crust becomes magnetized by the magnetic field that exists as the crust forms from magma. As it cools, tiny crystals of magnetite that form within the magma become aligned with the existing magnetic field and then remain that way after all of the rock has hardened, as shown in Figure 2.17.4. Crust that is forming today is being magnetized in a "normal" sense, but crust that formed 780,000 to 900,000 years ago, in the interval between the Brunhes and Jaramillo normal periods, was magnetized in the "reversed" sense.

Chapter 9 has a discussion of Earth's magnetic field, including where and how it is generated and why its polarity changes periodically.

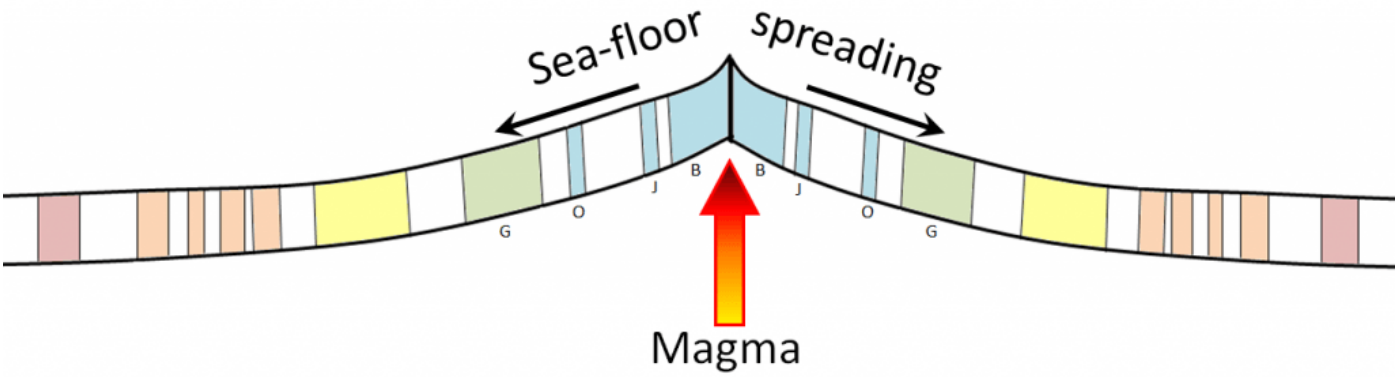


Figure 2.17.4 Depiction of the formation of magnetized oceanic crust at a spreading ridge. Coloured bars represent periods of normal magnetism, and the small capital letters denote the Brunhes, Jaramillio, Olduvai, and Gauss normal magnetic periods (see Figure 2.17.2).

Magnetic chronology can be used as a dating technique because we can measure the magnetic field of rocks using a magnetometer in a lab, or of entire regions by towing a magnetometer behind a ship or an airplane. For example, the Juan de Fuca Plate, which lies off of the west coast of B.C., Washington, and Oregon, is being and has been formed along the Juan de Fuca spreading ridge (Figure 2.17.5). The parts of the plate that are still close to the ridge have normal magnetism, while parts

that are farther away (and formed much earlier) have either normal or reversed magnetism, depending on when the rock formed. By carefully matching the sea-floor magnetic stripes with the known magnetic chronology, we can determine the age at any point on the plate. We can see, for example, that the oldest part of the Juan de Fuca Plate that has not subducted (off the coast of Oregon) is just over 8 million years old, while the part that is subducting underneath Vancouver Island is between 0 and about 6 million years old.

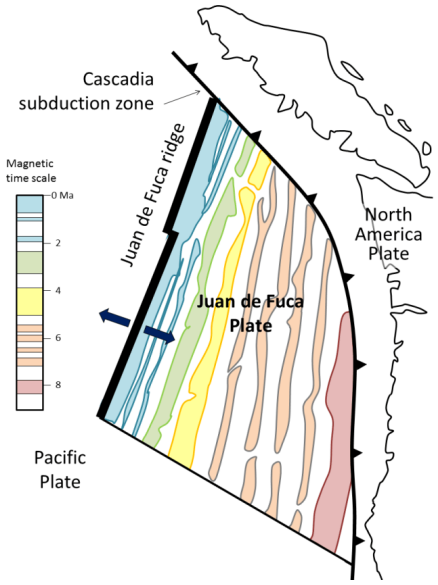


Figure 2.17.5 The pattern of magnetism within the area of the Juan de Fuca Plate, off the west coast of North America. The colored shapes represent parts of the sea floor that have normal magnetism, and the magnetic time scale is shown using the same colors. The blue bands represent Brunhes, Jaramillo, and Olduvai; the green represents Gauss; and so on. (Note that in this diagram, sea-floor magnetism is only shown for the Juan de Fuca Plate, although similar patterns exist on the Pacific Plate.)

Exercise 8.4 Magnetic dating

The fact that magnetic intervals can only be either *normal* or *reversed* places significant limits on the applicability of magnetic dating. If we find a rock with normal magnetism, we can't know which normal magnetic interval it represents, unless we have some other information.

Using Figure 2.17.3 for reference, determine the age of a rock with normal magnetism that has been found to be between 1.5 and 2.0 Ma based on fossil evidence.

How about a rock that is limited to 2.6 to 3.2 Ma by fossils and has reversed magnetism?

See Appendix 3 for Exercise 8.4 answers.

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- Figure 2.17.3: "Geomagnetic polarity late Cenozoic" by the USGS. Adapted by Steven Earle. Public domain.

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2.18: Measuring Geological Time- Understanding Geological Time

It's one thing to know the facts about geological time—how long it is, how we measure it, how we divide it up, and what we call the various periods and epochs—but it is quite another to really understand geological time. The problem is that our lives are short and our memories are even shorter. Our experiences span only a few decades, so we really don't have a way of knowing what 11,700 years means. What's more, it's hard for us to understand how 11,700 years differs from 65.5 million years, or even from 1.8 billion years. It's not that we can't comprehend what the numbers mean—we can all get that figured out with a bit of practice—but even if we do know the numerical meaning of 65.5 Ma, we can't really appreciate how long ago it was.

You may be wondering why it's so important to really "understand" geological time. There are some very good reasons. One is so that we can fully understand how geological processes that seem impossibly slow can produce anything of consequence. For example, we are familiar with the concept of driving from one major city to another: a journey of several hours at around 100 kilometers per hour. Continents move toward each other at rates of a fraction of a millimetre per day, or something in the order of 0.000000001 kilometers per hour, and yet, at this impossibly slow rate (try walking at that speed!), they can move thousands of kilometers. Sediments typically accumulate at even slower rates—less than a millimetre per year—but still they are thick enough to be thrust up into monumental mountains and carved into breathtaking canyons.

Another reason is that for our survival on this planet, we need to understand issues like extinction of endangered species and **anthropogenic** (human-caused) climate change. Some people, who don't understand geological time, are quick to say that the climate has changed in the past, and that what is happening now is no different. And it certainly has changed in the past—many times. For example, from the Eocene (50 Ma) to the present day, Earth's climate cooled by about 12°C. That's a huge change that ranks up there with many of the important climate changes of the distant past, and yet the rate of change over that time was only 0.000024°C/century. Anthropogenic climate change has been 1.1°C over the past century,[1]; that is 45,800 times faster than the rate of natural climate change since the Eocene!

One way to wrap your mind around geological time is to put it into the perspective of single year, because we all know how long it is from one birthday to the next. At that rate, each hour of the year is equivalent to approximately 500,000 years, and each day is equivalent to 12.5 million years.

If all of geological time is compressed down to a single year, Earth formed on January 1, and the first life forms evolved in late March (roughly 3,500 Ma). The first large life forms appeared on November 13 (roughly 600 Ma), plants appeared on land around November 24, and amphibians on December 3. Reptiles evolved from amphibians during the first week of December and dinosaurs and early mammals evolved from reptiles by December 13, but the dinosaurs, which survived for 160 million years, were gone by Boxing Day (December 26). The Pleistocene Glaciation got started at around 6:30 p.m. on New Year's Eve, and the last glacial ice left southern Canada by 11:59 p.m.

It's worth repeating: on this time scale, the earliest ancestors of the animals and plants with which we are familiar did not appear on Earth until mid-November, the dinosaurs disappeared after Christmas, and most of Canada was periodically locked in ice from 6:30 to 11:59 p.m. on New Year's Eve. As for people, the first to inhabit B.C. got here about one minute before midnight, and the first Europeans arrived about two seconds before midnight.

It is common for the popular press to refer to distant past events as being "prehistoric." For example, dinosaurs are reported as being "prehistoric creatures," even by the esteemed National Geographic Society.[2] The written records of our history date back to about 6,000 years ago, so anything prior to that can be considered "prehistoric." But to call the dinosaurs prehistoric is equivalent to—and about as useful as—saying that Singapore is beyond the city limits of Kamloops! If we are going to become literate about geological time, we have to do better than calling dinosaurs, or early horses (54 Ma), or even early humans (2.8 Ma), "prehistoric."

Exercise 8.5 What happened on your birthday?

Using the "all of geological time compressed to one year" concept, determine the geological date that is equivalent to your birthday. First go to Day Number of the Year Calculator to find out which day of the year your birth date is. Then divide that number by 365, and multiply that number by 4,570 to determine the time (in millions since the *beginning* of geological time). Finally subtract that number from 4,570 to determine the date back from the present.

For example, April Fool's Day (April 1) is day 91 of the year: 91/365 = 0.2493. 0.2493 x 4,570 = 1,139 million years from the start of time, and 4,570 – 1,193 = 3,377 Ma is the geological date.

Finally, go to the Foundation for Global Community's "Walk through Time" website to find out what was happening on your day. The nearest date to 3,377 Ma is 3,400 Ma. Bacteria ruled the world at 3,400 Ma, and there's a discussion about their lifestyles.

See Appendix 3 for Exercise 8.5 answers.

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1. Climate change data from NASA Goddard Institute for Space Studies: http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts.txt↵
2. http://science.nationalgeographic.com/science/prehistoric-world/ ↵

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2.19: Measuring Geological Time- Summary

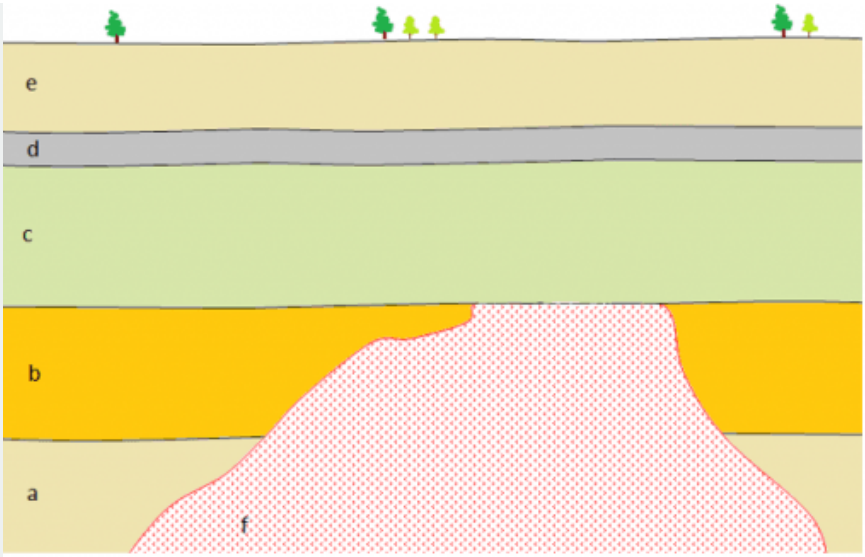
The topics covered in this chapter can be summarized as follows:

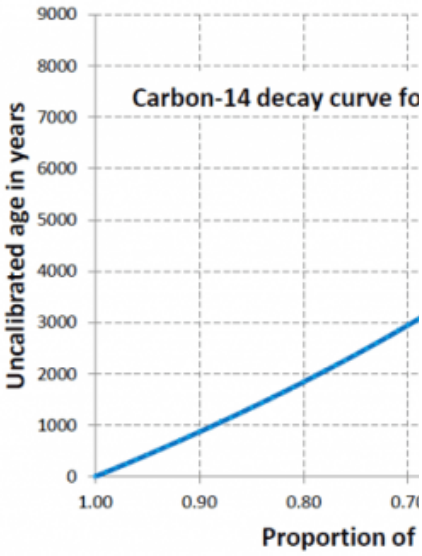
Section	Summary
2.12 The Geological Time Scale	The work of William Smith was critical to the establishment of the first geological time scale early in the 19th century, but it wasn't until the 20th century that geologists were able to assign reliable dates to the various time periods. Geological time is divided into eons, eras, periods, and epochs and the geological time scale is maintained and updated by the International Commission on Stratigraphy.
2.13 Relative Dating Methods	We can determine the relative ages of different rocks by observing and interpreting relationships among them, such as superposition, cross-cutting, and inclusions. Gaps in the geological record are represented by various types of unconformities.
2.15 Dating Rocks Using Fossils	Fossils are useful for dating rocks date back to about 600 Ma. If we know the age range of a fossil, we can date the rock, but some organisms lived for many millions of years. Index fossils represent shorter geological times, and if a rock has several different fossils with known age ranges, we can normally narrow the time during which the rock formed.
2.16 Isotopic Dating Methods	Radioactive isotopes decay at predictable and known rates, and can be used to date igneous and metamorphic rocks. Some of the more useful isotope systems are potassium-argon, rubidium-strontium, uranium-lead, and carbon-nitrogen. Radiocarbon dating can be applied to sediments and sedimentary rocks, but only if they are younger than 60 ka.
2.17 Other Dating Methods	There are many other methods for dating geological materials. Two that are widely used are dendrochronology and magnetic chronology. Dendrochronology, based on studies of tree rings, is widely applied to dating glacial events. Magnetic chronology is based on the known record of Earth's magnetic field reversals.
2.18 Understanding Geological Time	While knowing about geological time is relatively easy, actually comprehending the significance of the vast amounts of geological time is a great challenge. To be able to solve important geological problems and critical societal challenges, like climate change, we need to really understand geological time.

Questions for Review

Answers to Review Questions can be found in Physical Geology 2nd Edition, Steven Earle, Appendix 2.

1. A granitic rock contains inclusions (xenoliths) of basalt. What can you say about the relative ages of the granite and the basalt?
2. Explain the differences between:
    1. a disconformity and a paraconformity
    2. a nonconformity and an angular unconformity
3. What are the features of a useful index fossil?
4. The bellow shows a geological cross-section. The granitic rock "f" at the bottom is the one that you estimated the age of in Exercise 3. A piece of wood from layer "d" has been sent for radiocarbon dating and the result was 0.55 ^{14}C remaining. How old is layer "d"? (You can use the carbon-14 decay curve in the figure below to answer this question.)





Left: Cross section through the crust for questions 4 to 7. Right: ^{14}C decay curve for question 4.

5. Based on your answer to question 4, what can you say about the age of layer “c” in the figure above?
6. What type of unconformity exists between layer “c” and rock “f”?
7. What about between layer “c” and layer “b”?
8. We can’t use magnetic chronology to date anything younger than 780,000 years. Why not?
9. How did William Smith apply the principle of faunal succession to determine the relative ages of the sedimentary rocks of England and Wales?
10. Access a copy of the geological time scale (International Commission on Stratigraphy). What are the names of the last age (or stage) of the Cretaceous and the first age of the Paleogene? Print out the time scale and stick it on the wall above your desk!

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3: THE HYDROSPHERE

3.1: Introduction to the Hydrosphere and Objectives
3.2: Distribution of Earth's Water
3.3: Properties of Water
3.4: The Hydrologic Cycle
3.5: Water Resources and Climate Change
3.6: Review and Additional Resources
3.7: Overview of the Oceans
3.8: Ocean Circulation
3.9: Waves
3.10: Wave Basics
3.11: Waves at Sea
3.12: Waves on the Shore
3.13: Tsunamis
3.14: Coastal Oceanography
3.15: Beaches
3.16: Longshore Transport
3.17: Landforms of Coastal Erosion
3.18: Landforms of Coastal Deposition
3.19: Human Interference with Shorelines
3.20: Estuaries
3.21: Sea Level Change
3.22: Tides
3.23: Tidal Forces
3.24: Dynamic Theory of Tides
3.25: Tide Classification
3.26: Surface Water
3.27: Groundwater
3.28: Prelude to Galciers
3.29: Types of Glaciers
3.30: Glacier Formation and Movement
3.31: Glacial Budget
3.32: Glacial Landforms
3.33: Ice Age Glaciations
3.34: Anthropogenic Effects on Water Quality

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3.1: Introduction to the Hydrosphere and Objectives

Introduction to the Hydrosphere

In this chapter, we will dive into our study of the hydrosphere, exploring the life-sustaining vast, and dynamic Earth water system. We will start with the distribution and unique properties of water, essential to understanding the hydrologic cycle and the critical role of water resources in climate regulation. From the rhythmic regularity of ocean waves to the powerful surge of tsunamis, we'll uncover the forces that shape our oceans and coasts.

We'll study the basics of waves and their impact on the shore, examining coastal processes, erosion, and deposition, and the consequences of human interference. We will also the dynamics of tides and their classifications. Beyond the oceans, we'll investigate the role of running water in sculpting our landscapes, the importance for humanity of groundwater systems, and the historical importance of glaciers. Finally, we will consider the effects of climate change and human activity on water availability, quality, and glacial landscapes.

Learning Objectives

1. `Analyze the distribution and properties of Earth's water, including its significance within the hydrologic cycle and its role in climate regulation.
2. Explain ocean circulation patterns, wave dynamics, coastal processes, and the impact of tsunamis on shorelines and human activities.
3. Evaluate the processes of coastal erosion and deposition, human interference with shorelines, and the formation and significance of estuaries.
4. Describe the mechanisms behind sea level change, tidal forces, and the classification of tides, incorporating the dynamic theory of tides.
5. Assess the importance of groundwater and glaciers, including their formation, movement, and the impact of anthropogenic activities on water quality and glacial landscapes.

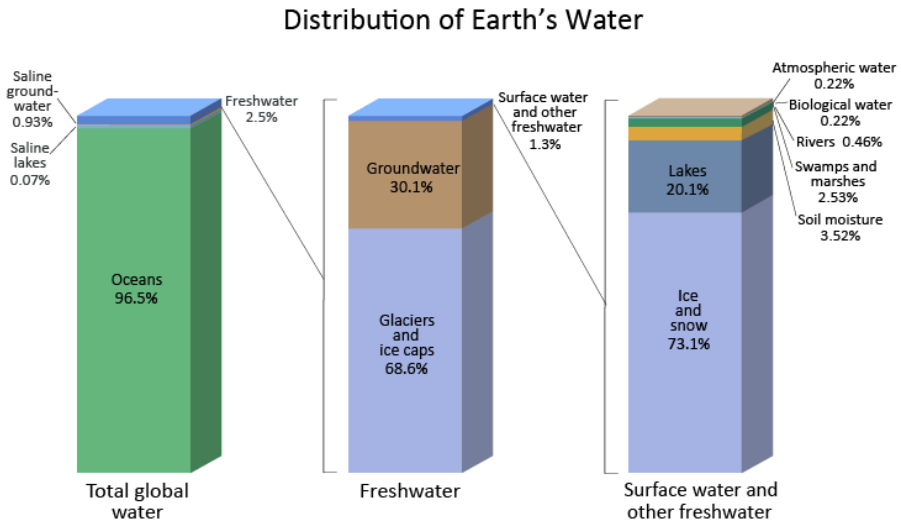


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3.2: Distribution of Earth's Water

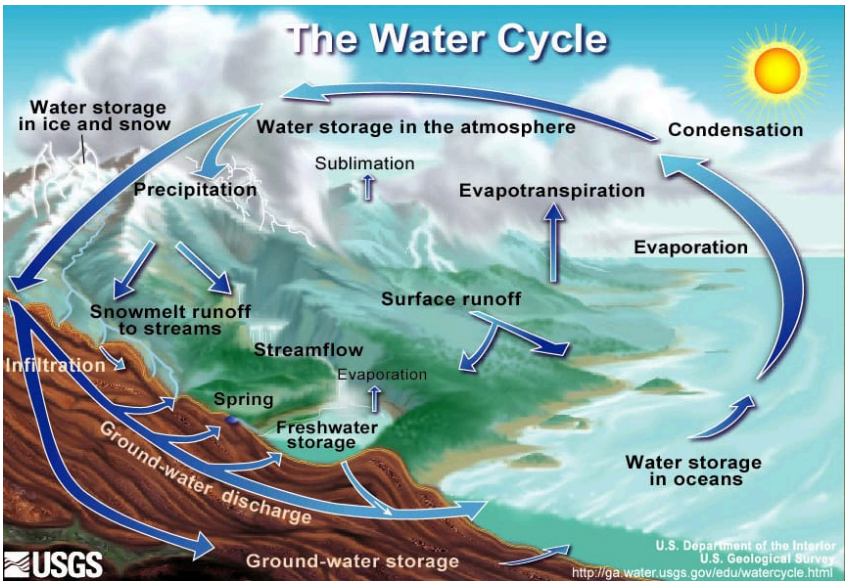
Earth's oceans contain 97% of the planet's water, so just 3% is fresh water, water with low concentrations of salts. Most fresh water is trapped as ice in the vast glaciers and ice sheets of Greenland. A storage location for water such as an ocean, glacier, pond, or even the atmosphere is known as a **reservoir**. A water molecule may pass through a reservoir very quickly or may remain for much longer. The amount of time a molecule stays in a reservoir is known as its residence time.Earth's oceans contain 97% of the planet's water, so just 3% is fresh water, water with low concentrations of salts. Most fresh water is trapped as ice in the vast glaciers and ice sheets of Greenland. A storage location for water such as an ocean, glacier, pond, or even the atmosphere is known as a reservoir. A water molecule may pass through a reservoir very quickly or may remain for much longer. The amount of time a molecule stays in a reservoir is known as its residence time.



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources.

Three States of Water

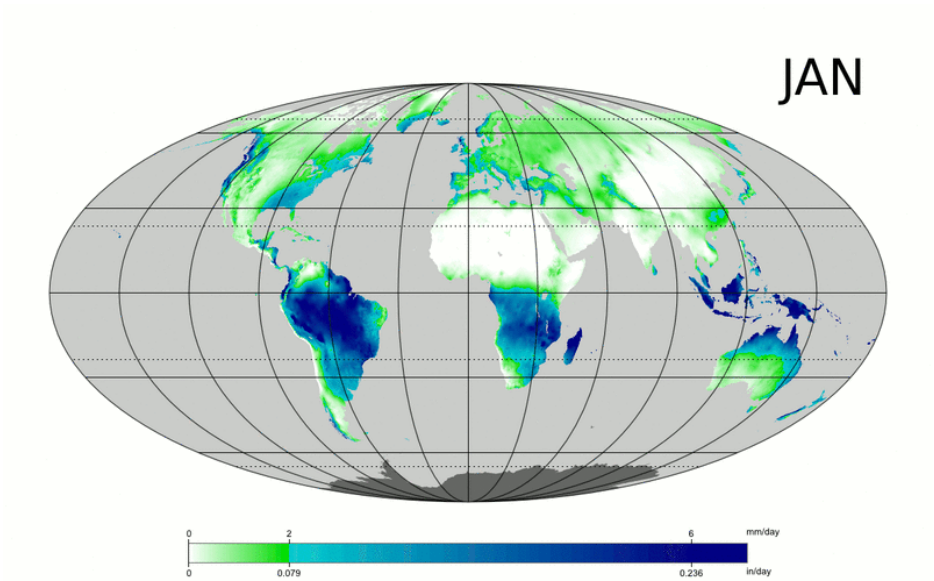
Because of the unique properties of water, water molecules can cycle through almost anywhere on Earth. The water molecule found in your glass of water today could have erupted from a volcano early in Earth history. In the intervening billions of years, the molecule probably spent time in a glacier or far below the ground. The molecule surely was high up in the atmosphere and maybe deep in the belly of a dinosaur. Where will that water molecule go next?Water is the only substance on Earth that is present in all three states of matter – as a solid, liquid or gas. Along with that, Earth is the only planet where water is present in all three states. Because of the ranges in temperature in specific locations around the planet, all three phases may be present in a single location or in a region. The three phases are solid (ice or snow), liquid (water), and gas (water vapor).



The Water Cycle

Because Earth's water is present in all three states, it can get into a variety of environments around the planet. The movement of water around Earth's surface is the **hydrologic (water) cycle**.The Sun, many millions of kilometers away, provides the energy that drives the water cycle. Our nearest star directly impacts the water cycle by supplying the energy needed for evaporation.Most of Earth's water is stored in the oceans where it can remain for hundreds or thousands of years. The oceans are discussed in detail in the chapter Earth's Oceans.

Water changes from a liquid to a gas by evaporation to become water vapor. The Sun's energy can evaporate water from the ocean surface or from lakes, streams, or puddles on land. Only the water molecules evaporate; the salts remain in the ocean or a freshwater reservoir. The water vapor remains in the atmosphere until it undergoes condensation to become tiny droplets of liquid. The droplets gather in clouds, which are blown about the globe by wind. As the water droplets in the clouds collide and grow, they fall from the sky as precipitation. Precipitation can be rain, sleet, hail, or snow. Sometimes precipitation falls back into the ocean and sometimes it falls onto the land surface.



This animation shows the annual cycle of monthly mean precipitation around the world.
Thumbnail for the embedded element "NASA | Earth's Water Cycle"

When water falls from the sky as rain it may enter streams and rivers that flow downward to oceans and lakes. Water that falls as

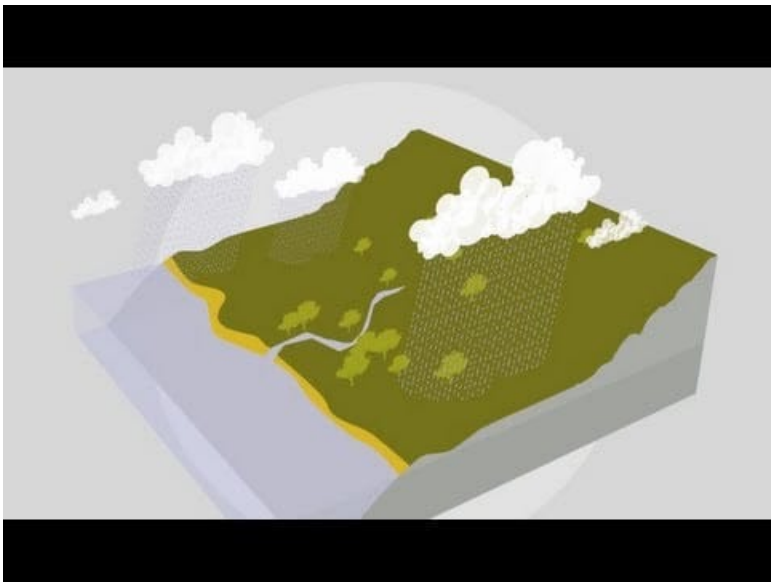
snow may sit on a mountain for several months. Snow may become part of the ice in a glacier, where it may remain for hundreds or thousands of years. Snow and ice may go directly back into the air by sublimation, the process in which a solid changes directly into a gas without first becoming a liquid. Although you probably have not seen water vapor sublimating from a glacier, you may have seen dry ice sublimate in air.

YouTube Video

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Snow and ice slowly melt over time to become liquid water, which provides a steady flow of fresh water to streams, rivers, and lakes below. A water droplet falling as rain could also become part of a stream or a lake. At the surface, the water may eventually evaporate and reenter the atmosphere.

A significant amount of water infiltrates into the ground. **Soil moisture** is an important reservoir for water. Water trapped in soil is important for plants to grow. Water may seep through dirt and rock below the soil through pores infiltrating the ground to go into Earth's groundwater system. Groundwater enters aquifers that may store fresh water for centuries. Alternatively, the water may come to the surface through springs or find its way back to the oceans. Plants and animals depend on water to live and they also play a role in the water cycle. Plants take up water from the soil and release large amounts of water vapor into the air through their leaves, a process known as transpiration. NASA has an excellent online guide of the hydrologic cycle.People also depend on water as a natural resource. Not content to get water directly from streams or ponds, humans create canals, aqueducts, dams, and wells to collect water and direct it to where they want it.

Use	United States	Global
Agriculture	34 percent	70 percent
Domestic (drinking, bathing)	12 percent	10 percent
Industry	5 percent	20 percent

Use	United States	Global
Power plant cooling	49 percent	small

The table above displays water use in the United States and globally (Estimated Use of Water in the United States in 2005, USGS). It is important to note that water molecules cycle around. If climate cools and glaciers and ice caps grow, there is less water for the oceans and sea level will fall. The reverse can also happen.

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3.3: Properties of Water

The most obvious feature of the oceans is that they contain water. Water is so ubiquitous that it may not seem like a very interesting substance, but it has many unique properties that impact global oceanographic and climatological processes. Many of these processes are due to **hydrogen bonds** forming between water molecules.

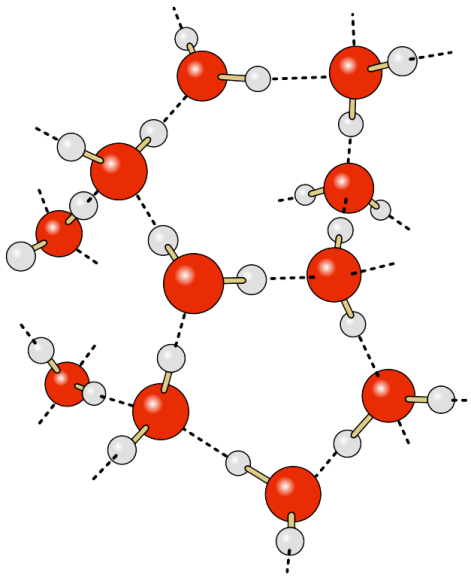


Figure 3.3.1 Hydrogen bonds (dashed lines) between water molecules. Oxygen atoms are shown in red, hydrogen atoms in white (Public domain, via Wikimedia Commons).

The water molecule consists of two hydrogen atoms and one oxygen atom. The electrons responsible for the bonds between the atoms are not distributed equally throughout the molecule, so that the hydrogen ends of water molecules have a slight positive charge, and the oxygen end has a slight negative charge, making water a **polar molecule**. The negative oxygen side of the molecule forms an attraction to the positive hydrogen end of a neighboring molecule. This rather weak force of attraction is called a hydrogen bond (Figure 3.3.1). If not for hydrogen bonds, water would vaporize at -68° C, meaning liquid water (and thus life) could not exist on Earth. These hydrogen bonds are responsible for some of water's unique properties:

1. Water is the only substance to naturally exist in a solid, liquid, and gaseous form under the normal range of temperatures and pressures found on Earth. This is due to water's relatively high freezing and vaporizing points (see below).

2. Water has a **high heat capacity**, which is the amount of heat that must be added to raise its temperature. Specific heat is the heat required to raise the temperature of 1 g of a substance by 1° C. Water has the highest specific heat of any liquid except ammonia (Table 5.1.1).

[table id=3 /]

Water is therefore one of the most difficult liquids to heat or cool; it can absorb large amounts of heat without increasing its temperature. Remember that temperature reflects the average kinetic energy of the molecules within a substance; the more vigorous the motion, the higher the temperature. In water, the molecules are held together by hydrogen bonds, and these bonds must be overcome to allow the molecules to move freely. When heat is added to water the energy must first go to breaking the hydrogen bonds before the temperature can begin to rise. Therefore, much of the added heat is absorbed by breaking H bonds, not by increasing the temperature, giving water a high heat capacity.

Hydrogen bonds also give water a high latent heat; the heat required to undergo a phase change from solid to liquid, or liquid to gas. The **latent heat of fusion** is the heat required to go from solid to liquid; 80 cal/g in the case of ice melting to water. Ice is a solid because hydrogen bonds hold the water molecules into a solid crystal lattice (see below). As ice is heated, the temperature rises up to 0° C. At that point, any additional heat goes to melting the ice by breaking the hydrogen bonds, not to increasing the temperature. So as long as ice is present, the water temperature will not increase. This is why your drink will remain cold as long

as it contains ice; any heat absorbed goes to melting the ice, not to warming the drink.

When all of the ice is melted, additional heat will increase the temperature of the water 1° C for each calorie of heat added, until it reaches 100° C. At that point, any additional heat goes to overcoming the hydrogen bonds and turning the liquid water into water vapor, rather than increasing the water temperature. The heat required to evaporate liquid water into water vapor is the **latent heat of vaporization** which has a value of 540 cal/g (Figure 3.3.2).

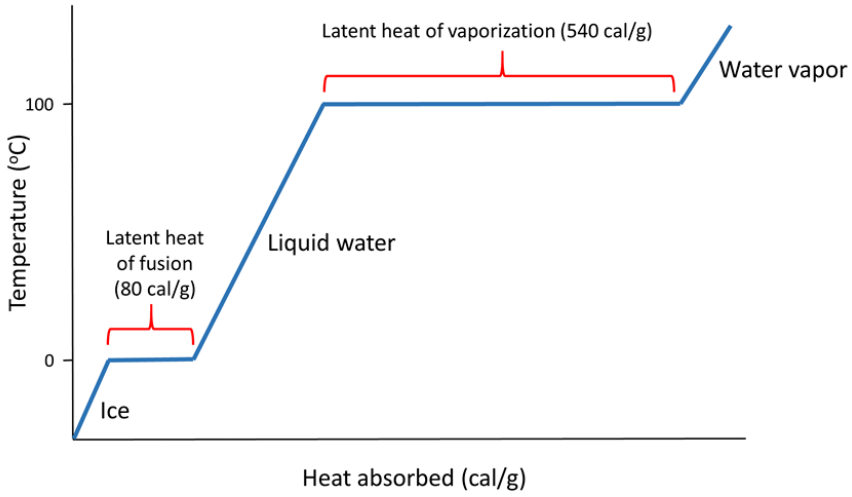


Figure 3.3.2 Latent heat required for phase changes in water. Latent heat of fusion is the heat required to melt ice (80 cal/g), and latent heat of vaporization is the heat required to turn liquid water into water vapor (540 cal/g) (PW).

The high heat capacity of water helps regulate global climate, as the oceans slowly absorb and release heat, preventing rapid swings in temperature (see section 8.1). It also means that aquatic organisms aren't as subjected to the same rapid temperature changes as terrestrial organisms. A deep ocean organism may not experience more than a 0.5^{o} C change in temperature over its entire life, while a terrestrial species may encounter changes of more than 20° C in a single day!

3. Water dissolves more substances than any other liquid; it is a **"universal solvent"**, which is why so many substances are dissolved in the ocean. Water is especially good at dissolving ionic salts; molecules made from oppositely charged ions such as NaCl (Na^{+} and Cl^{-}). In water, the charged ions attract the polar water molecules. The ions get surrounded by a layer of water molecules, weakening the bond between the ions by up to 80 times. With the bonds weakened between ions, the substance dissolves (Figure 3.3.3).

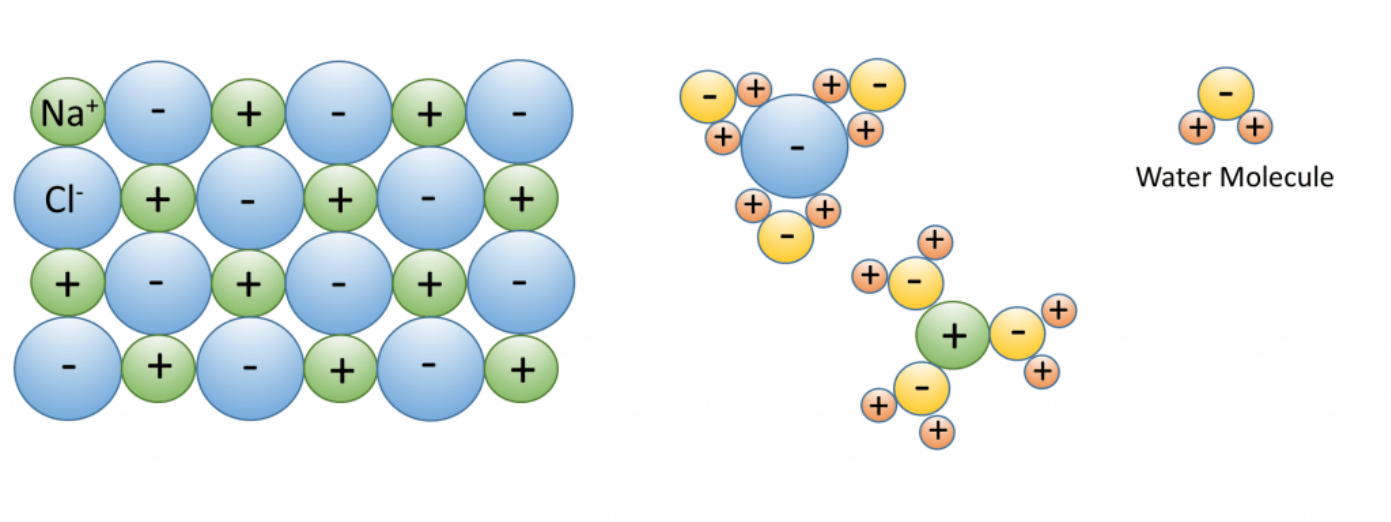


Figure 3.3.3 Attraction between polar water molecules and charged ions (such as in NaCl) is greater than the attraction between the charged ions, causing the ions to dissociate and the salt to dissolve (PW).

4. The **solid phase is less dense than the liquid phase**. In other words, ice floats. Most substances are denser in the solid form than in the liquid form, as their molecules are more closely packed together as a solid. Water is an exception: the density of fresh water is 1.0 g/cm^3, while the density of ice is 0.92 g/cm^3, and once again, this is due to the action of hydrogen bonds.

As water temperature cools the molecules slow down, eventually slowing enough that hydrogen bonds can form and hold the water molecules in a crystal lattice. The molecules in the lattice are spaced farther apart than the molecules in liquid water, which makes ice less dense than liquid water (Figure 3.3.4). This is familiar to anyone who has ever left a full water bottle in the freezer, only to have it burst as the water freezes and expands.

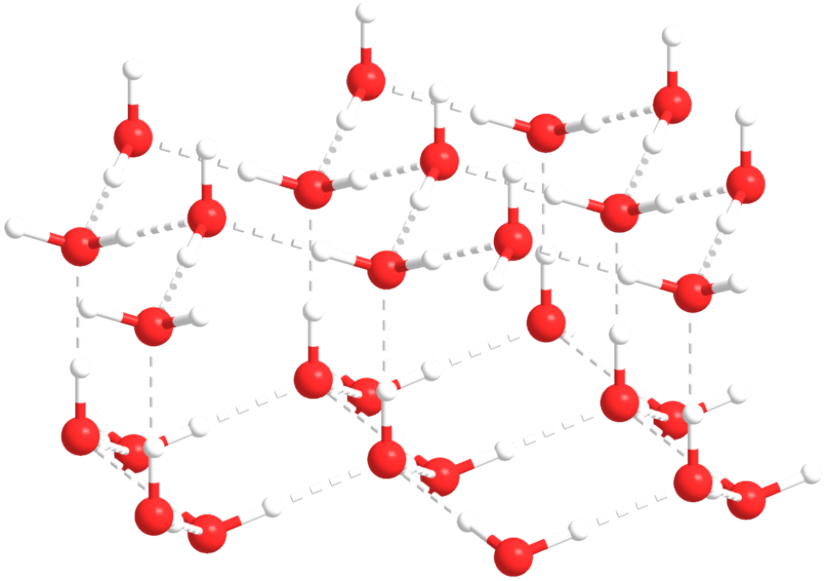


Figure 3.3.4 Crystal lattice structure of ice, showing water molecules held together by hydrogen bonds (By Adam001d (Own work) [CC BY-SA 3.0], via Wikimedia Commons).

But the relationship between temperature and water density is not a simple linear one. As water cools, its density increases as expected, as the water molecules slow down and get closer together. However, fresh water reaches its maximum density at a temperature of 4° C, and as it cools beyond that point its density declines as the hydrogen bonds begin to form and the intermolecular spacing increases (Figure 3.3.5 inset). The density continues to decline until the temperature reaches 0° C and ice crystals form, reducing the density dramatically (Figure 3.3.5).

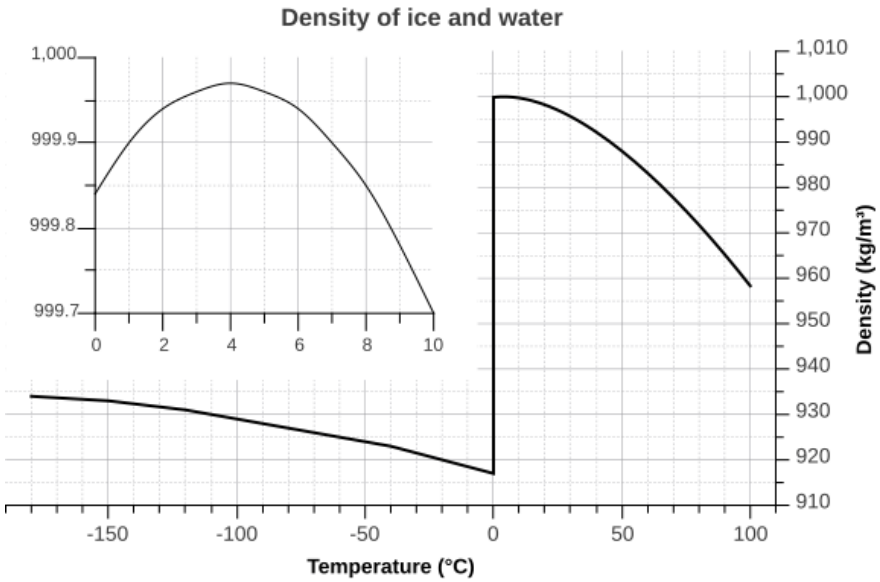


Figure 3.3.5 As temperature declines, the density of water increases until it reaches maximum density at 4° C (inset). Density then declines slightly down to 0° C, where it declines dramatically as ice crystals form (Klaus-Dieter Keller, [CC BY-SA 3.0], via Wikimedia Commons).

There are a number of important implications to ice being less dense than water. Ice floating on the surface of the ocean helps regulate ocean temperatures, and therefore global climate, by influencing the amount of sunlight that is reflected rather than absorbed (see section 8.1). On a smaller scale, surface ice can prevent lakes and ponds from freezing solid during the winter. As fresh surface water cools, the water gets denser, and sinks to the bottom. The new surface water then cools and sinks, and the process is repeated in what is referred to as **overturning**, with denser water sinking and less dense water moving to the surface only to be cooled and sink itself. In this way, the entire body of water is cooled somewhat evenly. This process continues until the surface water cools below 4° C. Below 4° C, the water becomes *less* dense as it cools, so it no longer sinks. Instead, it remains as the surface, getting colder and less dense, until it freezes at 0° C. Once fresh water freezes, the ice floats and insulates the rest of the water beneath it, reducing further cooling. The densest bottom water is still at 4° C, so it does not freeze, allowing the bottom of a lake or pond to remain unfrozen (which is good news for the animals living there) no matter how cold it gets outside.

The dissolved salts in seawater inhibit the formation of the crystal lattice, and therefore make it harder for ice to form. So seawater has a freezing point of about -2° C (depending on salinity), and freezes before a temperature of maximum density is reached. Thus seawater will continue to sink as it gets colder, until it finally freezes.

5. Water has a very **high surface tension**, the highest of any liquid except mercury (Table 5.1.2). Water molecules are attracted to each other by hydrogen bonds. For molecules not at the water surface, they are surrounded by other water molecules in all directions, so the attractive forces are evenly distributed in all directions. But for molecules at the surface there are few adjacent molecules above them, only below, so all of the attractive forces are directed inwards, away from the surface (Figure 3.3.6). This inwards force is what causes water droplets to take on a spherical shape, and water to bead up on a surface, as the spherical shape provides the minimum possible surface area. These attractive forces also cause the surface of the water to act like an elastic “skin” which allows things like insects to sit on the water’s surface without sinking.

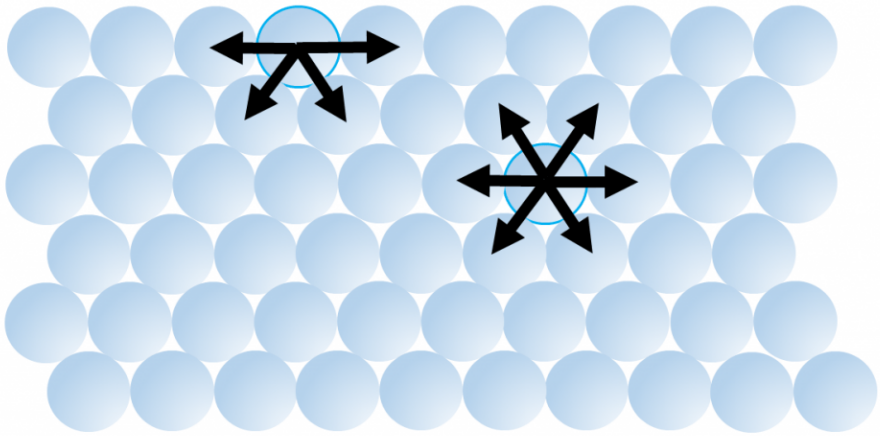


Figure 3.3.6 The net attractive force between molecules at the surface is inwards, leading to surface tension. For molecules in the center, the force is equal in all directions (PW).

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3.4: The Hydrologic Cycle

The ***hydrologic cycle***, or water cycle, is the cycling of water through the earth system. Not only is the hydrologic cycle a cycle of water, it is a cycle of energy as well. Over the next several pages we'll trace water as it passes through the earth system and the energy that accompanies it.

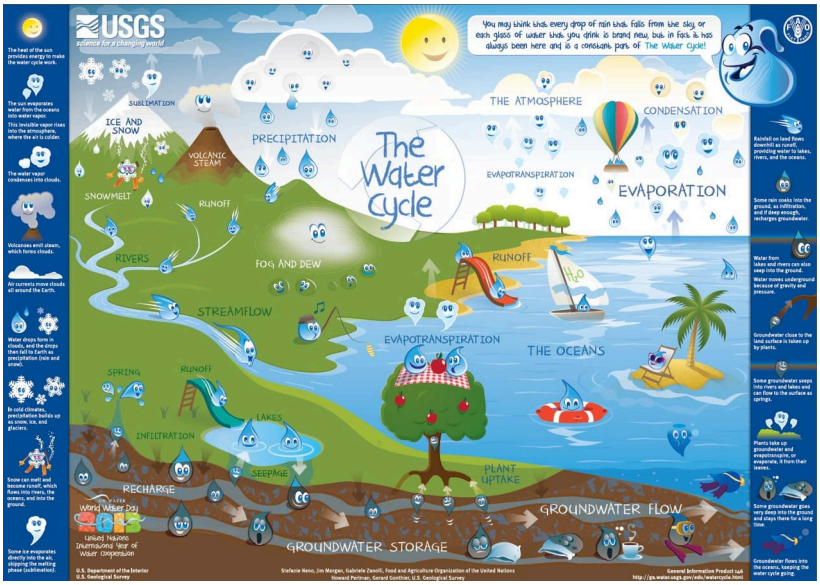


Figure 3.4.1: The Hydrologic cycle

Evaporation and Condensation

Evaporation is the phase change of liquid water into a vapor (gas). Evaporation is an important means of transferring energy between the surface and the air above. The energy used to evaporate water is called "latent energy". ***Latent energy*** is "locked up" in the water molecule when water undergoes the phase change from a liquid to a gas. Eighty-eight percent of all water entering the atmosphere originates from the ocean between 60° north and 60° south latitude. Most of the water evaporated from the ocean returns directly back to the ocean. Some water is transported over land before it is precipitated out. When water vapor condenses back into a liquid it releases latent heat, which is converted into sensible heat warming the surrounding air. The warming of the surrounding air fuels uplift to help promote adiabatic cooling and further condensation. As droplets of water coalesce into larger droplets they attain a size big enough to fall towards the earth as precipitation. Located high in the troposphere, rain drops possess a high degree of potential energy that is converted into kinetic energy once they begin to fall toward the surface. Impacting the surface they convert this kinetic energy into work done on the surface (erosion for example).

Interception and Infiltration

As water reaches the surface in various forms of precipitation, it is intercepted by plants or falls directly to the surface. Precipitation that collects on the leaves or stems of plants is known as ***interception***. The amount of water intercepted by a plant largely depends on plant form. Water is held on the leaf surface until it either drips off as ***through fall*** or trickles down the leaf stem finally reaching the ground as ***stem flow***. Interception of falling rain buffers the surface against erosion. Coniferous trees tend to intercept more water than deciduous trees on an annual basis because deciduous trees drop their leaves for a period of time.



Figure 3.4.2: Droplets of water intercepted by tree leaf. (Source: M. Marzot FAO. Used with permission)

Upon reaching the ground, some water infiltrates into the soil, possibly percolating down to the groundwater zone or it may run across the surface as ***runoff***. ***Infiltration*** refers to water that penetrates into the surface of soil. Infiltration is controlled by soil texture, soil structure, vegetation and soil moisture status. High infiltration rates occur in dry soils, with infiltration slowing as the soil becomes wet. Coarse textured soils with large well-connected pore spaces tend to have higher infiltration rates than fine textured soils. However, coarse textured soils fill more quickly than fine textured soils due to a smaller amount of total pore space in a unit volume of soil. Runoff is generated quicker than one might have with a finer textured soil.

Vegetation also affects infiltration. For instance, infiltration is higher for soils under forest vegetation than bare soils. Tree roots loosen and provide conduits through which water can enter the soil. Foliage and surface litter reduce the impact of falling rain keeping soil passages from becoming sealed.

Subsurface water

Groundwater and soil water together comprise approximately .5% of all water in the hydrosphere. Water beneath the surface can essentially be divided into two zones (Figure 3.4.3), the unsaturated zone (also known as the "zone of aeration") which includes soil water zone, and zone of saturation which includes ground water. Air and water occupies the pore spaces between earth materials in the zone of aeration. Sometimes, especially during times of high rainfall, these pore spaces are filled with water. The water table divides the zone of aeration from the zone of saturation. The height of the water table will fluctuate with precipitation, increasing in elevation during wet periods and decreasing during dry. Note how the water table intersects the level of the stream surface in Figure 3.4.3. Seepage of groundwater into a stream provides a base flow of water for perennial streams.

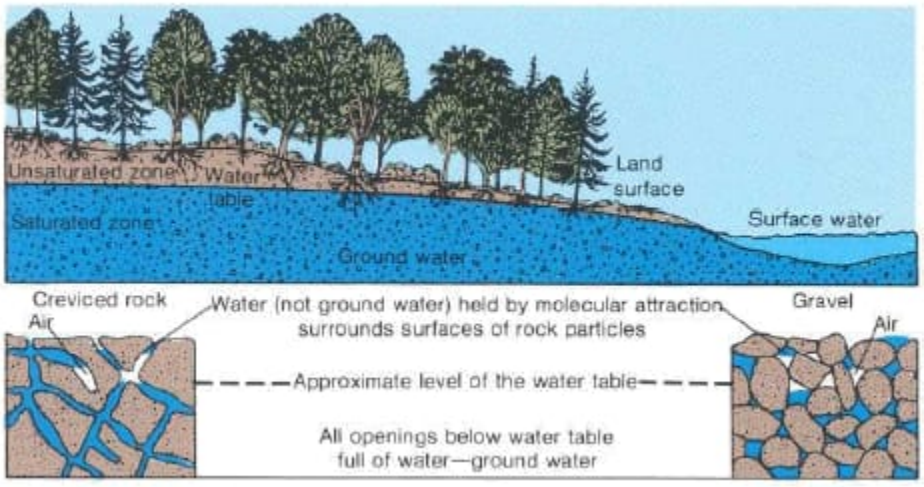


Figure 3.4.3: Zones of water beneath the surface (Courtesy USGS; Source)

Soil Water

Soil water is held in the pore spaces between particles of soil. Soil water is the water that is immediately available to plants.

Soil water can be further sub-divided into three categories, 1) hygroscopic water, 2) capillary water, and 3) gravitational water. ***Hygroscopic water*** is found as a microscopic film of water surrounding soil particles. This water is tightly bound to a soil particle by molecular attraction so powerful that it cannot be removed by natural forces. Hygroscopic water is bound to soil particles by adhesive forces that exceed 31 bars and may be as great as 10,000 bars (Recall that sea level pressure is equal to 1013.2 millibars which is just about 1 bar!). ***Capillary water*** is held by cohesive forces between the films of hygroscopic water. The binding pressure for capillary water is much less than hygroscopic water. This water can be removed by air drying or by plant absorption, but cannot be removed by gravity. Plants extract this water through their roots until the soil capillary force (force holding water to the particle) is equal to the extractive force of the plant root. At this point the plant cannot pull water from the plant-rooting zone and it wilts (called the ***wilting point***). ***Gravity water*** is water moved through the soil by the force of gravity. The amount of water held in the soil after excess water has drained is called the ***field capacity*** of the soil. The amount of water in the soil is controlled by the soil texture. Soils dominated by clay-sized particles have more total pore space in a unit volume than soils dominated by sand. As a result, fine grained soils have higher field capacities than coarse-grained soils.

Representative Porosity Ranges for Sedimentary Materials

Material	% Porosity
Soils	50 - 60
Clay	45 - 55
Silt	40 - 50
Uniform Sand	30 - 40
Gravel	30 - 40
Sandstone	10 - 20
Shale	1 - 10

Figure 3.4.4: Representative Porosity Ranges for Sedimentary Materials

The diagram below shows the relationship between soil texture, wilting point, field capacity, and available water. The difference between the wilting point and the field capacity is the ***available water***.

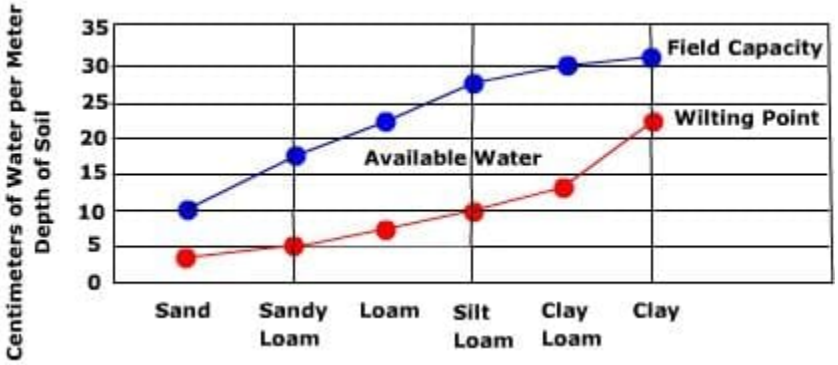


Figure 3.4.5: Relationship Between Available Water and Soil Texture

Note that the smallest amount of available water is associated with the coarsest soil texture, sand. The amount of available water increases toward the center of the graph where soils with a mixture of different sized particles (loamy soils) are found. The available water then drops off toward the fine textured soils on the right. How does one explain the relationship between available water and soil texture? Coarse soil does not have much available water because it doesn't hold much water to begin with. At the other end of the spectrum, low available water in fine soils is due to strong bond between soil particles and water. Plants have a harder time pulling water away from the soil particle under these conditions.

Groundwater

Groundwater occupies the zone of saturation. As depicted in the hydrologic cycle diagram, ground water moves downward through the soil by ***percolation*** and then toward a stream channel or large body of water as ***seepage***. The water table separates the zone of saturation from the zone of aeration. The water table fluctuates with moisture conditions, during wet times the water table will rise as more pore spaces are occupied with water. Groundwater is found in ***aquifers***, bodies of earth material that have the ability to hold and transmit water. Aquifers can be either unconfined or confined. Unconfined (open) aquifers are "connected" to the surface above. Confined (closed) aquifers are sandwiched in between dense impermeable layers of earth material called an ***aquiclude***. Ground water is replenished by percolation of water from the zone of aeration downward to the zone of saturation, or in the recharge zone of a confined aquifer. The recharge zone is where the confined aquifer is exposed at the surface and water can enter it.

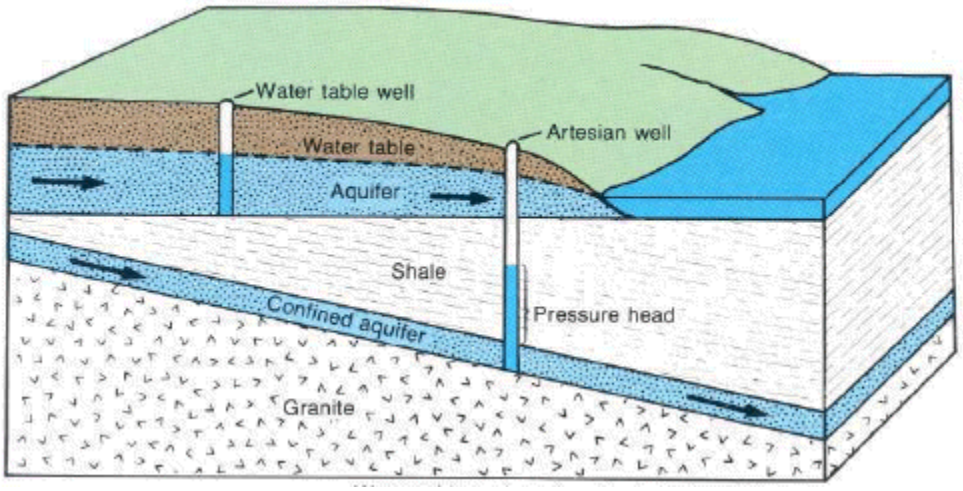


Figure 3.4.6: Unconfined and confined aquifers. (Courtesy USGS; Source)

Aquifers replenish their supply of water very slowly. The rate of groundwater flow depends on the permeability of the aquifer and the hydraulic gradient. Permeability is affected by the size and connectivity of pore spaces. Larger, better connected pore spaces creates highly permeable earth material. The ***hydraulic gradient*** is the difference in elevation between two points on the water table divided by the horizontal distance between them.

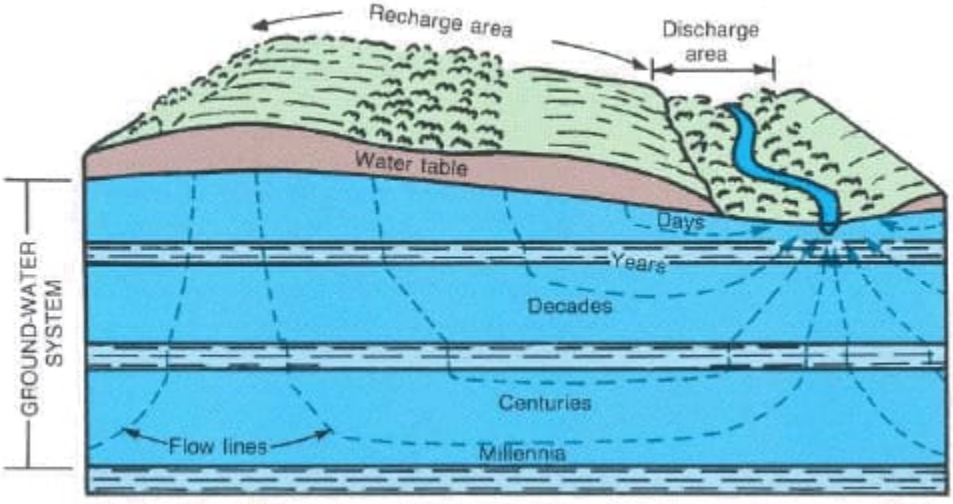


Figure 3.4.7: Ground water movement (Courtesy USGS; Source)



Figure 3.4.8: Pivot irrigation on a barley field in Saudi Arabia. The barley is used as fodder for milk cows. (Source: F. Mattioli, FAO Used with permission)

Groundwater and Human Activities

Groundwater is an important source of water for human activities such as agriculture and domestic drinking water.

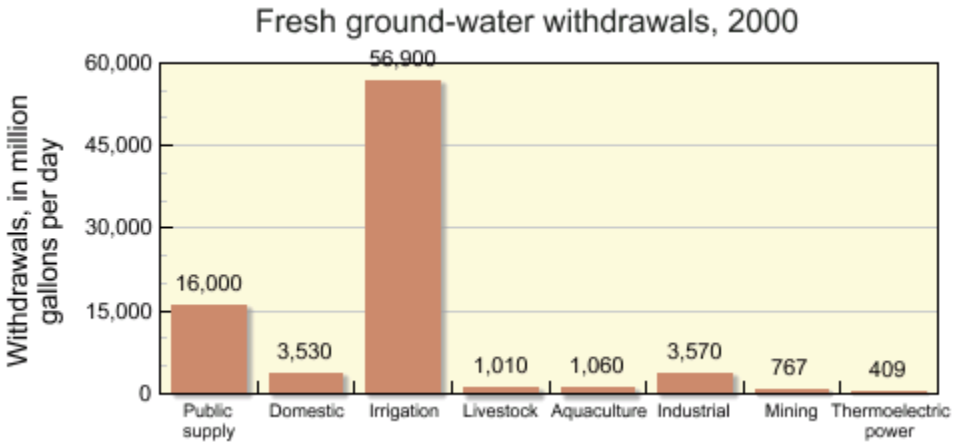


Figure 3.4.9: United States groundwater withdrawals (2000) (Courtesy USGs)

In dry regions and in places where soils are highly permeable, agriculture uses large amounts of ground water for irrigation. The high rate of water use for agriculture has fueled tensions between urban and rural interests.



Figure 3.4.10: Outcrop of the Ogallala (sandstone) Formation, the main water-bearing unit of the High Plains aquifer, near the Canadian River in Texas. (Courtesy USGS.)

However, the rate of groundwater removal by humans sometimes exceeds the recharge of the aquifer. Such is the case of the High Plains Aquifer of Arizona, Colorado, New Mexico, and Utah. Overpumping of ground water reserves can lead to compaction

and degradation of the aquifer. As the water is removed, the aquifer often collapses, causing the surface to subside. Aquifer compaction reduces pore space, making recharge more difficult. One of the most striking examples is that which has occured in the San Joaquin Valley of California. An August 6, 2013 NPR *All Things Considered* segment, "Wells Are Running Dry in Parts of Kansas", describes the plight of farmers and ranchers in Kansas where groundwater supplies are getting scarce.



Figure 3.4.11: Land subsidence in California. Joe Poland, USGS scientist shows subsidence from 1925 and 1977 10 miles southwest of Mendota, CA. Sign reads "San Joaquin Valley California, BM S661, Subsidence 9M, 1925-1977" (From USGS Professional Paper 1401-A, "Ground water in the Central Valley, California- A summary report"; Photo by Dick Ireland, USGS, 1977)

Surface Water

Once precipitation reaches the surface, water can infiltrate into the soil or move across the surface as **runoff**. Surface runoff generally occurs when the rainfall intensity exceeds the rate of infiltration, or if the soil is at its water holding capacity. Infiltration and water holding capacity are both a function of soil texture and structure. Soil composed of a high percentage of sand allows water to infiltrate through it quite rapidly because it has large, well-connected pore spaces. Soils dominated by clay have low infiltration rates due to their smaller sized pore spaces. However, there's actually less total pore space in a unit volume of coarse, sandy soil than that of soil composed mostly of clay. As a result, sandy soils fill rapidly and commonly generate runoff sooner than clay soils.

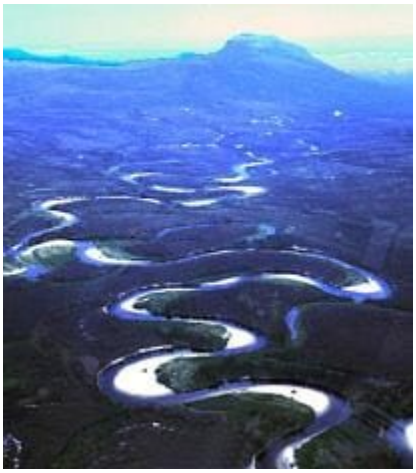


Figure 3.4.12: Meandering stream (Source: Geological Survey of Canada Used with Permission)

If the rainfall intensity exceeds the infiltration capacity of the soil, or if the soil has reached its field capacity, surface runoff occurs. Water runs across the surface as either confined or unconfined flow. ***Unconfined flow*** moves across the surface in broad sheets of water often creating sheet erosion. ***Confined flow*** refers to water confined to channels. Stream flow is a form of confined flow.

Stream flow is measured in a variety of ways, one of which is stream discharge. ***Stream discharge*** is the volume of water passing through a particular cross-section of a stream in a unit of time. Stream discharge is measured in cubic meters per second. The "normal" or base flow a stream is provided by seepage of groundwater into the stream channel. This seepage is what keeps perennial flowing streams going all year. When precipitation from a storm occurs, the stream discharge increases as water is added to the stream, either from direct precipitation into the channel or runoff.

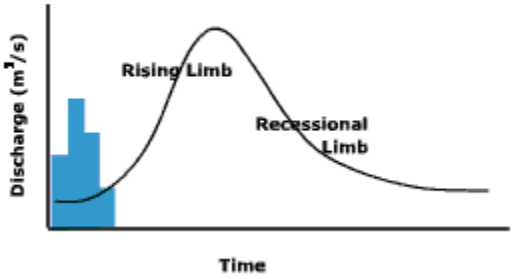


Figure 3.4.13: A stream hydrograph

A ***stream hydrograph*** (right) illustrates the relationship between discharge and runoff. The blue bar graph is precipitation and the line graph represents discharge. As time passes (measured along the x-axis) discharge increases as precipitation falls. Notice that the time of peak precipitation occurs before peak discharge. This is because it takes time for the water to flow across the surface and enter the stream.

The size, shape, land use, vegetation, and geology of the watershed all determine runoff and the shape of the discharge graph.

Surface water is an important source of water supplies, especially in the southwestern United States. Ever increasing population and development is straining regional water resources. As the Colorado River winds its way through the desert it loses half its flow to evaporation and the rest to irrigation and municipal water supplies. Recent drought and warmer temperatures predicted in the future will put a greater demand on this precious commodity. The lower course rarely reaches the Gulf of California as it did in times past. Now this once might river usually ends as a small stream or dry channel.

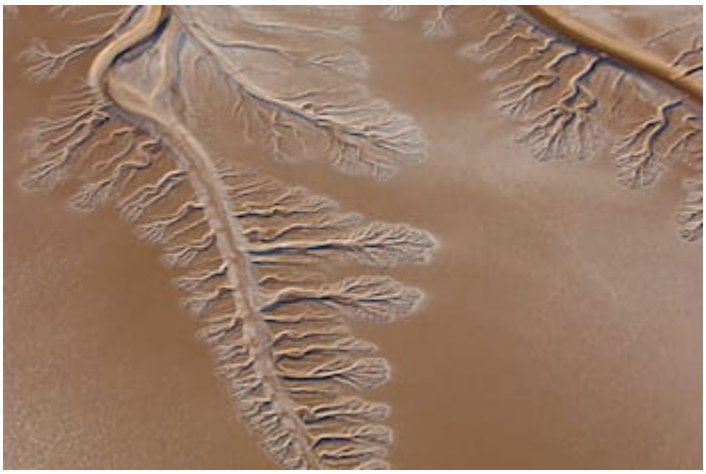


Figure 3.4.14: The now-dry Colorado River delta lies in the Baja/Sonoran Desert 5 miles north of the Sea of Cortex, Mexico (Courtesy USGS)

Some feel that we have reached maximum extraction rate for oil. In other words, we have reaches "peak" in our ability to extract oil and the rate of production will continue to decline. Can the same be said for our use of water? View the video below to explore the answer to this question.

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3.5: Water Resources and Climate Change

Changes to the patterns of current precipitation and those projected for the future on account of climate change are discussed in Chapter 6, "Future Geographies: Global Precipitation Patterns". The kind of precipitation is already changing, as northern regions are experiencing more rain than snow. Total snow cover has on average decreased in both hemispheres.The variability of precipitation is changing as well. Many subtropical regions have been or are gripped in devastating droughts. Precipitation is but one element of the hydrologic cycle, that will be affected by climate. The impact of climate change on water resources will have profound effects on ecosystems and humans.

Evapotranspiration

As noted earlier in this chapter, potential evapotranspiration is a measure of water need based primarily on the energy input. Potential evapotranspiration is expected to increase in nearly all regions. As temperature rises the saturation point of air increases, but relative humidity is not expected to change significantly. As a result, the evaporation of water increases yielding a larger amount of water vapor in the air. The increase evaporation of water from the soil places a greater strain on plants as their need for water to maintain growth processes increases. Actual evaporation is projected to increase over most bodies of water, the amount depending on the geographic variation in surface warming.

Plants take in carbon dioxide and release water vapor through their stomata. The increase in atmospheric carbon dioxide has competing roles in the affect of evapotranspiration from vegetation. At higher CO_2 concentrations, stomata need to open less to take in the same amount of carbon dioxide for photosynthesis. However, increased carbon dioxide can act a gaseous fertilizer to spur plant growth and leaf area. Increased leaf area results in more transpiration. The degree to which higher CO_2 concentration have depend on the type of vegetation, nutrient availability, temperature changes, and water availability

Surface water and Runoff

The impact of climate change on river flows and lake levels depend on changes in the amount, type, and timing of precipitation. Changes in evaporation rates also affect river and lake levels. Global scale climate and hydrological models project runoff increases in the wet tropics and high latitudes, and decreases in the mid-latitudes and some parts of the dry tropics. Most studies show that rising temperatures lead to changes in the seasonality of river flow due to changes in the type of precipitation. Higher winter flows occurring in the European Alps, Scandinavia, the Himalayas, western, central, and eastern North America will result from more precipitation falling as rain and earlier snow melt. The frequency of heavy precipitation events are expected to increase in an ever warming world for most regions. This will likely increase the threat for flash flooding and urban flooding.

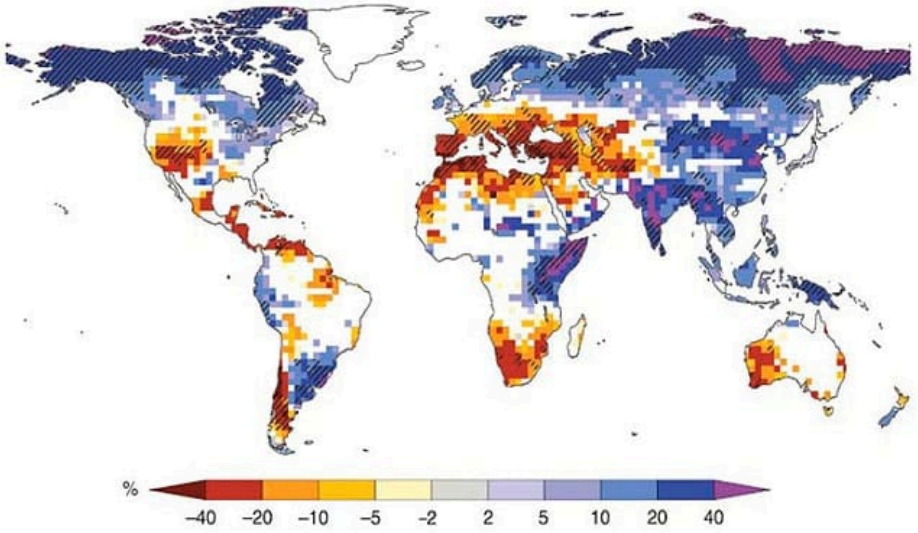


Figure 3.5.1: Runoff model projections of large-scale relative changes in annual runoff for the period 2090-2099 relative to 1980-1999. (Courtesy IPCC)

Ground water

Ground water levels are maintained when aquifers are adequately recharged. How this occurs varies with soil conditions, vegetation and precipitation intensity and timing. Generally speaking, if precipitation intensity is greater than the infiltration capacity of the soil, most water will runoff and not percolate down into the ground water zone. However, more frequent and larger precipitation events projected for some humid region may result in decreased groundwater recharge as the infiltration capacity of the soil is exceeded more often. In semi-arid and arid regions, groundwater level may rise with high-intensity storms as rainfall is ability to infiltrate downward before evaporating.

Soil moisture

The amount of moisture held in the soil depends on when and how much precipitation and evaporation occurs at a place. The resulting changes to the spatial patterns of soil moisture is expected to be quite similar to that of changes in precipitation. Though the amount of change is not well established, projections generally agree on the kind of change that will occur. A reduction in soil moisture in the subtropics and Mediterranean regions will accompany a decrease in precipitation. Projected decreases in snow cover at high latitudes will also result in less soil moisture. Soil moisture will likely increase in East Africa and central Asia where increases precipitation is expected to occur.

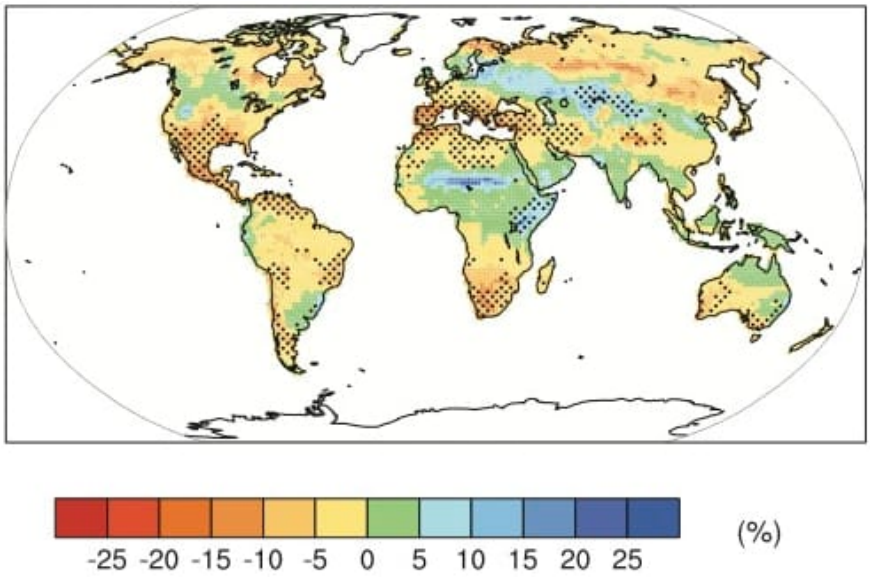


Figure 3.5.2: Fifteen-model mean changes in soil moisture. Stippled areas are those where 80% of models agree on sign of change. (Source: IPCC)

Water supply

Population growth, economic development and land use change largely determine the stress put on water supplies. Climate change will be an additional factor that affects stressed water resources. Glacier meltwater provides a source of water for many living in mountainous underdeveloped countries. Recent loss of glacier ice has or will place these people at risk. Peruvian glaciers have lost more than 20% of their mass in the past 35 years, resulting in a 12 percent decrease in runoff to the country's coastal region, where 60 percent of Peru's population live.

Agriculture, industry, and urban populations across the earth depend on major river systems to transpiration, irrigation, and drinking water. Millions of acres of farmland and tens of million people rely on the Colorado River system for water. Impoundment of water behind large dams regulate the flow and delivery of water supplies. The timing of when regulated flows deliver water is based on the experience of the past 100 years. Scheduled delivery of water may be missed 60 to 90 percent of the time as human-induced climate change continues to make the Colorado River basin drier.

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3.6: Review and Additional Resources

Review

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- *hydrosphere available at the end of this section.*
- *hydrologic cycle available at the end of this section.*
- *soil water available at the end of this section.*
- *groundwater available at the end of this section.*
- *evaporation available at the end of this section.*
- *latent energy available at the end of this section.*
- *precipitation available at the end of this section.*
- *interception available at the end of this section.*
- *infiltration available at the end of this section.*
- *zone of aeration available at the end of this section.*
- *zone of saturation available at the end of this section.*
- *groundwater zone available at the end of this section.*
- *water table available at the end of this section.*
- *hygroscopic water available at the end of this section.*
- *capillary water available at the end of this section.*
- *wilting point available at the end of this section.*
- *gravity water available at the end of this section.*
- *field capacity available at the end of this section.*
- *available water available at the end of this section.*
- *percolation available at the end of this section.*
- *seepage available at the end of this section.*
- *aquifer available at the end of this section.*
- *aquiclude available at the end of this section.*

- *hydraulic gradient available at the end of this section.*
- *groundwater flow rate available at the end of this section.*
- *runoff available at the end of this section.*
- *unconfined flow available at the end of this section.*
- *confined flow available at the end of this section.*
- *depression storage available at the end of this section.*
- *stream discharge available at the end of this section.*
- *stream hydrograph available at the end of this section.*
- *water balance available at the end of this section.*
- *precipitation available at the end of this section.*
- *actual evapotranspiration available at the end of this section.*
- *evaporation available at the end of this section.*
- *transpiration available at the end of this section.*
- *evapotranspiration available at the end of this section.*
- *potential evapotranspiration available at the end of this section.*
- *soil moisture storage available at the end of this section.*
- *change in soil moisture storage available at the end of this section.*
- *deficit available at the end of this section.*
- *surplus available at the end of this section.*
- *soil moisture recharge available at the end of this section.*
- *soil moisture utilization available at the end of this section.*

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "The Rise and Fall of Africa's Great Lake" *NASA Earth Observatory*

Connections: "Could California's drought make residents sick?" *NewsHour* (PBS) 09/03/2016 report

Physical Geography Today: Ground Water Climate Response Network - USGS

World of Change: Evaporation of the Aral Sea (*NASA Earth Observatory*)

Multimedia

"The Desert Springs of Mexico's Cuatro Cienegas", (8:56)

Readings

"Defining Drought" National Drought Mitigation Center, University of Nebraska - Lincoln

Web Sites

Water Resources of the United States - United States Geological Survey

National Oceanic and Atmospheric Administration (NOAA)

Answers

Important Terms and Concepts

often called the "water sphere" as it includes all the earth's water found in the oceans, glaciers, streams, lakes, the soil, groundwater, and in the air.

Important Terms and Concepts

aka water cycle. the cycling of water through the earth system. It is a cycle of energy as well.

Important Terms and Concepts

the water that is immediately available to plants.

Important Terms and Concepts

occupies the zone of saturation. Found in aquifers and replenished by percolation of water from the zone of aeration downward to the zone of saturation, or in the recharge zone of a confined aquifer.

Important Terms and Concepts

the phase change of liquid water into a vapor (gas)

Important Terms and Concepts

"locked up" in the water molecule when water undergoes the phase change from a liquid to a gas.

Important Terms and Concepts

droplets of water that fall from the clouds to the earth

Important Terms and Concepts

Precipitation that collects on the leaves or stems of plants

Important Terms and Concepts

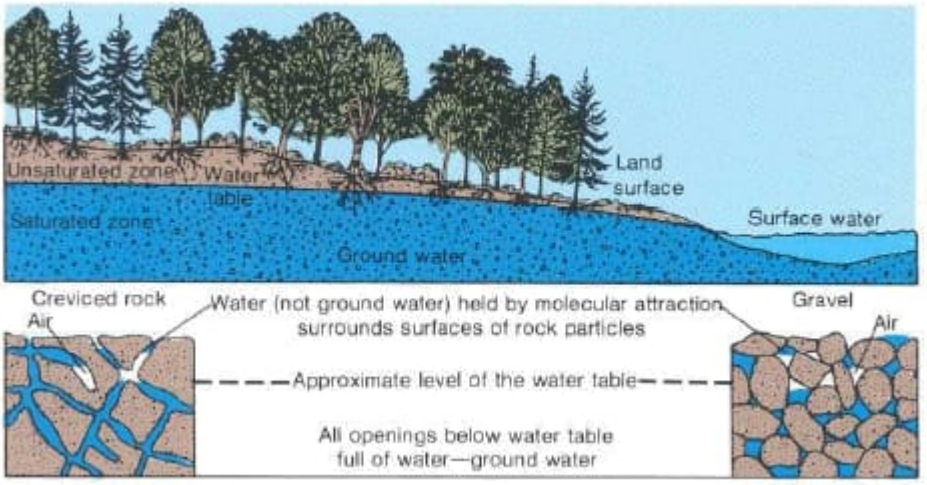
refers to water that penetrates into the surface of soil.

Important Terms and Concepts

aka "unsaturated zone", includes soil water zone. See image under "zone of saturation"

Important Terms and Concepts

includes ground water



Important Terms and Concepts

included in zone of saturation. See image under "zone of saturation"

Important Terms and Concepts

divides the zone of aeration from the zone of saturation. The height of the water table will fluctuate with precipitation, increasing in elevation during wet periods and decreasing during dry.

Important Terms and Concepts
a microscopic film of water surrounding soil particles

Important Terms and Concepts
held by cohesive forces between the films of hygroscopic water

Important Terms and Concepts
At this point the plant cannot pull water from the plant-rooting zone and it wilts

Important Terms and Concepts
water moved through the soil by the force of gravity

Important Terms and Concepts
The amount of water held in the soil after excess water has drained

Important Terms and Concepts
The difference between the wilting point and the field capacity

Important Terms and Concepts
the movement of water downward through the soil

Important Terms and Concepts
water that moves downward through the soil toward a stream channel of large body of water

Important Terms and Concepts
bodies of earth material that have the ability to hold and transmit water

Important Terms and Concepts
dense impermeable layers of earth material

Important Terms and Concepts
the difference in elevation between two points on the water table divided by the horizontal distance between them

Important Terms and Concepts
permeability X hydraulic gradient

Important Terms and Concepts
precipitation that moves across the surface

Important Terms and Concepts
moves across the surface in broad sheets of water often creating sheet erosion

Important Terms and Concepts
water confined to channels

Important Terms and Concepts
Water that became trapped in depressions

Important Terms and Concepts
the volume of water passing through a particular cross-section of a stream in a unit of time

Important Terms and Concepts
illustrates the relationship between discharge and runoff

Important Terms and Concepts
an accounting of the inputs and outputs of water

Important Terms and Concepts
makes up the primarily supply of water to the surface.

Important Terms and Concepts
the amount of water delivered to the air from evaporation and transpiration

Important Terms and Concepts
the phase change from a liquid to a gas releasing water from a wet surface into the air above

Important Terms and Concepts
represents a phase change when water is released into the air by plants

Important Terms and Concepts
combined transfer of water into the air by evaporation and transpiration

Important Terms and Concepts
the amount of water that would be evaporated under an optimal set of conditions, among which is an unlimited supply of water

Important Terms and Concepts
the amount of water held in the soil at any particular time

Important Terms and Concepts
the amount of water that is being added to or removed from what is stored

Important Terms and Concepts
demand for water exceeds that which is actually available; when potential evapotranspiration exceeds actual evapotranspiration (PE>AE)

Important Terms and Concepts

when P exceeds PE and the soil is at its field capacity (saturated); we have more water than we actually need to use given the environmental conditions at a place

Important Terms and Concepts

Precipitation satisfies the need for water with water left over and begins to replenish the soil moisture

Important Terms and Concepts

precipitation is no longer is able to meet the demands of potential evapotranspiration. Plants must extract water that is stored in the soil from the previous months

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3.7: Overview of the Oceans

Let's begin by looking at a few basic facts about the oceans. We often think of Earth in terms of its land area, but in reality 71% of the Earth's surface is covered by oceans, while only 29% is land. Oceans cover an area of 139 million miles^2 or 361 million km^2, and contain a volume of about 1.37 billion km^3 of water. All of this water is not distributed equally over the Earth; 61% of the Northern Hemisphere is covered by oceans, while in the Southern Hemisphere the oceans cover 81% of the surface area (Figure 3.7.1).

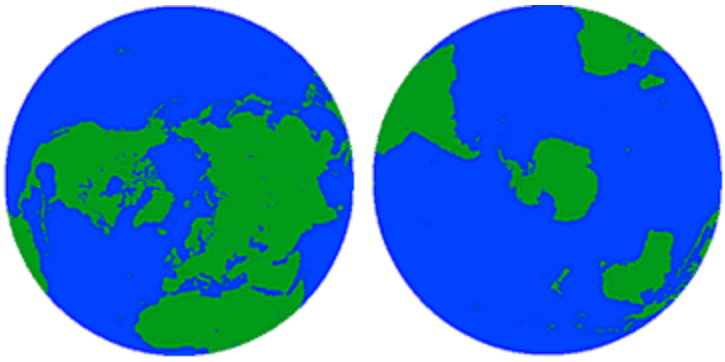


Figure 3.7.1 Ocean cover in the Northern (left) and Southern (right) Hemispheres.

Various sources differ in the number of recognized ocean basins. Historically the major oceans were recognized as the Pacific, Atlantic, Indian, and Arctic Oceans. More recently, the Southern Ocean has been recognized as fifth named ocean, comprising all of the water from the coast of Antarctica to 60° S (Figure 3.7.2). In 2000 these boundaries were submitted to the International Hydrographic Organization for official recognition, but several countries do not recognize it as a separate ocean, but rather as the southern extension of the other major oceans. The Southern Ocean has its own unique characteristics, so for the purposes of this book we will include it as a separate ocean.

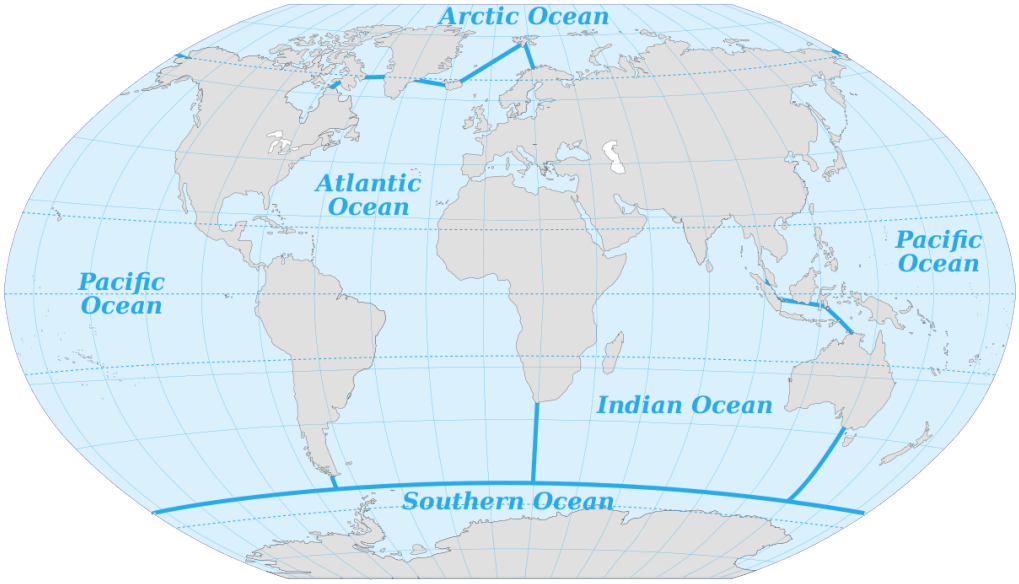


Figure 3.7.2 Map of the world oceans (By Pinpin [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0], via Wikimedia Commons).

The oceans account for vast amounts of water, containing 97% of the water on Earth's surface, with over half of the water in the Pacific alone (Table 1.1.1).

Table 3.7.1 Percentage of Earth's water in various locations

Pacific	52%
Atlantic	25%
Indian	20%
Ice	2%
Ground water	0.6%
Atmosphere, lakes & rivers	0.01%

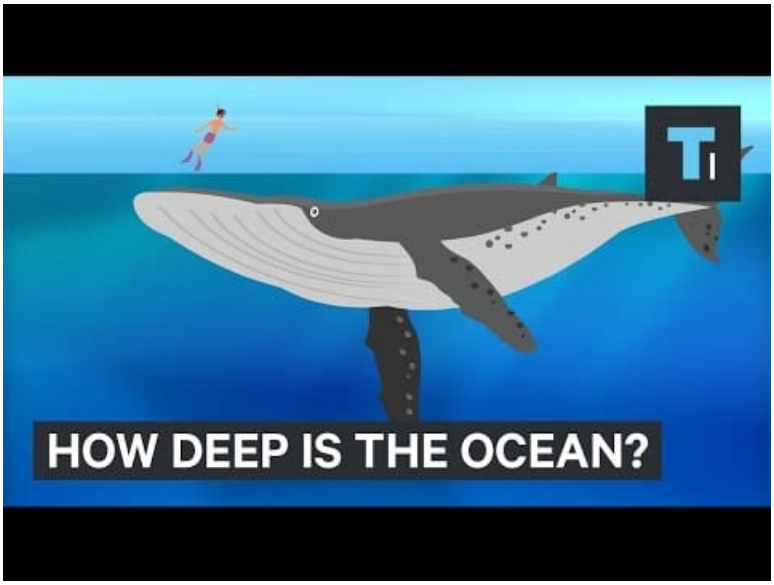
The average depth of the world ocean is about 3800m (12,500 ft), which is about four times deeper than the average land elevation is high (840m or 2800 ft). In fact Mt. Everest, the highest point on land, is 8848m (29,028 ft) high, while the deepest part of the ocean, the Challenger Deep of the Marianas Trench is 11,022m (36,200 ft) deep. So you could submerge Mt. Everest in the Marianas Trench and it would still be covered by over 2 km of water! Because there is so much more water on Earth than there is land, if you could smooth out the land elevation the entire Earth would still be covered by water about 2700 m deep.

Of the major ocean basins, the Pacific is the largest (almost as large as all of the others combined), and is the deepest (Table 1.1.2).

Table 3.7.2 Area and depth of the major oceans

	Area (million km^2)	**Average depth (m)**
Pacific	166	4282
Atlantic	87	3926
Indian	73	3963
Arctic	14	1205
Southern	20	4000

Watch the video below for some perspective on the size and depth of the oceans.



A YouTube element has been excluded from this version of the text. You can view it online here: https://rwu.pressbooks.pub/webboceanography/?p=24

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3.8: Ocean Circulation

Atmospheric Circulation

Differential heating of the Earth's surface results in equatorial regions receiving more heat than the poles. As air is warmed at the equator it becomes less dense and rises, while at the poles the cold air is denser and sinks. If the Earth was non-rotating, the warm air rising at the equator would reach the upper atmosphere and begin moving horizontally towards the poles. As the air reached the poles it would cool and sink, and would move over the surface of Earth back towards the equator. This would result in one large atmospheric convection cell in each hemisphere (Figure 3.8.1), with air rising at the equator and sinking at the poles, and the movement of air over the Earth's surface creating the winds. On this non-rotating Earth, the prevailing winds would thus blow from the poles towards the equator in both hemispheres (Figure 3.8.1).

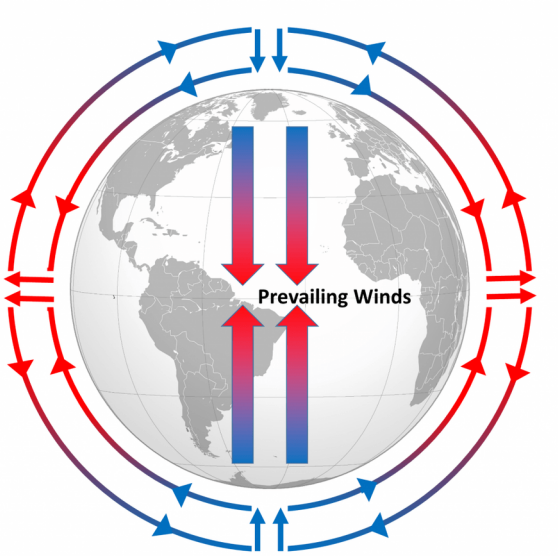


Figure 3.8.1: Hypothetical atmospheric convection cells on a non-rotating Earth. Air rises at the equator and sinks at the poles, creating a single convection cell in each hemisphere. The prevailing winds moving over the Earth's surface blow from the poles towards the equator in both hemispheres (Modified by Paul Webb from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

The non-rotating situation in Figure 3.8.1 is of course only hypothetical, and in reality the Earth's rotation makes this atmospheric circulation a bit more complex. The paths of the winds on a rotating Earth are deflected by the **Coriolis Effect**. The Coriolis Effect is a result of the fact that different latitudes on Earth rotate at different speeds. This is because every point on Earth must make a complete rotation in 24 hours, but some points must travel farther, and therefore faster, to complete the rotation in the same amount of time. In 24 hours a point on the equator must complete a rotation distance equal to the circumference of the Earth, which is about 40,000 km. A point right on the poles covers no distance in that time; it just turns in a circle. So the speed of rotation at the equator is about 1600 km/hr, while at the poles the speed is 0 km/hr. Latitudes in between rotate at intermediate speeds; approximately 1400 km/hr at 30° and 800 km/hr at 60°. As objects move over the surface of the Earth they encounter regions of varying speed, which causes their path to be deflected by the Coriolis Effect.

To explain the Coriolis Effect, imagine a cannon positioned at the equator and facing north. Even though the cannon appears stationary to someone on Earth, it is in fact moving east at about 1600 km/hr due to Earth's rotation. When the cannon fires the projectile travels north towards its target; but it also continues to move to the east at 1600 km/hr, the speed it had while it was still in the cannon. As the shell moves over higher latitudes, its momentum carries it eastward faster than the speed at which the ground beneath it is rotating. For example, by 30° latitude the shell is moving east at 1600 km/hr while the ground is moving east at only 1400 km/hr. Therefore, the shell gets "ahead" of its target, and will land to the east of its intended destination. From the point of view of the cannon, the path of the projectile appears to have been deflected to the right (red arrow, Figure 3.8.2). Similarly, a cannon located at 60° and facing the equator will be moving east at 800 km/hr. When its shell is fired towards the

equator, the shell will be moving east at 800 km/hr, but as it approaches the equator it will be moving over land that is traveling east *faster* than the projectile. So the projectile gets "behind" its target, and will land to the west of its destination. But from the point of view of the cannon facing the equator, the path of the shell still appears to have been deflected to the right (green arrow, Figure 3.8.2). Therefore, in the Northern Hemisphere, the apparent Coriolis deflection will *always* be to the **right**.

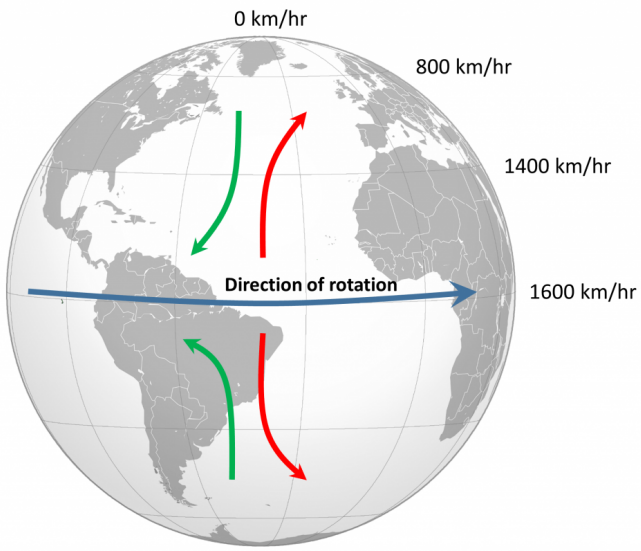


Figure 3.8.2: The Coriolis Effect. Objects moving from the equator towards the poles (red arrows) move into a region of slower rotational speed and their paths are deflected "ahead" of their point of origin. Movement from high latitudes to low latitudes (green arrows) goes from a region of low speed to a region of higher rotation speed, and there is deflection "behind" their point of origin. In the Northern Hemisphere this deflection is always to the right from the point of origin, and in the Southern Hemisphere the deflection is always to the left (Modified by Paul Webb from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

In the Southern Hemisphere the situation is reversed (Figure 3.8.2). Objects moving towards the equator from the south pole are moving from low speed to high speed, so are left behind and their path is deflected to the left. Movement from the equator towards the south pole also leads to deflection to the left. In the Southern Hemisphere, the Coriolis deflection is always to the **left** from the point of origin.

The magnitude of the Coriolis deflection is related to the difference in rotation speed between the start and end points. Between the poles and 60° latitude, the difference in rotation speed is 800 km/hr. Between the equator and 30° latitude, the difference is only 200 km/hr (Figure 3.8.2). Therefore the strength of the Coriolis Effect is stronger near the poles, and weaker at the equator.

Because of the rotation of the Earth and the Coriolis Effect, rather than a single atmospheric convection cell in each hemisphere, there are three major cells per hemisphere. Warm air rising at the equator cools as it moves through the upper atmosphere, and it descends at around 30° latitude. The convection cells created by rising air at the equator and sinking air at 30° are referred to as **Hadley Cells**, of which there is one in each hemisphere. The cold air that descends at the poles moves over the Earth's surface towards the equator, and by about 60° latitude it begins to rise, creating a **Polar Cell** between 60° and 90°. Between 30° and 60° lie the **Ferrel Cells**, composed of sinking air at 30° and rising air at 60° (Figure 3.8.3). With three convection cells in each hemisphere that rotate in alternate directions, the surface winds no longer always blow from the poles towards the equator as in the non-rotating Earth in Figure 3.8.1. Instead, surface winds in both hemispheres blow towards the equator between 90° and 60° latitude, and between 0° and 30° latitude. Between 30° and 60° latitude, the surface winds blow towards the poles (Figure 3.8.3).

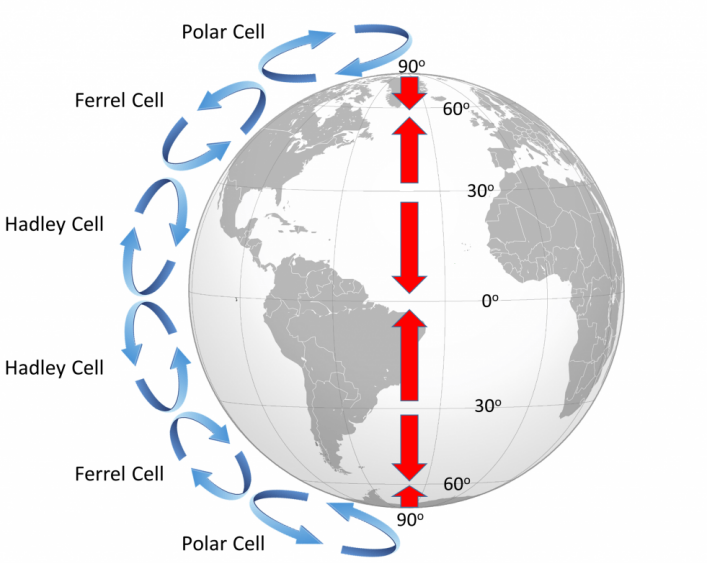


Figure 3.8.3: On a rotating Earth, there are three atmospheric convection cells in each hemisphere, leading to alternating bands of surface winds (red arrows)
(Modified by Paul Webb from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

The surface winds created by the atmospheric convection cells are also influenced by the Coriolis Effect as they change latitudes. The Coriolis Effect deflects the path of the winds to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Adding this deflection leads to the pattern of prevailing winds illustrated in Figure 3.8.4. Between the equator and 30° latitude are the **trade winds**; the northeast trade winds in the Northern Hemisphere and the southeast trade winds in the Southern Hemisphere (note that winds are named based on the direction from which they originate, not where they are going). The **westerlies** are the dominant winds between 30° and 60° in both hemispheres, and the **polar easterlies** are found between 60° and the poles.

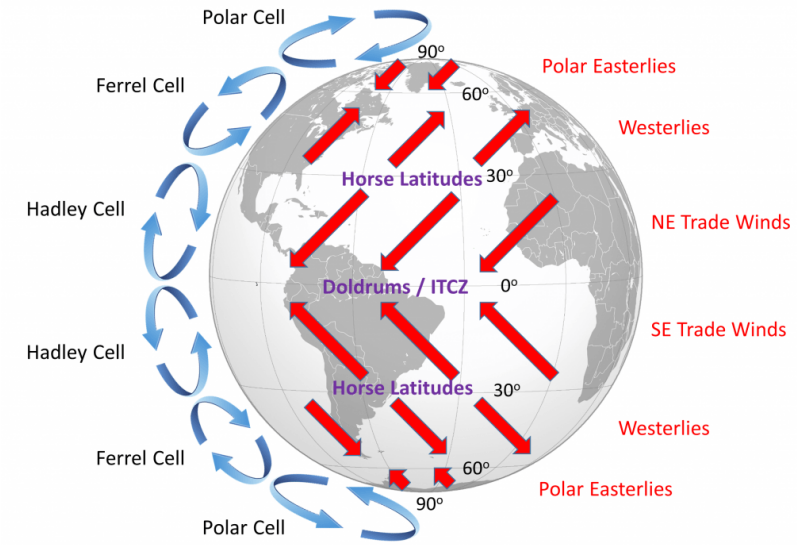


Figure 3.8.4: The prevailing wind patterns of Earth (Modified by PW from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

In between these wind bands lie regions of high and low pressure. High pressure zones occur where air is descending, while low pressure zones indicate rising air. Along the equator the rising air creates a low pressure region called the **doldrums**, or the **Intertropical Convergence Zone** (ITCZ) (convergence zone because this is where the trade winds converge). At 30° latitude there are high pressure zones of descending air known as the **horse latitudes**, or the subtropical highs. Finally, at 60° lies

another low pressure region called the **polar front**. It should be noted that these high and low pressure zones are not fixed in place; their latitude fluctuates depending on the season, and these fluctuations have important implications for regional climates.

Doldrums, horse latitudes, and trade winds may seem like some odd names for these atmospheric phenomena, but many of them can be traced back to maritime traditions and lore. The **doldrums** refer to regions of low pressure around the equator. In these areas, air is rising rather than moving horizontally, so these regions commonly encounter very light winds. The lack of wind could leave sailing ships becalmed for days or weeks at a time, which was not good for the morale of the ship's crew. Like the doldrums the **horse latitudes** are also areas with light winds, this time due to descending air, which could leave ships becalmed. The term **trade winds** may have originally derived from the terms for "track" or "path", but the term may have become more common during European exploration and commercialization of the New World. Mariners sailing from Europe to the New World could sail south until they reached the trade winds, which would then propel their ships across the Atlantic to the Caribbean. To return to Europe, ships could sail to the northeast until they entered the westerlies, which would then steer them back to Europe.

In addition to their role in creating the surface winds, these high and low pressure systems also influence other climatic phenomena (Figure 3.8.5. Along the equator air is rising as it is warmed by solar radiation. Warm air contains more water vapor than cold air, which is why we experience humidity during the summer and not during the winter. The water content of air roughly doubles with every 10° C increase in temperature. So the air rising at the equator is warm and full of water vapor; as it rises into the upper atmosphere it cools, and the cool air can no longer hold as much water vapor, so the water condenses and forms rain. Therefore, low pressure systems are associated with precipitation, and we see wet habitats like tropical rainforests near the equator (Figure 3.8.5.

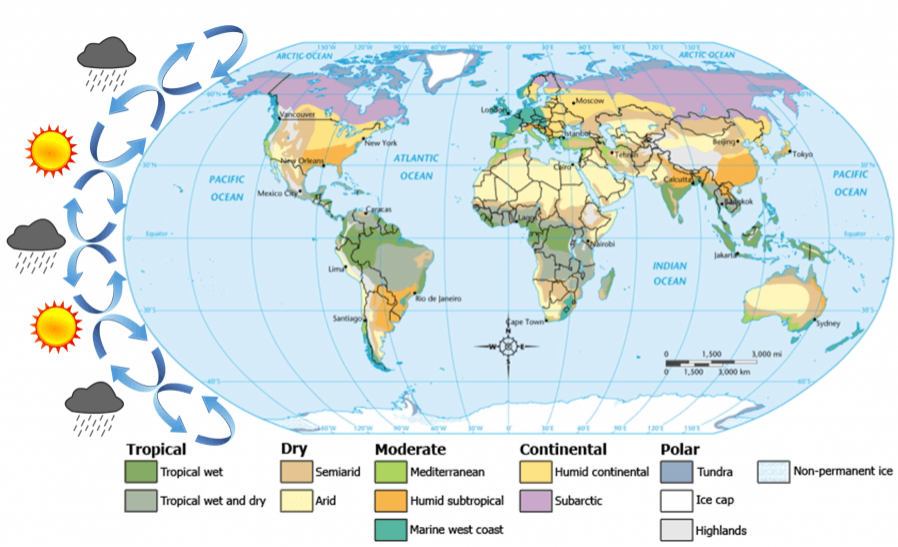


Figure 3.8.5: Major global climatic regions in relation to atmospheric convection cells. Rising air and low pressure creates rain and wet environments at 0° and 60° latitudes, while high pressure, sinking air creates drier conditions at 30° and 90° latitudes. (Modified by Paul Webb; Map by Waitak at en.Wikipedia Later version(s) were uploaded by Splette at en.Wikipedia; Sun by Inductiveload (Own work Based on File:Nuvola_apps_kweather.svg); Raincloud by Calusarul (Own work); all [CC BY-SA 3.0], via Wikimedia Commons).

After rising and producing rain near the equator, the air masses move towards 30° latitude and sink back towards Earth as part of the Hadley convection cells. This air has lost most of its moisture after producing the equatorial rains, so the sinking air is dry, resulting in arid climates near 30° latitude in both hemispheres. Many of the major desert regions on Earth are located near 30° latitude, including much of Australia, the Middle East, and the Sahara Desert of Africa (Figure 3.8.5. The air also becomes compressed and heats up as it sinks, absorbing any moisture from the clouds and creating clear skies. Thus high pressure systems are associated with dry weather and clear skies. This cycle of high and low pressure regions continues with the Ferrel and Polar convection cells, leading to rain and the boreal forests at 60° latitude in the Northern Hemisphere (there are no corresponding large land masses at these latitudes in the Southern Hemisphere). At the poles, descending, dry air produces little precipitation, leading to the polar desert climate.

The elevation of the land also plays a role in precipitation and climactic characteristics. As moist air moves over land and encounters mountains it rises, expands, and cools because of the declining pressure and temperature. The cool air holds less water vapor, so condensation occurs and rain falls on the windward side of the mountains (Figure 3.8.6. As the air passes over the mountains to the leeward side, it is now dry air, and as it sinks the pressure increases, it heats back up, any moisture revaporizes, and it creates dry, deserts regions behind the mountains (Figure 3.8.6. This phenomenon is referred to as a **rain shadow**, and can be found in areas such as the Tibetan Plateau and Gobi Desert behind the Himalayas, Death Valley behind the Sierra Nevada mountains, and the dry San Joaquin Valley in California.

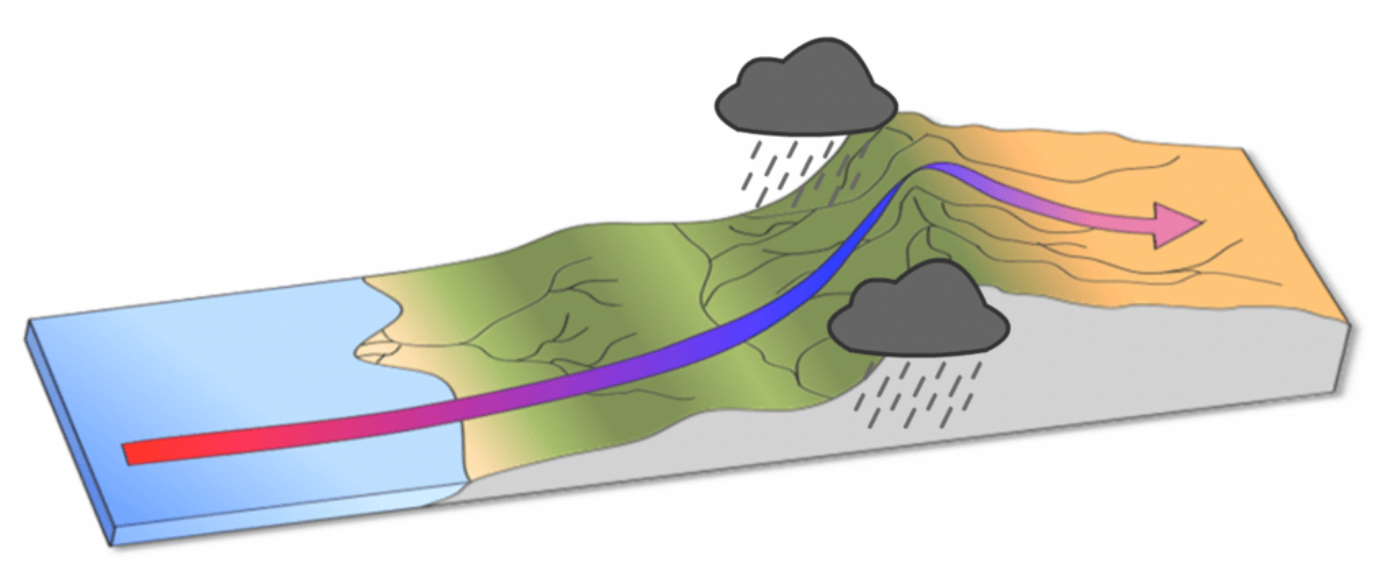


Figure 3.8.6: A rain shadow. Air rising over mountains cools and condenses and forms rain, leaving dry descending air and arid conditions on the other side of the mountain (Modified by Paul Webb from Thebiologyprimer, Public domain via Wikimedia Commons).

Ocean Circulation

Not unexpectedly, the oceans are warmest near the equator—typically 25° to 30°C—and coldest near the poles—around 0°C (Figure 3.8.7). (Sea water will remain unfrozen down to about -2°C.) Variations in sea-surface temperatures (SST) are related to redistribution of water by ocean currents, as we'll see below. A good example of that is the plume of warm Gulf Stream water that extends across the northern Atlantic. St. John's, Newfoundland, and Brittany in France are at about the same latitude (47.5° N), but the average SST in St. John's is a frigid 3°C, while that in Brittany is a reasonably comfortable 15°C.

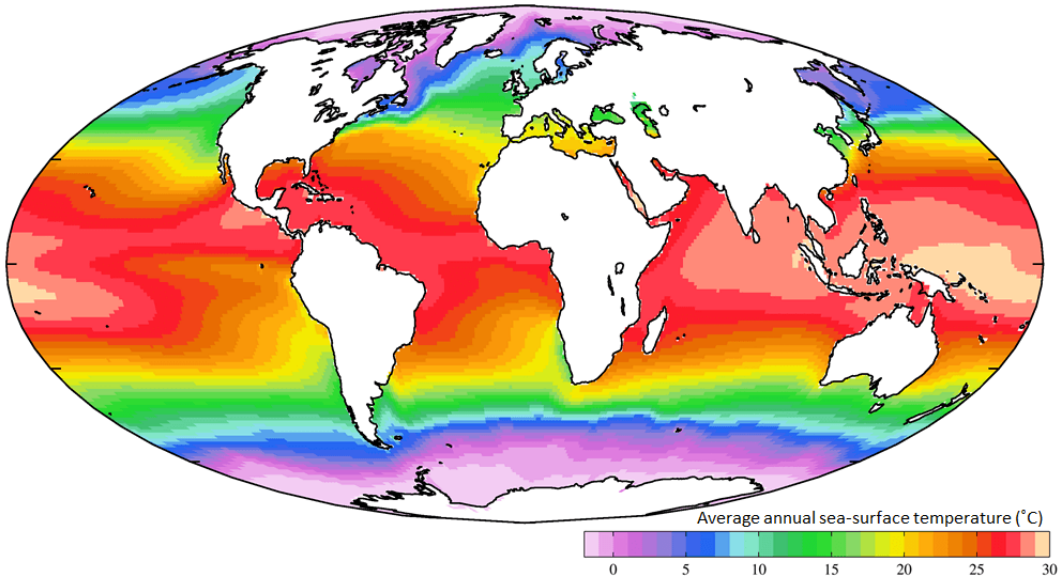


Figure 3.8.7: The global distribution of average annual sea-surface temperatures.
[© Plumbago. CC BY-SA. *https://upload.wikimedia.org/wikiped..._TMP_AYool.png*]

Currents in the open ocean are created by wind moving across the water and by density differences related to temperature and salinity. An overview of the main ocean currents is shown in Figure 3.8.8. As you can see, the northern hemisphere currents form circular patterns (**gyres**) that rotate clockwise, while the southern hemisphere gyres are counter-clockwise. This happens for the same reason that the water in your northern hemisphere sink rotates in a clockwise direction as it flows down the drain; this is caused by the **Coriolis effect**.

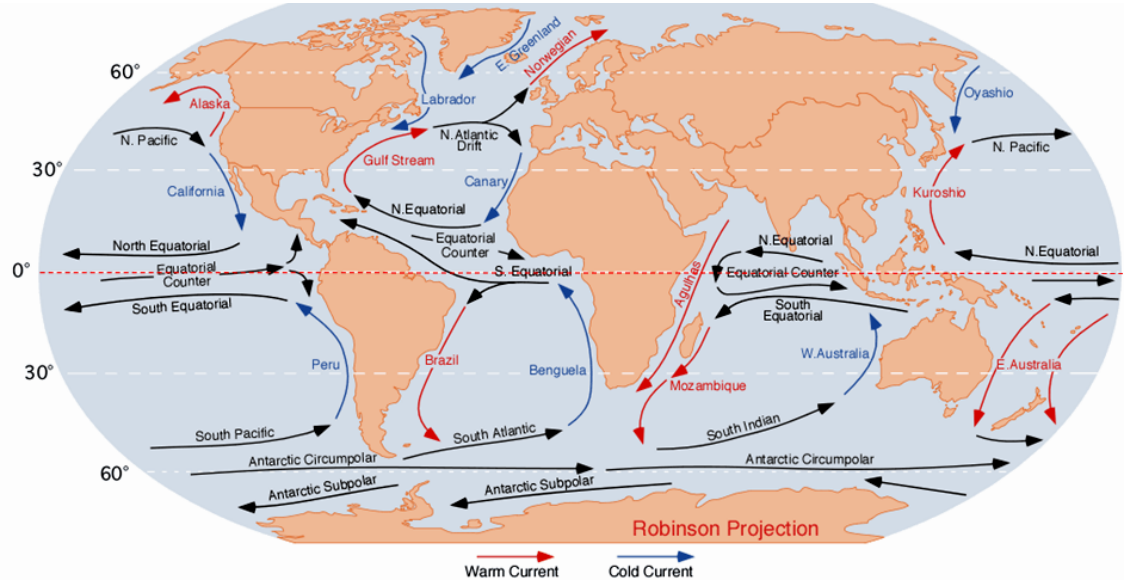


Figure 3.8.8: Overview of the main open-ocean currents. Red arrows represent warm water moving toward colder regions. Blue arrows represent cold water moving toward warmer regions. Black arrows represent currents that don't involve significant temperature changes.
["Corrientes Oceanicas" by Dr. Michael Pidwirny. Public domain. From: *https://upload.wikimedia.org/wikiped...-oceanicas.png*]

Because the ocean basins aren't like bathroom basins, not all ocean currents behave the way we would expect. In the North Pacific, for example, the main current flows clockwise, but there is a secondary current in the area adjacent to our coast—the Alaska Current—that flows counter-clockwise, bringing relatively warm water from California, past Oregon, Washington, and B.C. to Alaska. On Canada's eastern coast, the cold Labrador Current flows south past Newfoundland, bringing a stream of icebergs past the harbour at St. John's (Figure 3.8.9). This current helps to deflect the Gulf Stream toward the northeast, ensuring that Newfoundland stays cool, and western Europe stays warm.



Figure 3.8.9: An iceberg floating past Exploits Island on the Labrador Current.
"Newfoundland Iceberg just off Exploits Island" © Shawn. CC BY-SA.

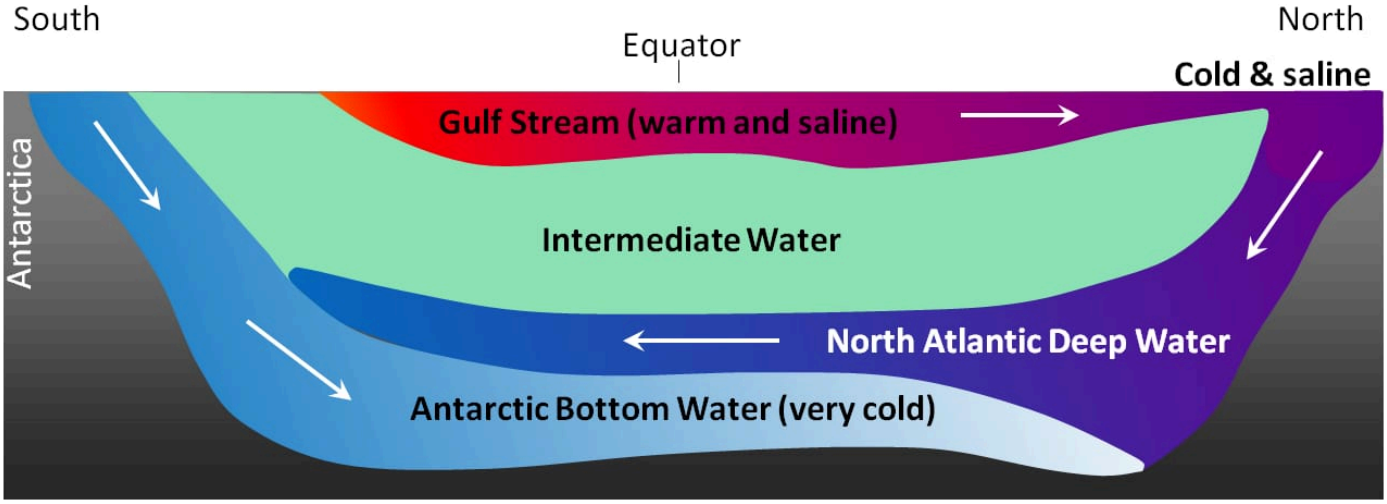


Figure 3.8.10: A depiction of the vertical movement of water along a north-south cross-section through the Atlantic basin.
© Steven Earle. CC BY.

The currents shown in Figure 3.8.8 are all surface currents, and they only involve the upper few hundred meters of the oceans. But there is much more going on underneath. The Gulf Stream, for example, which is warm and saline, flows past Britain and Iceland into the Norwegian Sea (where it becomes the Norwegian Current). As it cools down, it becomes denser, and because of its high salinity, which also contributes to its density, it starts to sink beneath the surrounding water (Figure 3.8.10). At this point, it is known as **North Atlantic Deep Water** (NADW), and it flows to significant depth in the Atlantic as it heads back south. Meanwhile, at the southern extreme of the Atlantic, very cold water adjacent to Antarctica also sinks to the bottom to become **Antarctic Bottom Water** (AABW) which flows to the north, underneath the NADW.

The descent of the dense NADW is just one part of a global system of seawater circulation, both at surface and at depth, as illustrated in Figure 3.8.11. The water that sinks in the areas of deep water formation in the Norwegian Sea and adjacent to Antarctica moves very slowly at depth. It eventually resurfaces in the Indian Ocean between Africa and India, and in the Pacific Ocean, north of the equator.

Image of depiction of the vertical movements of water along north south throught the Atlanic Basin

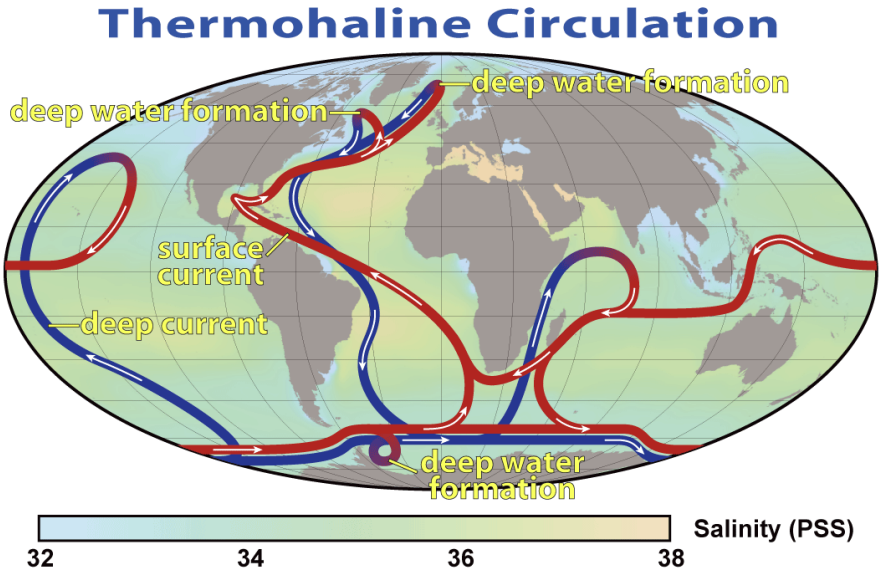


Figure 3.8.11: The thermohaline circulation system, also known as the Global Ocean Conveyor.
["Thermohaline Circulation" by NASA. Public domain from: *https://en.Wikipedia.org/wiki/Thermo...culation_2.png*]

The thermohaline circulation is critically important to the transfer of heat on Earth. It brings warm water from the tropics to the poles, and cold water from the poles to the tropics, thus keeping polar regions from getting too cold and tropical regions from getting too hot. A reduction in the rate of thermohaline circulation would lead to colder conditions and enhanced formation of sea ice at the poles. This would start a positive feedback process that could result in significant global cooling. There is compelling evidence to indicate that there were major changes in thermohaline circulation, corresponding with climate changes, during the Pleistocene Glaciation.

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3.9: Waves

Learning Objectives

After reading this chapter you should:

- know the parts of a basic wave
- know the terminology used to describe the motion of a wave (i.e. period, frequency, speed etc.)
- understand the circular motion of water particles involved in wave motion
- understand the difference between deep water waves and shallow water waves
- know what factors influence wave speed in deep and shallow waves
- know the three factors that determine the energy of wind-generated waves
- understand the concept of restoring force
- understand the difference between seas and swell
- understand the concepts of destructive, constructive and mixed interference
- understand why waves break as they approach shore
- know the differences in the different types of breakers, and how the bottom topography impacts breaker type
- understand why waves always approach parallel to shore, and why waves are larger off of points and smaller in bays
- understand what causes tsunamis, and how they behave in the ocean

What was the largest wave ever recorded? 50 feet? 100 feet? Not even close. That record belongs to a wave created in Lituya Bay, Alaska, on July 9, 1958. On that day, a magnitude 7.8 earthquake caused a massive rockslide that slid down a mountainside and into the headwaters of the bay. The rockslide created a splash wave that was high enough to flatten vegetation up to 1722 ft (525 m) above sea level! The wave then moved through the narrow bay towards the sea, destroying a number of fishing boats along the way. Miraculously, a father and son on one fishing boat were carried above the trees by the wave, and survived to tell the story. This is by far the largest wave, a megatsunami, ever reliably recorded. The waves we will discuss in this chapter may not be quite that dramatic, but it is still important to know how they form, how they are propagated, and what happens to them as they interact with the shore.



A view of Lituya Bay taken a few weeks after the 1958 megatsunami. The rockslide occurred in the mountains at the head of the bay, producing the wave that them moved through the bay towards the sea (D.J. Miller, United States Geological Survey, [Public domain], via Wikimedia Commons).

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3.10: Wave Basics

Waves generally begin as a disturbance of some kind, and the energy of that disturbance gets propagated in the form of waves. We are most familiar with the kind of waves that break on shore, or rock a boat at sea, but there are many other types of waves that are important to oceanography:

- **Internal waves** form at the boundaries of water masses of different densities (i.e. at a pycnocline), and propagate at depth. These generally move more slowly than surface waves, and can be much larger, with heights exceeding 100 m. However, the height of the deep wave would be unnoticeable at the surface.
- **Tidal waves** are due to the movement of the tides. What we think of as tides are basically enormously long waves with a wavelength that may span half the globe (see section 11.1). Tidal waves are not related to tsunamis, so don't confuse the two.
- **Tsunamis** are large waves created as a result of earthquakes or other seismic disturbances. They are also called seismic sea waves (section 10.4).
- **Splash waves** are formed when something falls into the ocean and creates a splash. The giant wave in Lituya Bay that was described in the introduction to this chapter was a splash wave.
- **Atmospheric waves** form in the sky at the boundary between air masses of different densities. These often create ripple effects in the clouds (Figure 3.10.1).



Figure 3.10.1 Wake patterns in cloud cover over Possession Island, East Island, Ile aux Cochons, Ile de Pingouins. The ripple pattern is a result of internal waves in the atmosphere (NASA [Public domain], via Wikimedia Commons).

There are several components to a basic wave (Figure 3.10.2):

- **Still water level:** where the water surface would be if there were no waves present and the sea was completely calm.
- **Crest:** the highest point of the wave.
- **Trough:** the lowest point of the wave.
- **Wave height:** the distance between the crest and the trough.
- **Wavelength:** the distance between two identical points on successive waves, for example crest to crest, or trough to trough.
- **Wave steepness:** the ratio of wave height to length (H/L). If this ratio exceeds 1/7 (i.e. height exceeds 1/7 of the wavelength) the wave gets too steep, and will break.

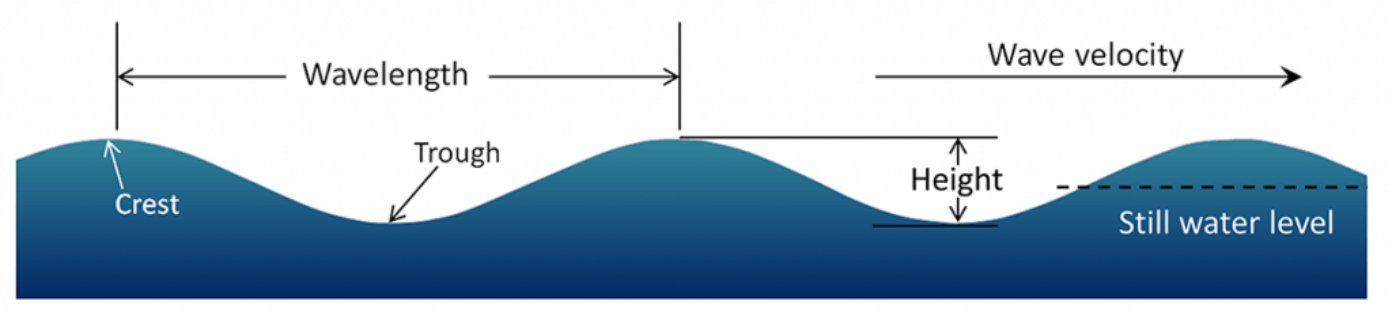


Figure 3.10.2 Components of a basic wave (Modified by PW from Steven Earle "Physical Geology").

There are also a number of terms used to describe wave motion:

- **Period:** the time it takes for two successive crests to pass a given point.
- **Frequency:** the number of waves passing a point in a given amount of time, usually expressed as waves per second. This is the inverse of the period.
- **Speed**: how fast the wave travels, or the distance traveled per unit of time. This is also called celerity (c), where

c = wavelength x frequency

Therefore, the longer the wavelength, the faster the wave.

Although waves can travel over great distances, the water itself shows little horizontal movement; it is the *energy* of the wave that is being transmitted, not the water. Instead, the water particles move in circular orbits, with the size of the orbit equal to the wave height (Figure 3.10.3). This orbital motion occurs because water waves contain components of both longitudinal (side to side) and transverse (up and down) waves, leading to circular motion. As a wave passes, water moves forwards and up over the wave crests, then down and backwards into the troughs, so there is little horizontal movement. This is evident if you have ever watched an object such as a seabird floating at the surface. The bird bobs up and down as the wave pass underneath it; it does not get carried horizontally by a single wave crest.

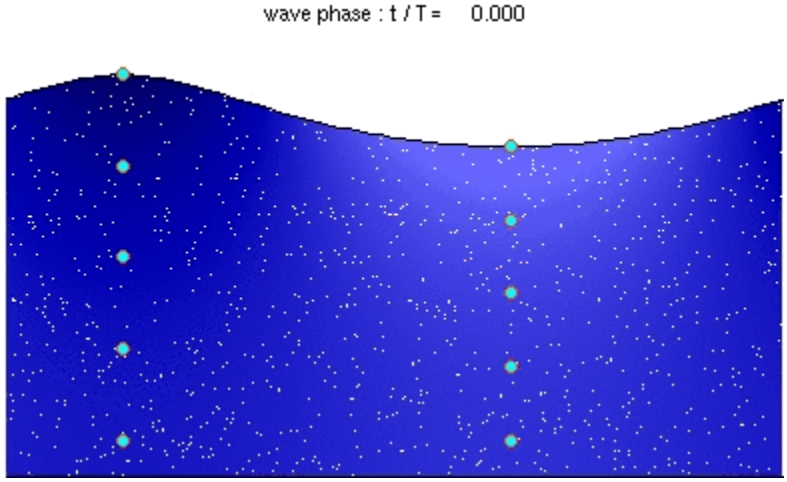


Figure 3.10.3 Animation showing the orbital motion of particles in a surface wave (By Kraaiennest (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 4.0], via Wikimedia Commons).

The circular orbital motion declines with depth as the wave has less impact on deeper water and the diameter of the circles is reduced. Eventually at some depth there is no more circular movement and the water is unaffected by surface wave action. This depth is the **wave base** and is equivalent to half of the wavelength (Figure 3.10.4). Since most ocean waves have wavelengths of less than a few hundred meters, most of the deeper ocean is unaffected by surface waves, so even in the strongest storms marine life or submarines can avoid heavy waves by submerging below the wave base.

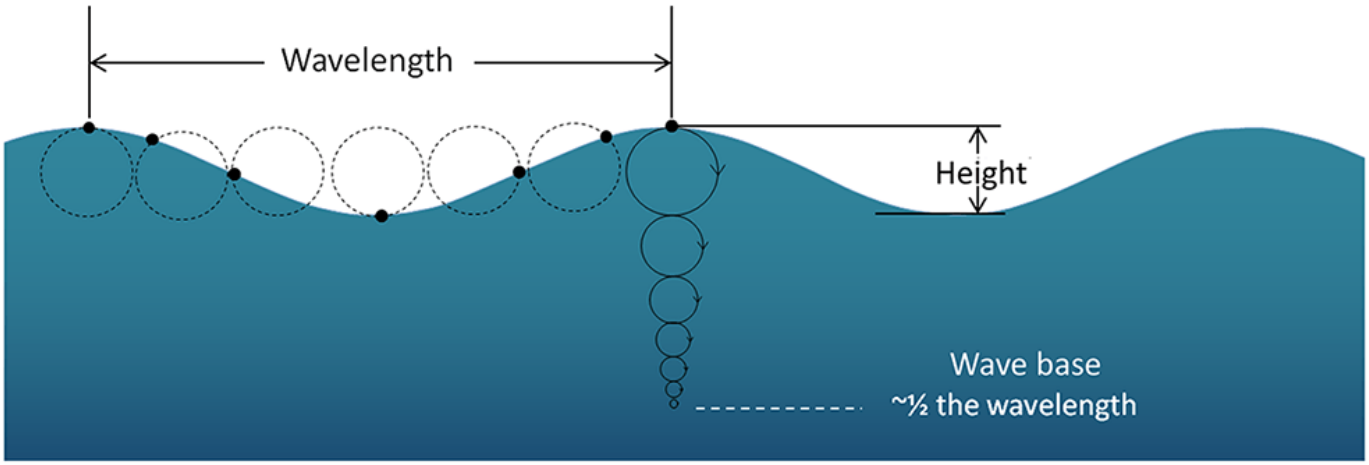


Figure 3.10.4 Orbital motion of water within a wave, extending down to the wave base at a depth of half of the wavelength (Modified by PW from Steven Earle, "Physical Geology").

When the water below a wave is deeper than the wave base (deeper than half of the wavelength), those waves are called **deep water waves**. Most open ocean waves are deep water waves. Since the water is deeper than the wave base, deep water waves experience no interference from the bottom, so their speed only depends on the wavelength:

$$s)} = \sqrt{\frac{gL}{2\pi}}$$

where g is gravity and L is wavelength in meters. Since g and π are constants, this can be simplified to:

$$s)} = 1.25\sqrt{L}$$

Shallow water waves occur when the depth is less than 1/20 of the wavelength. In these cases, the wave is said to "touch bottom" because the depth is shallower than the wave base so the orbital motion is affected by the seafloor. Due to the shallow depth, the orbits are flattened, and eventually the water movement becomes horizontal rather than circular just above the bottom. The speed of shallow water waves depends only on the depth:

$$s)} = \sqrt{gd}$$

where g is gravity and d is depth in meters. This can be simplified to:

$$s)} = 3.13\sqrt{d}$$

Intermediate or **transitional waves** are found in depths between ½ and 1/20 of the wavelength. Their behavior is a bit more complex, as their speed is influenced by both wavelength and depth. The speed of an intermediate wave is calculated as:

$$s)} = \sqrt{\frac{gL}{2\pi}\tanh(2\pi{\frac{d}{L}})}$$

which contains both depth and wavelength variables.

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3.11: Waves at Sea

Most ocean waves are generated by wind. Wind blowing across the water's surface creates little disturbances called **capillary waves**, or ripples that start from gentle breezes (Figure 3.11.1). Capillary waves have a rounded crest with a V-shaped trough, and wavelengths less than 1.7 cm. These small ripples give the wind something to "grip" onto to generate larger waves when the wind energy increases, and once the wavelength exceeds 1.7 cm the wave transitions from a capillary wave to a wind wave. As waves are produced, they are opposed by a **restoring force** that attempts to return the water to its calm, equilibrium condition. The restoring force of the small capillary waves is surface tension, but for larger wind-generated waves gravity becomes the restoring force.



Figure 3.11.1 Small capillary waves or ripples caused by winds blowing over the surface of calm water (By Blue Elf (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0], via Wikimedia Commons).

As the energy of the wind increases, so does the size, length and speed of the resulting waves. There are three important factors determining how much energy is transferred from wind to waves, and thus how large the waves will get:

- Wind **speed.**
- The **duration** of the wind, or how long the wind blows continuously over the water.
- The distance over which the wind blows across the water in the same direction, also known as the **fetch**.

Increasing any of these factors increases the energy of wind waves, and therefore their size and speed. But there is an upper limit to how large wind-generated waves can get. As wind energy increases, the waves receive more energy and they get both larger and steeper (recall from section 10.1 that wave steepness = height/wavelength). When the wave height exceeds 1/7 of the wavelength, the wave becomes unstable and collapses, forming whitecaps. Under strong wind conditions, the ocean surface becomes an irregular mixture of choppy, whitecapped wind-generated waves. The term **sea state** describes the size and extent of the wind-generated waves in a particular area. When the waves are at their maximum size for the existing wind speed, duration, and fetch, it is referred to as a fully developed sea. The sea state is often reported on the **Beaufort scale**, ranging from 0-12, where 0 means calm, windless and waveless conditions, while Beaufort 12 is a hurricane (see box below).

The Beaufort Scale

The Beaufort scale is used to describe the wind and sea state conditions on the ocean. It is an observational scale based on the judgement of the observer, rather than one dictated by accurate measurements of wave height. Beaufort 0 represents calm, flat conditions, while Beaufort 12 represents a hurricane.



BEAUFORT FORCE 0
WIND SPEED: LESS THAN 1 KNOT

SEA: SEA LIKE A MIRROR



BEAUFORT FORCE 1
WIND SPEED: 1-3 KNOTS

SEA: WAVE HEIGHT .1M (.25FT), RIPPLES WITH THE APPEARANCE OF SCALES, BUT WITHOUT FOAM CRESTS



BEAUFORT FORCE 2
WIND SPEED: 4-6 KNOTS

SEA: WAVE HEIGHT .2-.3M (.5-1FT), SMALL WAVELETS, CRESTS HAVE A GLASSY APPEARANCE AND DO NOT BREAK



BEAUFORT FORCE 3
WIND SPEED: 7-10 KNOTS

SEA: WAVE HEIGHT .6-1M (2-3FT), LARGE WAVELETS, CRESTS BEGIN TO BREAK, ANY FOAM HAS GLASSY APPEARANCE, SCATTERED WHITECAPS



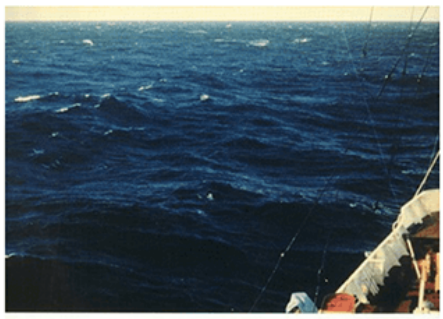
BEAUFORT FORCE 4
WIND SPEED: 11-16 KNOTS

SEA: WAVE HEIGHT 1-1.5M (3.5-5FT), SMALL WAVES BECOMING LONGER, FAIRLY FREQUENT WHITE HORSES



BEAUFORT FORCE 5
WIND SPEED: 17-21 KNOTS

SEA: WAVE HEIGHT 2-2.5M (6-8FT), MODERATE WAVES TAKING MORE PRONOUNCED LONG FORM, MANY WHITE HORSES, CHANCE OF SOME SPRAY



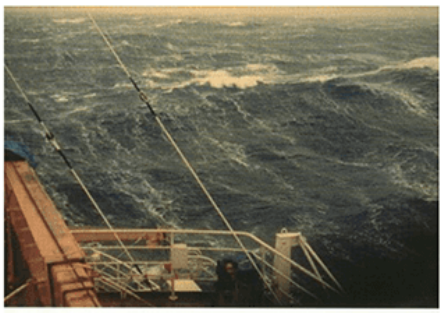
BEAUFORT FORCE 6
WIND SPEED: 22-27 KNOTS

SEA: WAVE HEIGHT 3-4M (9.5-13 FT), LARGER WAVES BEGIN TO FORM, SPRAY IS PRESENT, WHITE FOAM CRESTS ARE EVERYWHERE



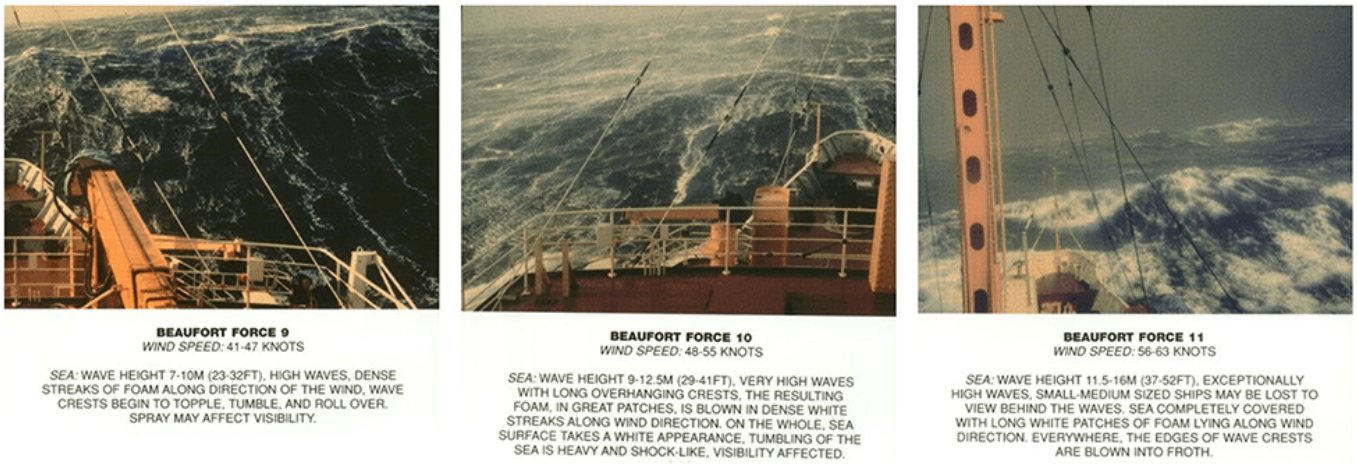
BEAUFORT FORCE 7
WIND SPEED: 28-33 KNOTS

SEA: WAVE HEIGHT 4-5.5M (13.5-19 FT), SEA HEAPS UP, WHITE FOAM FROM BREAKING WAVES BEGINS TO BE BLOWN IN STREAKS ALONG THE WIND DIRECTION



BEAUFORT FORCE 8
WIND SPEED: 34-40 KNOTS

SEA: WAVE HEIGHT 5.5-7.5M (18-25FT), MODERATELY HIGH WAVES OF GREATER LENGTH, EDGES OF CREST BEGIN TO BREAK INTO THE SPINDRIFT, FOAM BLOWN IN WELL MARKED STREAKS ALONG WIND DIRECTION.





(Images by United States National Weather Service (http://www.crh.noaa.gov/mkx/marinefcst.php) [Public domain], via Wikimedia Commons).

A fully developed sea often occurs under stormy conditions, where high winds create a chaotic, random pattern of waves and whitecaps of varying sizes. The waves will propagate outwards from the center of the storm, powered by the strong winds. However, as the storm subsides and the winds weaken, these irregular seas will sort themselves out into more ordered patterns. Recall that open ocean waves will usually be deep water waves, and their speed will depend on their wavelength (section 10.1). As the waves move away from the storm center, they sort themselves out based on speed, with longer wavelength waves traveling faster than shorter wavelength waves. This means that eventually all of the waves in a particular area will be traveling with the same wavelength, creating regular, long period waves called **swell** (Figure 3.11.2). We experience swell as the slow up and down or rocking motion we feel on a boat, or with the regular arrival of waves on shore. Swell can travel very long distances without losing much energy, so we can observe large swells arriving at the shore even where there is no local wind; the waves were produced by a storm far offshore, and were sorted into swell as they traveled towards the coast.

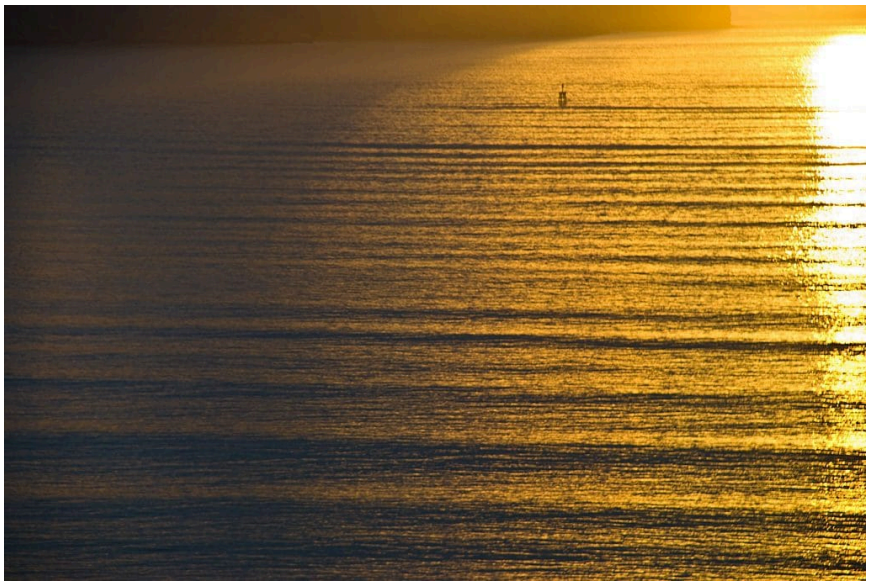


Figure 3.11.2 Ocean swell, the regular pattern of waves of equal wavelength (Phillip Capper [CC BY 2.0], via Wikimedia Commons).

Because swell travels such long distances, eventually swells coming from different directions will run into each other, and when they do they create interference patterns. The interference pattern is created by adding the features of the waves together, and the type of interference that is created depends on how the waves interact with each other (Figure 3.11.3). **Constructive interference** occurs when the two waves are completely in phase; the crest of one wave lines up exactly with the crest of the other wave, as do the troughs of the two waves. Adding the two crest together creates a crest that is higher than in either of the source waves, and adding the troughs creates a deeper trough than in the original waves. The result of constructive interference is therefore to create waves that are larger than the original source waves. In **destructive interference**, the waves interact completely out of phase, where the crest of one wave aligns with the trough of the other wave. In this case, the crest and the trough work to cancel each other out, creating a wave that is smaller than either of the source waves. In reality, it is rare to find perfect constructive or destructive interference as displayed in Figure 3.11.3. Most interference by swells at sea is **mixed interference**, which contains a mix of both constructive and destructive interference. The interacting swells do not have the same wavelength, so some points show constructive interference, and some points show destructive interference, to varying degrees. This results in an irregular pattern of both small and large waves, called **surf beat**.

It is important to point out that these interference patterns are only temporary disturbances, and do not affect the properties of the source waves. Moving swells interact and create interference where they meet, but each wave continues on unaffected after the swells pass each other.

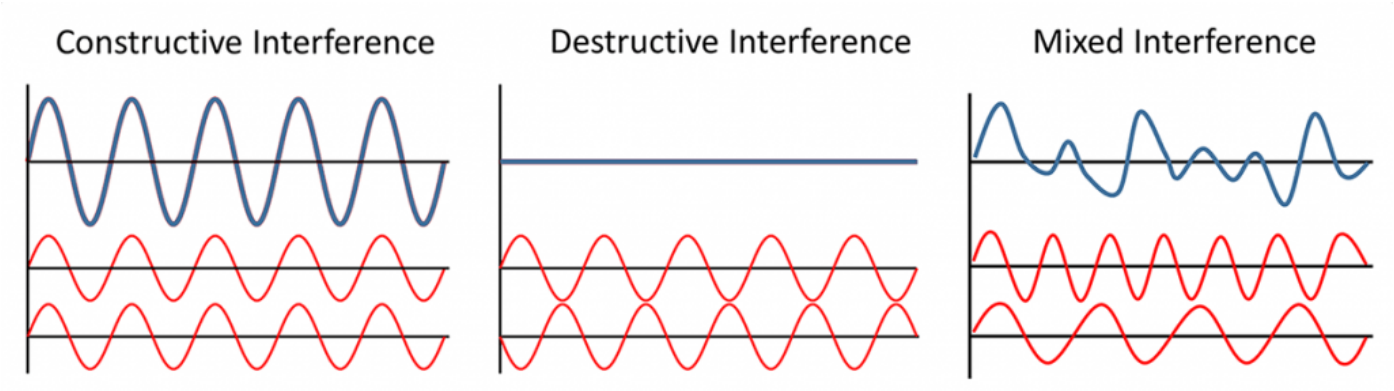


Figure 3.11.3 Wave interference patterns. In constructive interference the source waves (red) are completely in phase, and when added together produce waves that are larger than the original waves (blue). In destructive interference the source waves are out of phase, so they cancel each other out and produce waves that are smaller than the originals. In mixed interference, constructive and destructive interference occur at various point, creating an irregular wave pattern. (Modified by PW from original version: Haade; vectorization: Wjh31, Quibik (Vecorized from File:Interference of two waves.png) [CC BY-SA 3.0 or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons).

About half of the waves in the open sea are less than 2 m high, and only 10-15% exceed 6 m. But the ocean can produce some

extremely large waves. The largest wind wave reliably measured at sea occurred in the Pacific Ocean in 1935, and was measured by the navy tanker the USS Ramapo. Its crew measured a wave of 34 m or about 112 ft high! Occasionally constructive interference will produce waves that are exceptionally large, even when all of the surrounding waves are of normal height. These random, large waves are called **rogue waves** (Figure 3.11.4). A rogue wave is usually defined as a wave that is at least twice the size of the significant wave height, which is the average height of the highest one-third of waves in the region. It is not uncommon for rogue waves to reach heights of 20 m or more.

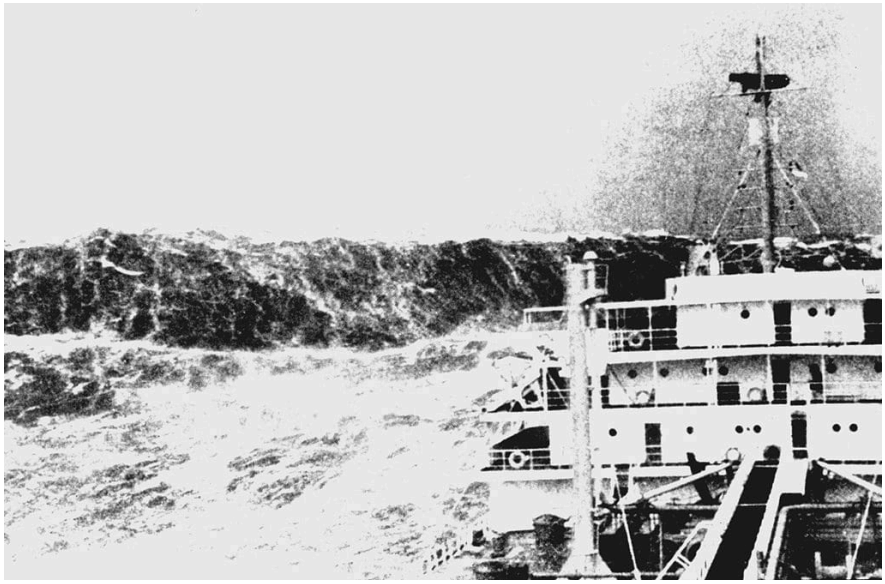


Figure 3.11.4 A rogue wave in the Bay of Biscay, off of the French coast, ca. 1940 (NOAA, [Public domain], via Wikimedia Commons).

Rogue waves are particularly common off of the southeast coast of South Africa, a region referred to as the "wild coast." Here, Antarctic storm waves move north into the oncoming Agulhas Current, and the wave energy gets focused over a narrow area, leading to constructive interference. This area may be responsible for sinking more ships than anywhere else on Earth. On average about 100 ships are lost every year across the globe, and many of these losses are probably due to rogue waves.

Waves in the Southern Ocean are generally fairly large (the red areas in Figure 3.11.2) because of the strong winds and the lack of landmasses, which provide the winds with a very long fetch, allowing them to blow unimpeded over the ocean for very long distances. These latitudes have been termed the "Roaring Forties", "Furious Fifties", and "Screaming Sixties" due to the high winds.

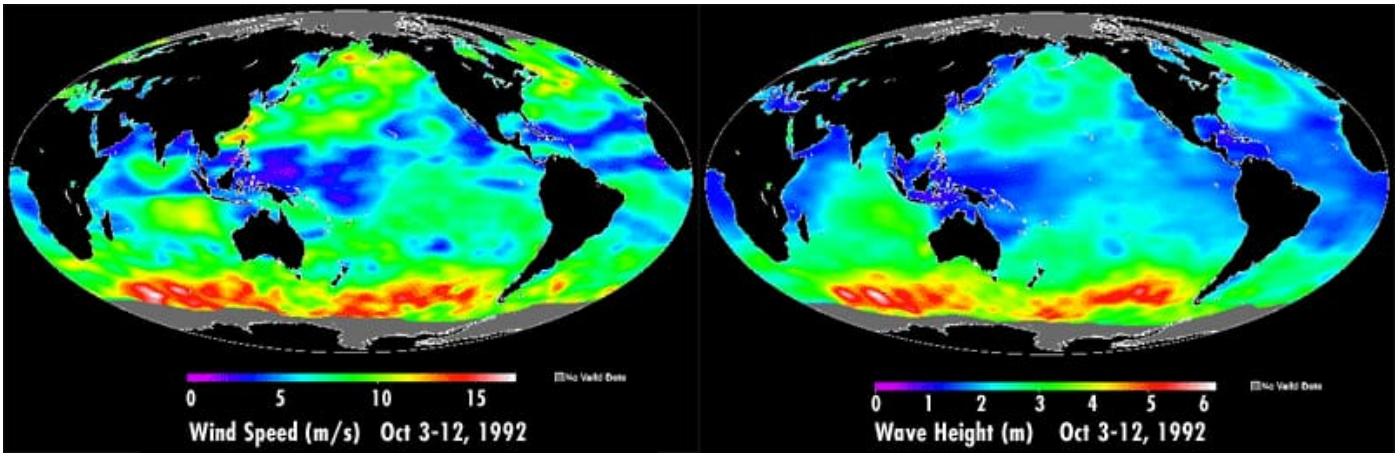


Figure 3.11.5 Wind speed and wave height data for a 9-day period in 1992. The Southern Ocean is notorious for its high winds and large waves (NASA, Public Domain via Wikimedia Commons).

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3.12: Waves on the Shore

Most of the waves discussed in the previous section referred to deep water waves in the open ocean. But what happens when these waves move towards shore and encounter shallow water? Remember that in deep water, a wave's speed depends on its wavelength, but in shallow water wave speed depends on the depth (section 10.1). When waves approach the shore they will "touch bottom" at a depth equal to half of their wavelength; in other words, when the water depth equals the depth of the wave base (Figure 3.12.1). At this point their behavior will begin to be influenced by the bottom.

When the wave touches the bottom, friction causes the wave to slow down. As one wave slows down, the one behind it catches up to it, thus decreasing the wavelength. However, the wave still contains the same amount of energy, so while the wavelength decreases, the wave height increases. Eventually the wave height exceeds 1/7 of the wavelength, and the wave becomes unstable and forms a **breaker**. Often breakers will start to curl forwards as they break. This is because the bottom of the wave begins to slow down before the top of the wave, as it is the first part to encounter the seafloor. So the crest of the wave gets "ahead" of the rest of the wave, but has no water underneath it to support it (Figure 3.12.1).

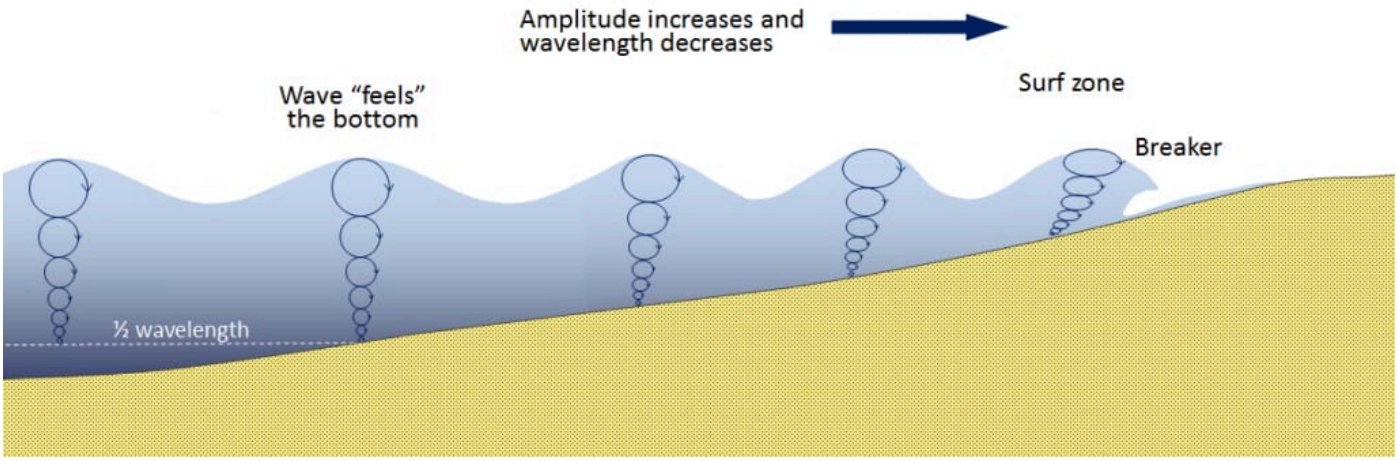


Figure 3.12.1 As waves approach shore they "touch bottom" when the depth equals half of the wavelength, and the wave begins to slow down. As is slows, the wavelength decreases and the wave height increases, until the wave breaks (Steven Earle "Physical Geology").

There are three main types of breakers: spilling, plunging, and surging. These are related to the steepness of the bottom, and how quickly the wave will slow down and its energy will get dissipated.

- **Spilling** breakers form on gently sloping or flatter beaches, where the energy of the wave is dissipated gradually. The wave slowly increases in height, then slowly collapses on itself (Figure 3.12.2). For surfers, these waves provide a longer ride, but they are less exciting.

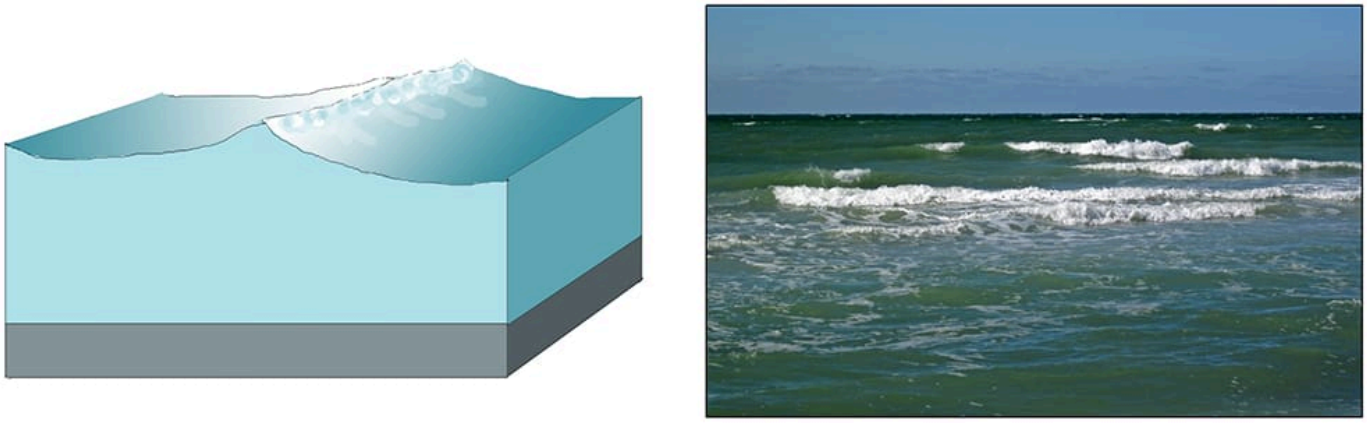


Figure 3.12.2 A spilling breaker. The gentle slope of the bottom causes the wave height to slowly increase until the wave collapses on itself (left: JR, right: James St. John, [CC-BY-2.0], https://www.flickr.com/photos/jsjgeology/23769708334).

- **Plunging** breakers form on more steeply-sloped shores, where there is a sudden slowing of the wave and the wave gets higher very quickly. The crest outruns the rest of the wave, curls forwards and breaks with a sudden loss of energy (Figure 3.12.3). These are the “pipeline” waves that surfers seek out.

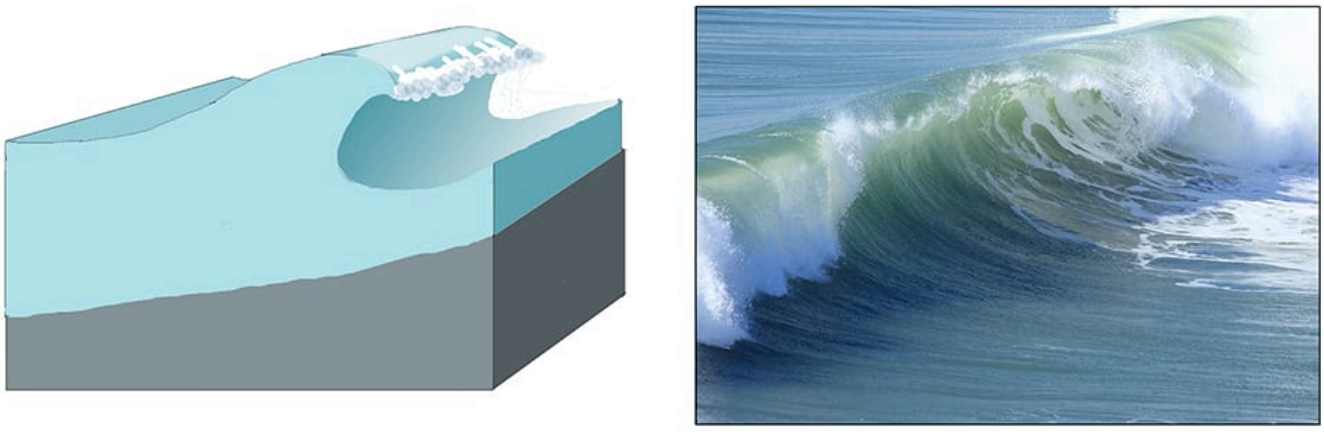


Figure 3.12.3 A plunging breaker. The steeper slope causes the wave height to increase more rapidly, with the crest of the wave outrunning the base of the wave, causing it to curl as it breaks (left: JR, right: Andrew Schmidt, Public Domain [CC-0], publicdomainpictures.net).

- **Surging** breakers form on the steepest shorelines. The wave energy is compressed very suddenly right at the shoreline, and the wave breaks right onto the beach (Figure 3.12.4). These waves give too short (and potentially painful) a ride for surfers to enjoy.

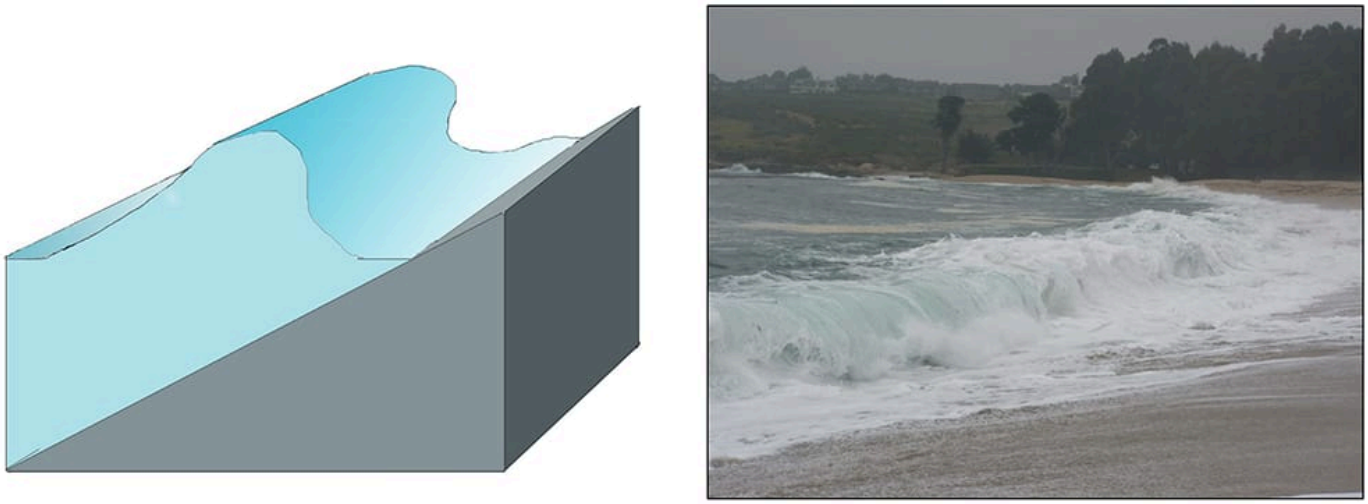


Figure 3.12.4 A surging breaker. The very steep slope causes the wave height to increase suddenly and break right on the beach (left: JR, right: Tewy, [CC-BY-SA-3.0], via Wikimedia Commons).

Wave Refraction

Swell can be generated anywhere in the ocean and therefore can arrive at a beach from almost any direction. But if you have ever stood at the shore you have probably noticed that the waves usually approach the shore somewhat parallel to the coast. This is due to wave refraction. If a wave front approaches shore at an angle, the end of the wave front closest to shore will touch bottom before the rest of the wave. This will cause that shallower part of the wave to slow down first, while the rest of the wave that is still in deeper water will continue on at its regular speed. As more and more of the wave front encounters shallower water and slows down, the wave font refracts and the waves tend to align themselves nearly parallel to the shoreline (they are refracted towards the region of slower speed). As we will see in section 13.2, the fact that the waves do not arrive perfectly parallel to the beach causes longshore currents and longshore transport that run parallel to the shore.

Refraction can also explain why waves tend to be larger off of points and headlands, and smaller in bays. A wave front approaching

shore will touch the bottom off of the point before it touches bottom in a bay. Once again, the shallower part of the wave front will slow down, and cause the rest of the wave front to refract towards the slower region (the point). Now all of the initial wave energy is concentrated in a relatively small area off of the point, creating large, high energy waves (Figure 3.12.6). In the bay, the refraction has caused the wave fronts to refract away from each other, dispersing the wave energy, and leading to calmer water and smaller waves. This makes the large waves of a "point break" ideal for surfing, while water is calmer in a bay, which is where people would launch a boat. This difference in wave energy also explains why there is net erosion on points, while sand and sediments get deposited in bays (see section 13.3).

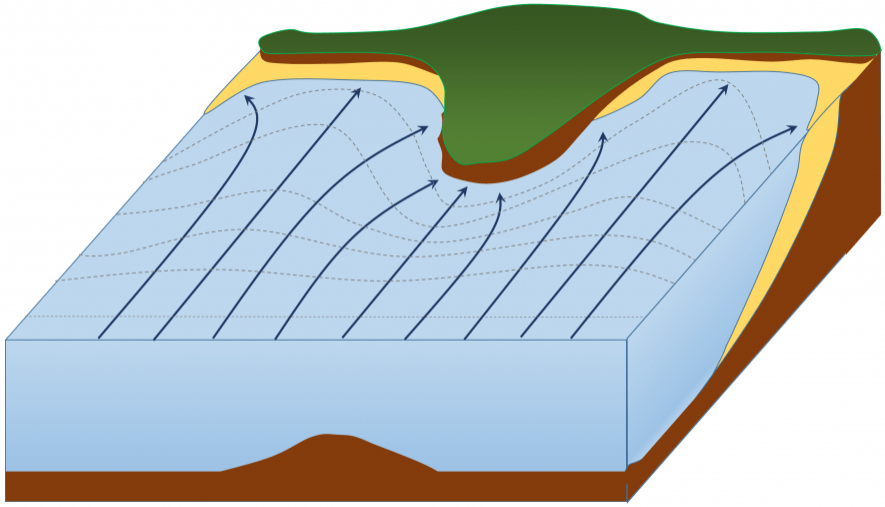


Figure 3.12.6 Waves approaching shore (blue lines) touch bottom sooner off of points and are refracted towards the points, concentrating their wave energy. Wave energy is spread out in bays, causing smaller waves. Dotted lines represent the bottom contours (PW).

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3.13: Tsunamis

Tsunamis loom large in popular culture, but there are a number of misconceptions about these large waves. First, tsunamis have nothing to do with the tides, so it is a misnomer to refer to them as “tidal waves.” There are actual tidal waves (see section 11.1), but they are not related to tsunamis. Second, the giant, curling wave that is taller than skyscrapers and destroys cities in science fiction movies is also a fabrication, as tsunamis do not behave that way, as described below.

Tsunamis are large waves that are usually the result of seismic activity, such as the rising or falling of the seafloor due to earthquakes, although volcanic activity and landslides can also cause tsunamis in the form of splash waves (see section 10.1). As the seafloor rises or falls, so does the water column above it, creating waves. Only vertical seismic disturbances cause tsunamis, not horizontal movements. These vertical seafloor movements are usually less than 10 m high, so the resulting wave will be of an equal or lesser height at sea. While the tsunamis have a relatively small height at the point of origin, they have very long wavelengths (100-200 km). Because of the long wavelength, they behave as shallow water waves throughout the entire ocean; the depth of the ocean is always shallower than half of their wavelength. As shallow water waves, their speed depends on water depth, but they can still travel at speeds over 750 km/hr (Figure 3.13.1)!

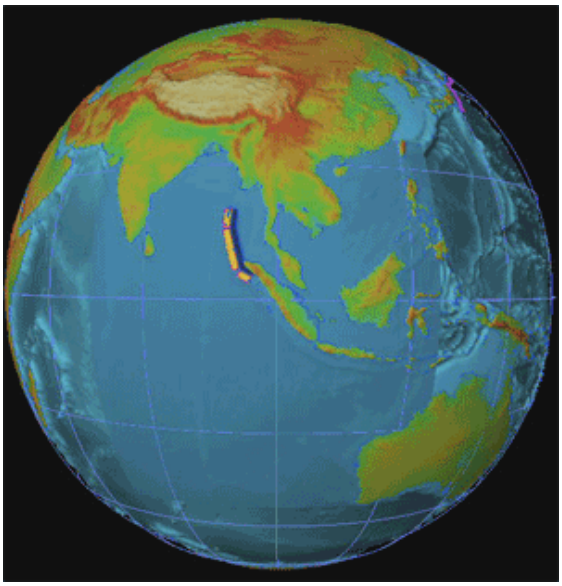


Figure 3.13.1 Animation of the spread of tsunamis created during the 2004 Indonesia earthquake (NOAA Center for Tsunami Research (NCTR) [Public domain]).

When tsunamis approach land, they behave just like any other wave; as the depth becomes shallower, the waves slow down and the wave height begins to increase. However, contrary to popular belief, tsunamis do not arrive on shore as giant, cresting waves. Since their wavelength is so long, it is impossible for their height to ever exceed 1/7 of their wavelength, so the waves don’t actually curl or break. Instead, they usually hit the shore as sudden surges of water causing a very rapid increase in sea level, like that of an enormous rise in tide. It may take several minutes for the wave to pass, during which time sea level can rise to 40 m higher than usual.

Large tsunamis occur every 2-3 years, with very large, damaging events happening every 15-20 years. The most devastating tsunami in terms of loss of life resulted from a magnitude 9 earthquake in Indonesia in 2004 (Figure 3.13.2), which created waves up to 33 m tall and left about 230,000 people dead in Indonesia, Thailand, and Sri Lanka. In 2011 a 9.0 magnitude earthquake in Japan triggered a tsunami up to 40.5 m high, which resulted in over 18,000 deaths. This earthquake also caused the Fukishima nuclear accident, and moved Japan about 8 inches closer to the U.S.



Figure 3.13.2 A village in Sumatra following the Indonesia Tsunami in December 2004 (U.S. Navy photo by Photographer's Mate 2nd Class Philip A. McDaniel [Public domain via Wikimedia Commons]).

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3.14: Coastal Oceanography

Learning Objectives

- After reading this chapter you should:
- recognize the various zones of a beach
- understand how the relationship between swash and backwash determines the composition of a beach
- understand the concept of longshore transport
- know the different erosional and depositional structures created by longshore transport
- understand the issues associated with different forms of hard stabilization: groins, jetties etc.
- know what an estuary is
- know the four types of geological estuaries, and how they form
- know the four types of estuaries based on salinity and mixing patterns

For most people, their image of the coast is the place where the land meets the sea, most likely in the form of a beach. But it is more than just the narrow strip along the water line; technically the term “coast” refers to the range of land over which the ocean has an effect on climate, foliage, and other environmental processes. This range may extend for tens of kilometers inland from the water’s edge. Furthermore, what we recognize as the coast today, may not have been a coastal area in the past, as sea level has varied from about 6 m above to 125 m below its current height over the past two million years.

This chapter begins with the features of coastal regions, the processes that shape the coastline, and how humans try to control these processes. Following that, we will examine the different types of estuaries that are found in coastal areas.



-  Topic hierarchy 

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3.15: Beaches

For most people, when they think of coastal areas they picture a beach, and the beach that they imagine is probably a typical sandy beach composed of quartz sand grains (section 12.2). But beaches are comprised of whatever types of sediments are dominant in the local area. For example, parts of Hawaii and Iceland are famous for their black sand beaches, made up of eroded basalt and other volcanic materials. The beautiful tropical white sand beaches we see in travel ads are largely composed of the crushed calcium carbonate remains of coral skeletons (much of which has been chewed up and excreted by a fish before we happily run our toes through it!) Other beaches may lack sand altogether and instead be dominated by small shells, or larger rocks or pebbles (Figure 3.15.1).



Figure 3.15.1 Various beach substrates. Clockwise from top left: Punaluu Black Sand Beach, Hawaii, USA (Diego Delso [CC BY-SA 3.0], via Wikimedia Commons); Shell Beach, Shark Bay, Western Australia (Brian W. Schaller (Own work) [CC BY-NC-SA 3.0], via Wikimedia Commons); white coral sand beach in the Maldives (http://www.elitedivingagency.com/, [CC BY-SA 3.0] via Wikimedia Commons); rocky beach at Killbear Provincial Park in Ontario, Canada (John Vetterli (originally posted to Flickr as Beach) [CC BY-SA 2.0], via Wikimedia Commons).

The shoreline is divided up into multiple zones (Figure 3.15.2). The **backshore** is the region of the beach above the high tide line, which is only submerged under unusually high wave conditions, such as during storms. The **foreshore** lies between the high tide and low tide lines; it is submerged during high tide and is exposed during low tide. The **nearshore** extends from the low tide line to the depth where wave action is no longer influenced by the bottom, i.e. to where the depth exceeds the wave base (section 10.1). Finally, the **offshore** zone represents the depths beyond the nearshore region.

Along the beach itself, the area above the high tide line is called the **berm**, which is usually dry and relatively flat. The berm often ends with a berm crest or berm **scarp**, which is a steeper wall carved out by wave action that leads down to the foreshore. The foreshore has a number of other names, including the **beach face**, the **intertidal** or **littoral zone**, and if the area is fairly flat, the **low tide terrace**. Just off shore from the beach there are often **longshore bars** and longshore troughs running parallel to the beach. The longshore bars are accumulations of sand that are deposited by wave action and longshore currents (section 13.2). The decrease in depth above longshore bars is what often causes waves to start to break well before reaching the beach (section 10.3).

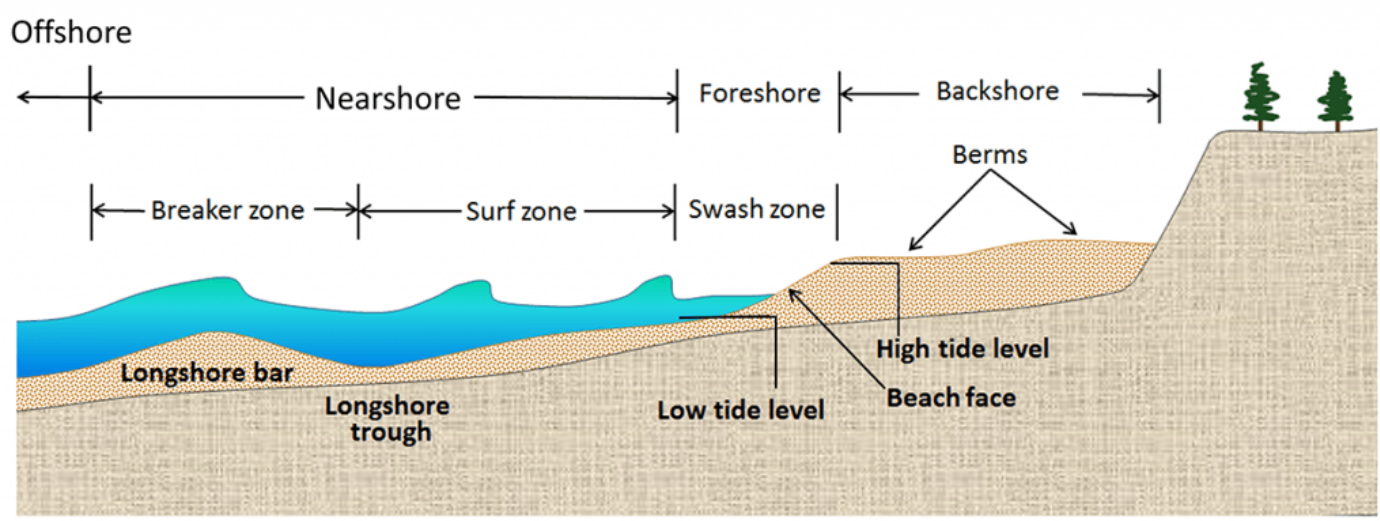


Figure 3.15.2 The zones of a typical beach (Modified by PW from Steven Earle, “Physical Geology”).

The sand or other particles that make up the beach are distributed by wave action. The water that moves over a beach through incoming waves is called **swash**, and it also contains suspended sand grains that can get deposited on the beach. Some of the swash percolates into the sand while the rest of the water washes back out as **backwash** as the wave recedes. Backwash removes sand from the beach and returns it to the ocean. Sand will therefore be deposited or eroded depending on which process is dominant. If wave action is light, a lot of incoming water gets absorbed by the sand, so swash dominates. Under heavier waves the beach becomes saturated with water, so less can be absorbed, and backwash is dominant. This leads to seasonal cycles in beach structure; waves are heavier during the winter as a result of stormier conditions at sea, so backwash dominates and sand is removed from the beach and deposited offshore in longshore bars. In the summer the waves are gentler, swash dominates, and the sand is transported from the longshore bar and deposited on the shore to create a wider, sandy beach (Figure 3.15.3).

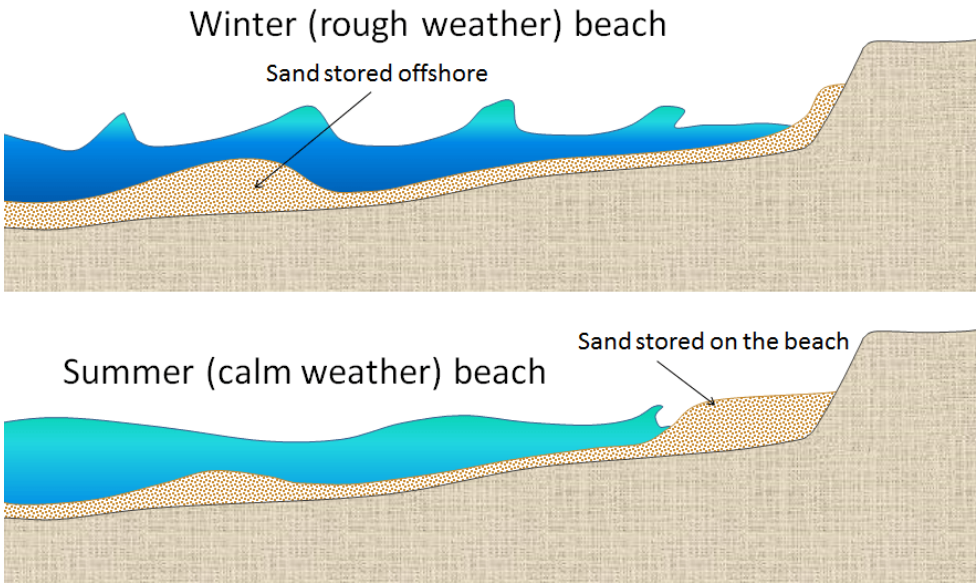


Figure 3.15.3 The differences between summer and winter on beaches in areas where the winter conditions are rougher and waves have a shorter wavelength but higher energy. In winter, sand from the beach is stored offshore (Steven Earle, “Physical Geology”).

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3.16: Longshore Transport

We learned in section 10.3 that refraction causes waves to approach parallel to shore. However, most waves still reach the shore at a small angle, and as each one arrives, it pushes water along the shore, creating what is known as a **longshore current** within the surf zone (the areas where waves are breaking) (Figure 3.16.1). Longshore currents can move up to 4 km/hr, strong enough to carry people with them, as everyone knows who has been swimming in the ocean only to look up and see that they have been carried far down the beach from their towel!

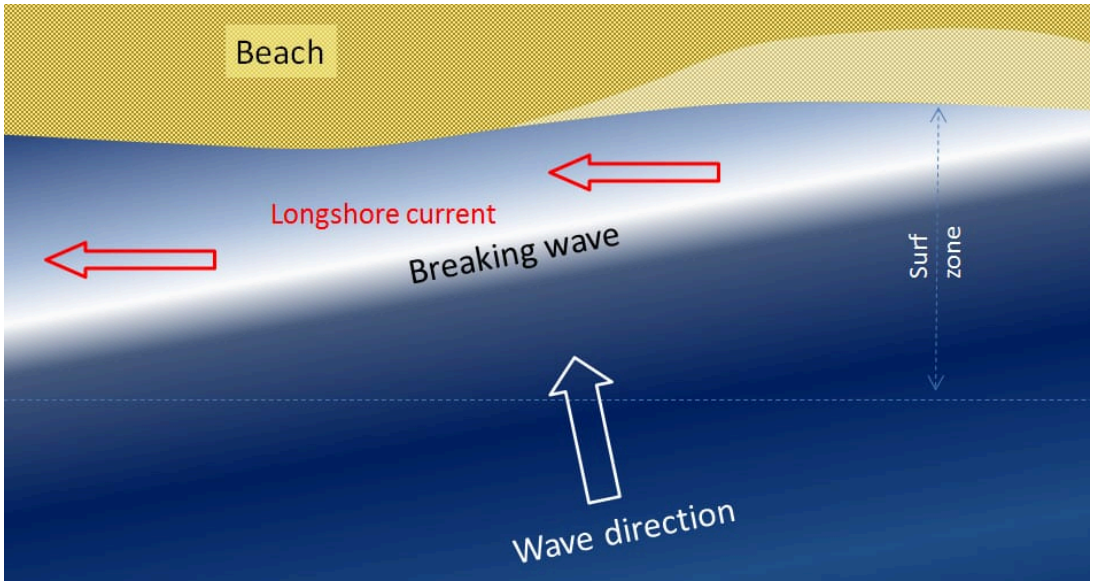


Figure 3.16.1 Longshore currents are caused by waves approaching shore at a small angle, moving water parallel to the shore (Steven Earle, "Physical Geology").

Another important effect of waves reaching the shore at an angle is that when they wash up onto the beach, they do so at an angle, but when that same wave water washes back down the beach, it moves straight down the slope of the beach (Figure 3.16.2). The upward-moving water, known as the swash, pushes sediment particles along the beach, while the downward-moving water, the backwash, brings them straight back. With every wave that washes up and then down the beach, particles of sediment are moved along the beach in a zigzag pattern.

The combined effects of sediment transport within the surf zone by the longshore current and sediment movement along the beach by swash and backwash is known as **longshore transport**, or **littoral drift**. Longshore transport moves a tremendous amount of sediment along coasts (both oceans and large lakes) around the world, and it is responsible for creating a variety of depositional features that we will discuss in section 13.4. The net movement of sediment due to longshore transport is to the south along both coasts of the continental United States, because the storms and high winds that originally create the swell tend to occur at higher latitudes and move to the south.

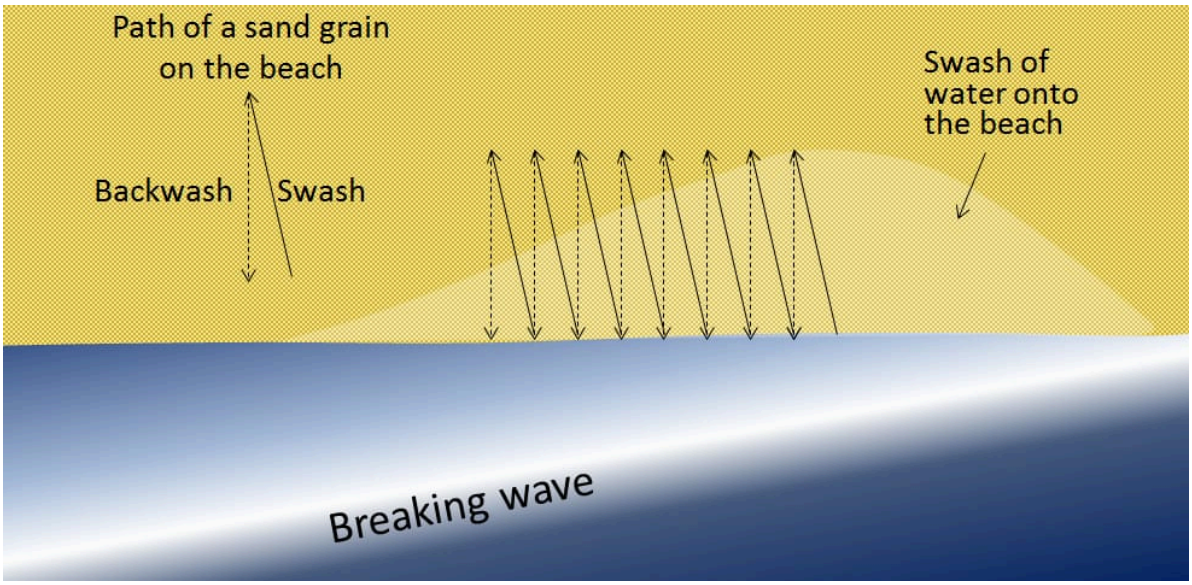


Figure 3.16.2 The zigzag pattern of sediment movement along a beach creating longshore transport. In this figure the longshore transport moves particles to the left (Steven Earle, "Physical Geology").

A **rip current** (often incorrectly called a "rip tide"; they are not really related to tides) is another type of current that develops in the nearshore area, and has the effect of returning water that has been pushed up to the shore by incoming waves or accumulated through longshore currents, particularly converging longshore currents. Rip currents often occur where there is a channel between sandbars that makes it easier for the retreating water to escape. As shown in Figure 3.16.3, rip currents flow straight out from the shore, and because the water is directed through a narrow space, the current can be very strong. The currents lose strength quickly just outside of the surf zone, but they can be dangerous to swimmers who get caught in them and are pulled away from shore. Swimmers caught in a rip current should not try to swim directly back to shore, as it is difficult to fight the current and the swimmer can quickly tire. Instead, swim parallel to the beach for a short distance until you are outside of the rip current, and then you can easily swim to shore.

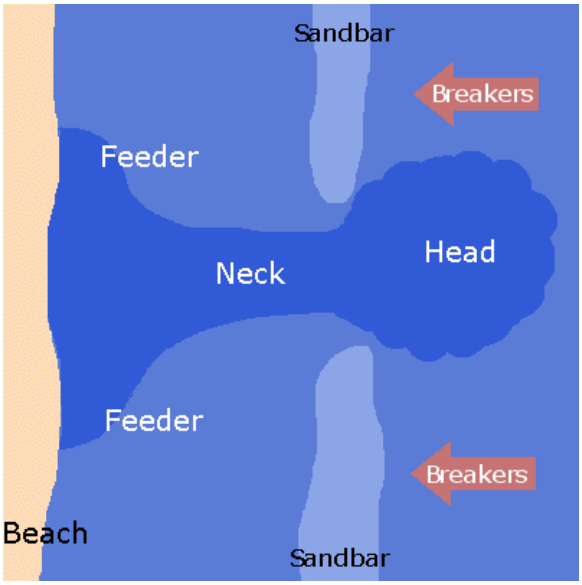


Figure 3.16.3 Creation of a rip current from wave action and longshore transport. Water accumulates on the beach, and then rushes out to sea through a narrow channel, creating a strong current (National Weather Service, Wilmington, NC (NOAA) [Public domain], via Wikimedia Commons).

Rip currents are visible in Figure 3.16.4, a beach at Tunquen in Chile near Valparaiso. As is evident from the photo, the rips correspond with embayments in the beach profile. Three of them are indicated with arrows, but it appears that there may be several others farther along the beach.

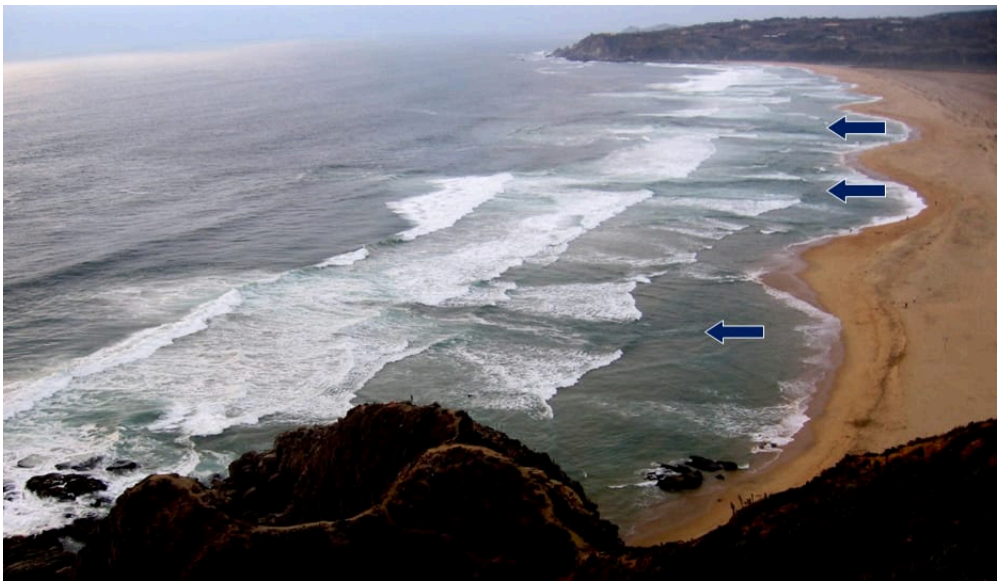


Figure 3.16.4 Rip currents along a beach in Chile, indicated by the arrows. Longshore currents converging in a curved beach have nowhere to go but straight back out to sea, creating a rip current (Steven Earle, “Physical Geology”).

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3.17: Landforms of Coastal Erosion

Large waves crashing onto a shore bring a tremendous amount of energy that has a significant eroding effect, and several unique erosion features commonly form on rocky shores with strong waves.

When waves approach an irregular shore, they are slowed down to varying degrees, depending on differences in the water depth, and as they slow, they are bent or refracted (section 10.3). In Figure 3.17.1, wave energy is represented by the blue arrows. That energy is evenly spaced out in the deep water, but because of refraction, the energy of the waves is being focused on the **headlands**. On irregular coasts, the headlands receive much more wave energy than the intervening bays, and thus they are more strongly eroded. The result of this is **coastal straightening**, where an irregular coast will eventually become straightened, although that process may take millions of years.

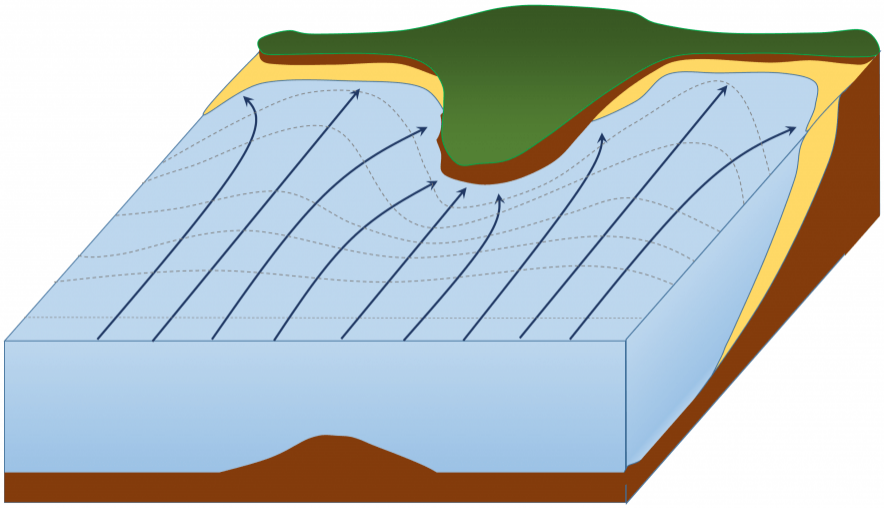


Figure 3.17.1 The approach of waves (blue lines) towards a coastal headland. The blue arrows represent wave energy; most of that energy is focused on the headlands, causing greatest erosion in this area (PW).

Wave erosion is greatest in the surf zone, where the wave base is impinging strongly on the seafloor and where the waves are breaking. The result is that the substrate in the surf zone is typically eroded to a flat surface known as a **wave-cut platform** (or **wave-cut terrace**) (Figure 3.17.2). A wave-cut platform extends across the intertidal zone.



Figure 3.17.2 A wave-cut platform in bedded sedimentary rock on Gabriola Island, B.C. The wave-eroded surface is submerged at high tide (Steven Earle, "Physical Geology").

Arches and **sea caves** form as a result of the erosion of relatively non-resistant rock. Wave action and strong longshore currents can carve a cave into a headland, and if the erosion extends all the way through, it becomes an arch. If a hole develops in the ceiling of a cave, a **blowhole** can be created, shooting water into the air when waves crash in the cave. An arch in the Barachois River area of western Newfoundland, Canada, is shown in Figure 3.17.3. This feature started out as a sea cave, and then, after being eroded from both sides, became an arch. During the winter of 2012-2013, the arch collapsed, leaving a small stack at the end of the point.



Figure 3.17.3 Top: An arch in tilted sedimentary rock at the mouth of the Barachois River, Newfoundland, July 2012. Bottom: The same location in June 2013. The arch has collapsed and a small stack remains (Photo: Dr. David Murphy, used with permission in Steven Earle, "Physical Geology").

The tower of rock left behind from a collapsed arch is called a **sea stack** (Figure 3.17.4). But sea stacks can also form during the formation of wave-cut platforms or other features, when relatively resistant rock that does not get completely eroded remains behind to form the stack.



Figure 3.17.4 A sea stack, likely created from the collapse of a sea arch (Doug Lee [CC BY-SA 2.0], via Wikimedia Commons).

Figure 3.17.5 summarizes the process of transformation of an irregular coast into a straightened coast with **sea cliffs** (wave-eroded escarpments) and the remnants of stacks, arches, and wave-cut platforms. The next stages of this process would be the continued landward erosion of the sea cliffs and the complete erosion of the stacks and wave-cut platforms in favor of a continuous and nearly straight sandy beach.

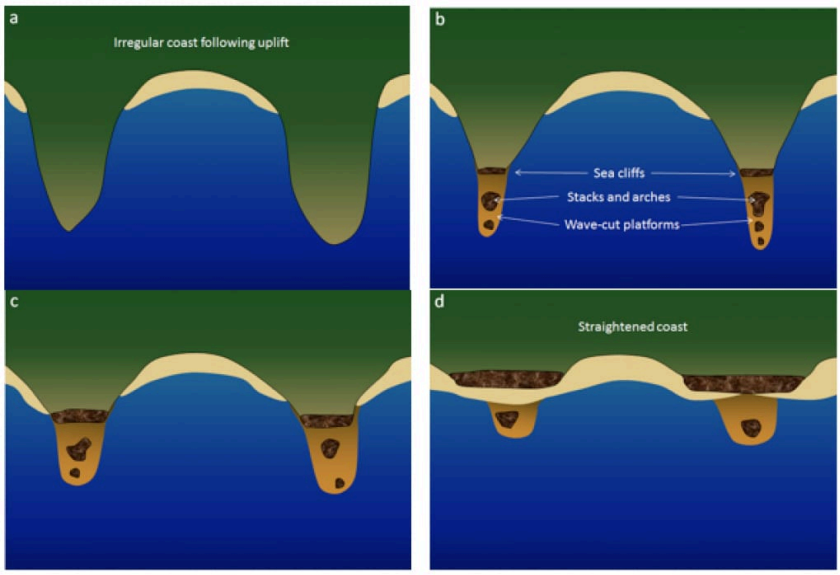


Figure 3.17.5 Evolution of a straightened coast through the erosion to stacks and arches, sea cliffs, and wave-cut platforms (Steven Earle, "Physical Geology").

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3.18: Landforms of Coastal Deposition

Some coastal areas are dominated by erosion, an example being the Pacific coast of North America, while others are dominated by deposition, examples being the Atlantic and Caribbean coasts of the United States. But on almost all coasts, both deposition and erosion are happening to varying degrees most of the time, although in different places. On deposition-dominant coasts, the coastal sediments are still being eroded from some areas and deposited in others.

On coasts that are dominated by depositional processes, most of the sediment being deposited typically comes from large rivers. Much of the sediment is immediately deposited at the mouth of the river, creating large fan-shaped **deltas**. An obvious example is where the Mississippi River flows into the Gulf of Mexico at New Orleans; another is the Yellow (Huang He) River in China (Figure 3.18.1).



Figure 3.18.1 The Yellow River delta in China, created by one of the most sediment-laden rivers on Earth (NASA [Public domain], via Wikimedia Commons).

The evolution of sandy depositional features on sea coasts is primarily influenced by waves and currents, especially longshore currents. As sediment is transported along a shore, either it is deposited on beaches, or it creates other depositional features. A **spit**, for example is an elongated sandy deposit that extends out into open water in the direction of a longshore current (Figure 3.18.2).



Figure 3.18.2 Farewell Spit, on the northern shore of New Zealand's South Island (By NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team (NASA's Earth Observatory) [Public domain], via Wikimedia Commons).

A spit that extends across a bay to the extent of closing, or almost closing it off, is known as a **baymouth bar** (Figure 3.18.3). Most bays have streams flowing into them, and since this water has to get out, it is rare that a baymouth bar will completely close the entrance to a bay.



Figure 3.18.3 Left: Illustration of a baymouth bar and tombolo (Steven Earle, "Physical Geology"). Right: A baymouth bar at the mouth of the Klamath River in northern California (Linda Tanner, https://www.flickr.com/photos/goingslo/5827465324, Creative Commons CC-BY 2.0).

Tombolos are common where islands are abundant, and they typically form where there is a wave shadow behind a nearshore island (Figure 3.18.4). This becomes an area with reduced energy, and so the longshore current slows and sediments accumulate. Eventually enough sediments accumulate to connect the island to the mainland with a tombolo (Figure 3.18.5).

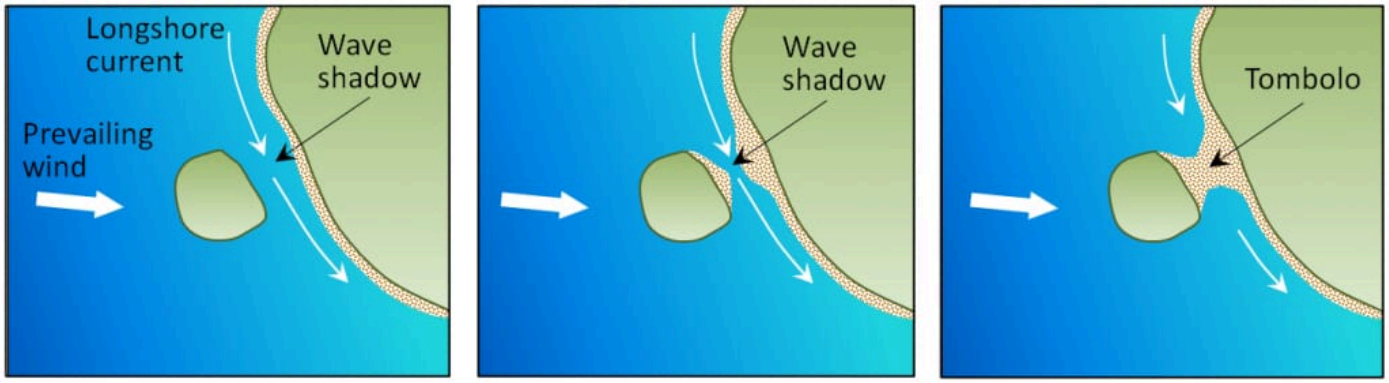


Figure13.4.4 Formation of a tombolo. In the wind shadow of an island, there is little wave action, so the sediment moved by longshore transport gets deposited, eventually linking the island to the mainland (Steven Earle, “Physical Geology”).



Figure 3.18.5 A stack (with a wave-cut platform) connected to the mainland by a tombolo, Leboeuf Bay, Gabriola Island, British Columbia (Steven Earle, “Physical Geology”).

In areas where coastal sediments are abundant and coastal relief is low (because there has been little or no recent coastal uplift), it is common for **barrier islands** to form (Figure 3.18.6). Barrier islands are elongated islands composed of sand that form offshore from the mainland, potentially reaching several kilometers wide and hundreds of kilometers long. They are common along the U.S. Gulf Coast from Texas to Florida, and along the U.S. Atlantic Coast from Florida to Massachusetts. The islands often form as the result of sediment moving offshore through river discharge, while wave action works to push the sediment back towards the shore. The resulting sediment buildup is then stretched into long barrier islands by longshore transport.



Figure 3.18.6 Assateague Island on the Maryland coast, U.S. This barrier island is about 60 km long and only 1 km to 2 km wide. The open Atlantic Ocean is to the right and the lagoon is to the left. This part of Assateague Island has recently been eroded by a tropical storm, which pushed massive amounts of sand into the lagoon. (http://soundwaves.usgs.gov/2014/04/i...ial_ViewCV.jpg).

Mature barrier islands contain a number of ecological zones. Beginning on the ocean side of the island there is a beach, consisting of the zones we discussed in section 13.1. Behind the beach lie dunes that are built up by sand transported by wind. The ocean side of the dunes are home to grasses and other plants which help stabilize the sand from erosion, and also help slow down the wind to allow sand to settle and accumulate. Beyond the dunes lies a more heavily vegetated barrier flat, covered by larger shrubs and trees that are tolerant to the high winds and salty conditions. As the land slopes down on the side of the island facing the mainland, the low-lying areas transition into a salt marsh or mud flat habitat, which is protected from wave action, but is influenced by tidal changes. The mud flats are colonized by grasses, which slow down the movement of water and lead to increased sediment deposition, building up the land in the marsh. Different species of grasses eventually dominate the different elevations of the salt marsh, depending on their tolerance for submersion in seawater. These salt marshes are very important habitats for many invertebrates, birds, and juvenile fish. Between the island and the mainland lies a lagoon, which usually contains brackish water from the mixing of fresh water runoff from the land and the seawater within a somewhat enclosed space. Barrier islands, although attractive locations for beach houses, are not permanent structures, and people should be wary of building on them. Over time, the erosion on the seaward side of the island, and the expansion of the marsh on the landward side, causes the island to slowly move towards the mainland, eventually closing off the lagoon. Maintaining dune grasses is one way to slow this movement, and as we will see in the next section, people have developed a number of other strategies to try to curtail the natural erosion of beaches.

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3.19: Human Interference with Shorelines

The continued erosion and deposition of coastal sediments is a natural process, with features forming and disappearing as sea level and other conditions change. However, we have also come to enjoy and rely on many of these beaches and other coastal features for commerce, recreation, and living space. So from our perspective, we often see the transient nature of the coast as a threat to our activities, and as a result we have developed a number of ways to try and influence the erosion process, usually through **hard stabilization**, or the building of structures to stop the flow of sand. While some of these efforts have been successful, many others have actually exacerbated the problem, as we will see below.

Groins (or groynes) are barriers built perpendicular to the shore (Figure 3.19.1 *left*). Groins are built to interrupt longshore transport and trap sand upstream of the groin, which they do very well. But downstream of the groin the source of replacement sand is cut off, while sand continues to be removed, so erosion can become even more pronounced on that side of the groin. To prevent that erosion, another groin must be built downstream of the first one, which then creates its own erosion problems, leading to another groin, and so on. Eventually a beach may become covered in a series of groins, called a **groin field**, all trying to stabilize the natural flow of sand (Figure 3.19.1 *right*).



Figure 3.19.1 Left: A groin on Bolinas Beach, California. Longshore transport would be moving from right to left, accumulating sand on the right of the groin (Beatrice Murch, https://www.flickr.com/photos/blmurch/952523971, CC BY-SA 2.0). Right: A groin field. Longshore transport would move from the bottom of the picture towards the top (https://pxhere.com/en/photo/1048378, Public Domain, CC0).

Jetties are like longer groins, often built to protect the mouths of harbors to prevent them from filling with sand. Because they are longer they can trap more sand than groins, and they also can contribute to increased erosion on the downstream side (Figure 3.19.2). If too much sand accumulates upstream of the jetty it can spread past the jetty and into the mouth of the harbor, in which case the jetty may need to be extended.



Figure 3.19.2 The jetties protecting Santa Cruz harbor, California. Sand has accumulated on the left (north) side of the harbor, and the beach is eroded on the right (south) side (Google Maps, Map Data: Google).

Breakwaters are walls that are usually built parallel to the shore. Their purpose is not necessarily to interfere with sediment transport, but instead to protect the areas behind them from heavy wave action, so they are often deployed at the mouth of a harbor, or to protect the boats in a mooring field. But breakwaters do have an unintended impact on sediment distribution. Longshore transport continues to move sand along the beach, but once it gets behind the breakwater the lack of wave action interrupts the flow, and the sand settles and accumulates. The beach grows behind a breakwater, until eventually they may become connected (Figure 3.19.3). With the longshore transport interrupted, increased erosion can occur downstream of the breakwater.



Figure 3.19.3 A series of breakwaters along the coast in Skagen, Denmark. In this case, sand has accumulated to the point that they now connect the breakwaters to land (Google Maps; Imagery: DigitalGlobe, Aerodata,International Surveys, TerraMetrics, Data SIO, NOAA, US Navy, NGA, GEBCO, Map Data: Google).

Santa Monica Pier

The beach around the Santa Monica Pier in California provides a good example of the effects of breakwaters on a sandy shore. A breakwater was constructed in the early 1930s to protect the pier and the boats that moored near it. Following the construction, the once-straight beach became much wider behind the breakwater as sand accumulated in the absence of strong wave action (*below left*). Now that the breakwater is no longer in place, the bulge in the shoreline is gone, and the beach is much straighter once again (*below right*).



Left; aerial image of Santa Monica Pier and breakwater from 1936 (Courtesy of Santa Monica Public Library Image Archives/ Spence Air Photos). Right; Santa Monica Pier in 2011 (© JCS, CC BY-SA 3.0, via Wikimedia Commons).

Seawalls are constructed at the top of the surf zone, where the waves crash against the shore. The walls are designed as a barrier between the waves and the shore, to prevent the land from being eroded (Figure 3.19.4). They are often utilized in beachfront property to prevent the ground under a home from being undermined by the waves. However, as with the other forms of hard stabilization we have discussed, seawalls are not without their own environmental consequences. The sudden release of wave energy on a seawall can create turbulence, which undermines the sediment at the base of the wall and causes it to erode. Furthermore, on a softer, natural coastline some of the wave energy is absorbed or dissipated, but with a hard seawall most of the wave energy is reflected, leading to stronger longshore currents and faster erosion. In many places where seawalls have been built the beaches are getting steeper, and erosion rates have increased, with the potential for seawalls to collapse along with whatever they are supporting. Because of this, some coastal communities are phasing out seawall construction to try to return to more natural beach fronts.



Figure 3.19.4 A sea wall at Horsey Gap, UK (Evelyn Simak [CC BY-SA 2.0], via Wikimedia Commons).

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3.20: Estuaries

Estuaries are partially enclosed bodies of water where the salt water is diluted by fresh water input from land, creating **brackish** water with a salinity somewhere between fresh water and normal seawater. Estuaries include many bays, inlets, and sounds, and are often subject to large temperature and salinity variations due to their enclosed nature and smaller size compared to the open ocean.

Estuaries can be classified geologically into four basic categories based on their method of origin. In all cases they are a result of rising sea level over the last 18,000 years, beginning with the end of the last ice age; a period that has seen a rise of about 130 m. The rise in sea level has flooded coastal areas that were previously above water, and prevented the estuaries from being filled in by all of the sediments that have been emptied into them.

The first type is a **coastal plain estuary**, or **drowned river valley**. These estuaries are formed as sea level rises and floods an existing river valley, mixing salt and fresh water to create the brackish conditions where the river meets the sea. These types of estuaries are common along the east coast of the United States, including major bodies such as the Chesapeake Bay, Delaware Bay, and Narragansett Bay (Figure 3.20.1). Coastal plain estuaries are usually shallow, and since there is a lot of sediment input from the rivers, there are often a number of depositional features associated with them such as spits and barrier islands.

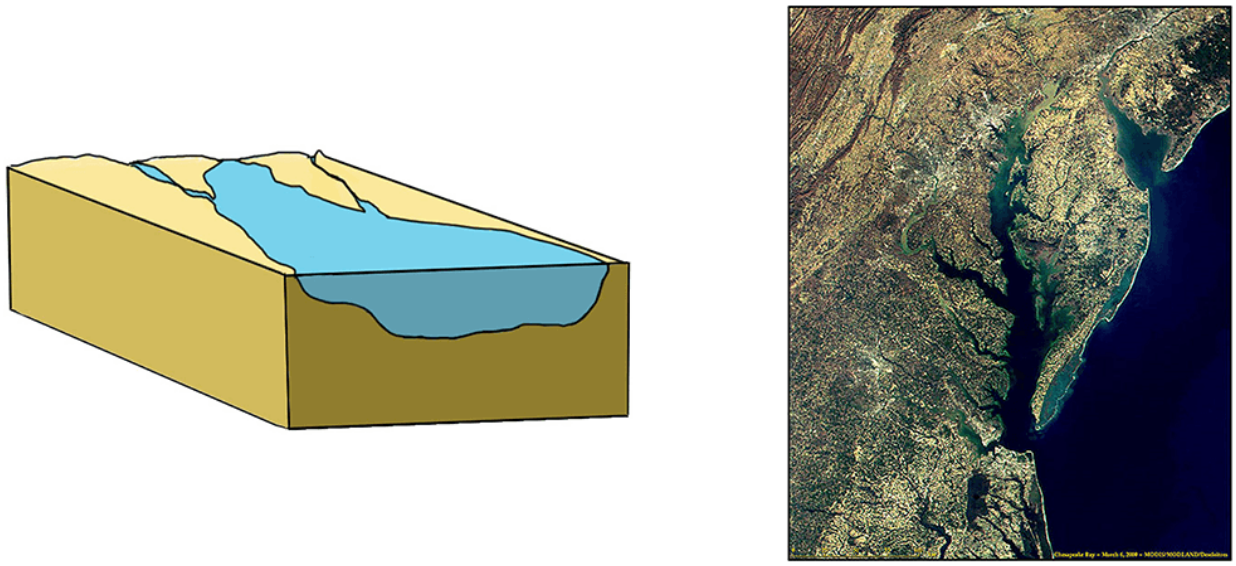


Figure 3.20.1 A coastal plain estuary. Sea level has risen and flooded what was once a river valley. The satellite image shows Chesapeake Bay and Delaware Bay, two coastal plain estuaries (left: JR, right: NASA, Public Domain via Wikimedia Commons).

The presence of sand bars, spits, and barrier islands can lead to **bar-built estuaries**, where a barrier is created between the mainland and the ocean. The water that remains inside the sand bar is cut off from complete mixing with the ocean, and receives freshwater input from the mainland, creating estuarine conditions (Figure 3.20.2).

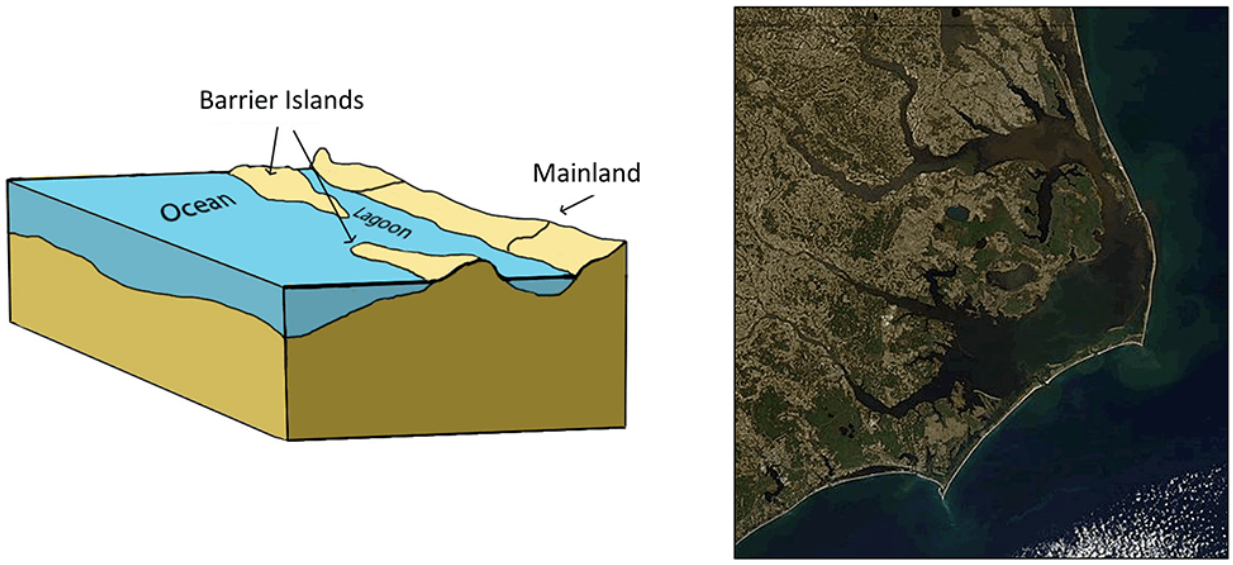


Figure 3.20.2 A bar-built estuary. Sand bars and barrier islands have partially isolated a lagoon from the rest of the ocean. Freshwater input into the lagoon from the mainland creates brackish conditions in the estuary. At right is a satellite image of Pamlico Sound, North Carolina, a bar-built estuary surrounded by spits and barrier islands (left: JR, right: NASA, Public Domain via Wikimedia Commons).

Fjords are estuaries formed in deep, U-shaped basins that were carved out by advancing glaciers. When the glaciers melted and retreated, sea level rose and filled these troughs, creating deep, steep-walled fjords (Figure 3.20.3). Fjords are common in Norway, Alaska, Canada, and New Zealand, where there are mountainous coastlines once covered by glaciers.

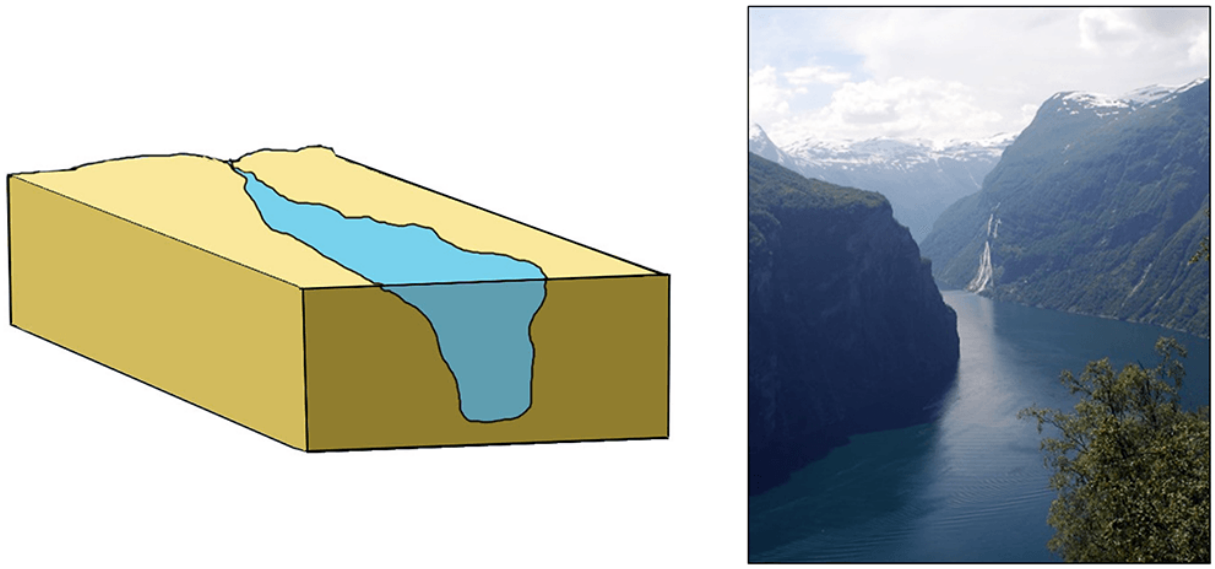


Figure 3.20.3 A fjord is a deep estuary that was carved out by glacial movements. At right is Geirangerfjord, Norway (left: JR, right: Fgmedia, [CC-BY-SA-3.0], via Wikimedia Commons).

Tectonic estuaries are the result of tectonic movements, where faulting causes some sections of the crust to subside, and those lower elevation sections then get flooded with seawater. San Francisco Bay is an example of a tectonic estuary (Figure 3.20.4).

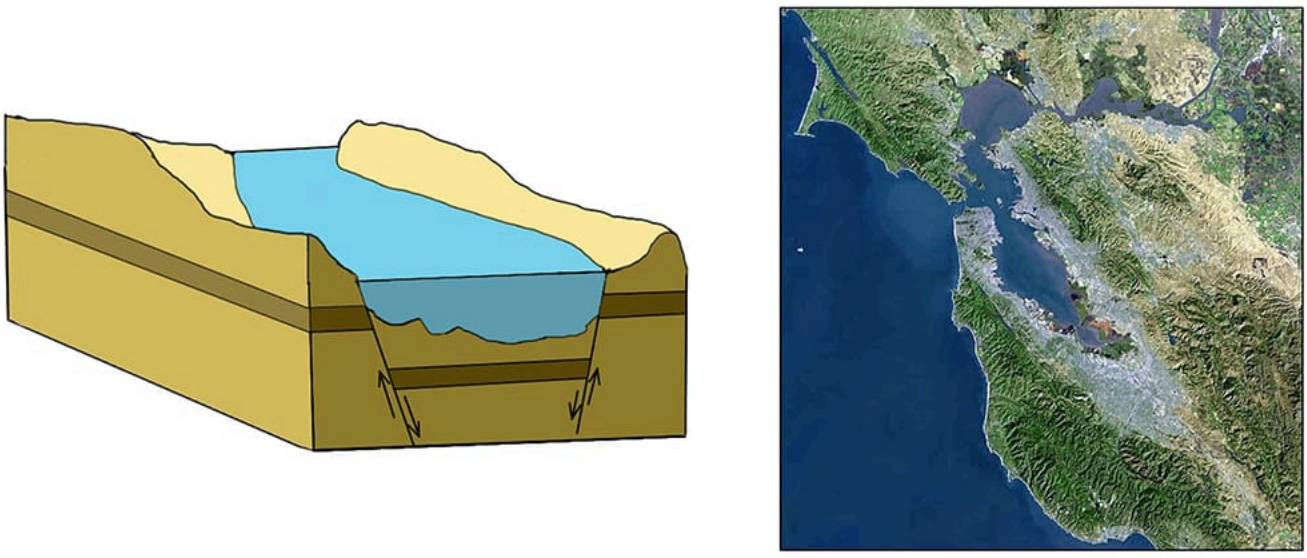


Figure 3.20.4 A tectonic estuary, formed from the subsidence of crust along fault lines, and the subsequent filling by seawater. San Francisco Bay is a tectonic estuary, shown at right (left: JR, right: USGS, Public Domain, via Wikimedia Commons).

Estuaries are also classified based on their salinity and mixing patterns. The amount of mixing of fresh and salt water in an estuary depends on the rate at which fresh water enters the head of the estuary from river input, and the amount of seawater that enters the estuary mouth as a result of tidal movements. The input of fresh water is reflected in the **flushing time** of the estuary. This refers to the time it would take for the in-flowing fresh water to completely replace all the fresh water currently in the estuary. Seawater input is measured by the **tidal volume**, or **tidalprism**, which is the average volume of sea water entering and leaving the estuary during each tidal cycle. In other words, it is the volume difference between high and low tides. The interaction between the flushing time, tidal volume, and the shape of the estuary will determine the extent and type of water mixing within the estuary.

In a **vertically mixed**, or **well-mixed** estuary there is complete mixing of fresh and salt water from the surface to the bottom. In a particular location the salinity is constant at all depths, but across the estuary the salinity is lowest at the head where the fresh water enters, and is highest at the mouth, where the seawater comes in. This type of salinity profile usually occurs in shallower estuaries, where the shallow depths allow complete mixing from the surface to the bottom.

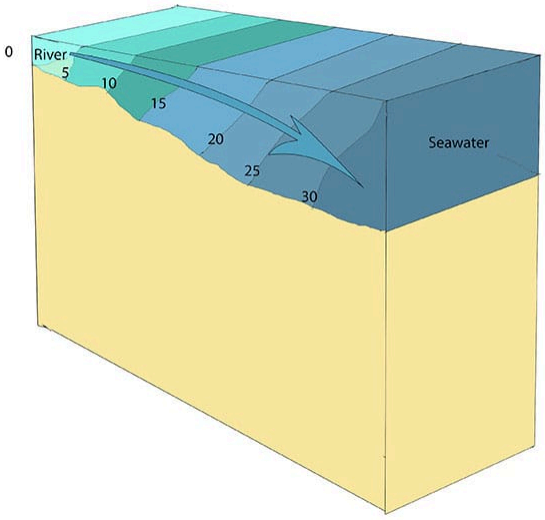


Figure 3.20.5 A well-mixed estuary. The shallow basin allows nearly complete mixing or fresh and seawater from top to bottom. Salinities are in ppt (JR).

Slightly stratified or **partially mixed** estuaries have similar salinity profiles to vertically mixed estuaries, where salinity

increases from the head to the mouth, but there is also a slight increase in salinity with depth at any point. This usually occurs in deeper estuaries than those that are well-mixed, where waves and currents mix the surface water, but the mixing may not extend all the way to the bottom.

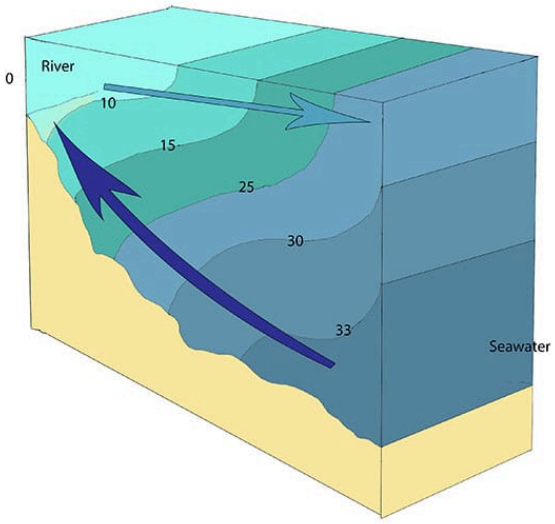


Figure 3.20.6 A slightly-stratified estuary. Generally deeper than a well-mixed estuary, the inflow of seawater (dark blue arrow) and fresh water (light blue arrow) create an estuary where salinity increases with depth, and at the surface when moving from the head to the mouth of the estuary. Salinities are in ppt (JR).

A **salt wedge** estuary occurs where the outflow of fresh water is strong enough to prevent the denser ocean water to enter through the surface, and where the estuary is deep enough that surface waves and turbulence have little mixing effect on the deeper water. Fresh water flows out along surface, salt water flows in at depth, creating a wedge shaped lens of seawater moving along the bottom. The surface water may remain mostly fresh throughout the estuary if there is no mixing, or it can become brackish depending on the level of mixing that occurs.

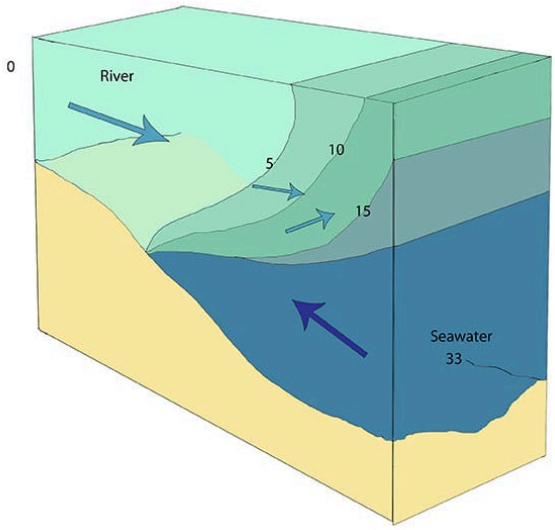


Figure 3.20.7 A salt wedge estuary. Strong river outflow (light blue arrows) creates a layer of mostly fresh water that sits on top of a wedge of encroaching seawater along the bottom (dark blue arrow). Salinities are in ppt (JR).

Highly stratified profiles are found in very deep estuaries, such as in fjords. Because of the depth, mixing of fresh and salt water only occurs near the surface, so in the upper layers salinity increases from the head to the mouth, but the deeper water is of standard ocean salinity.

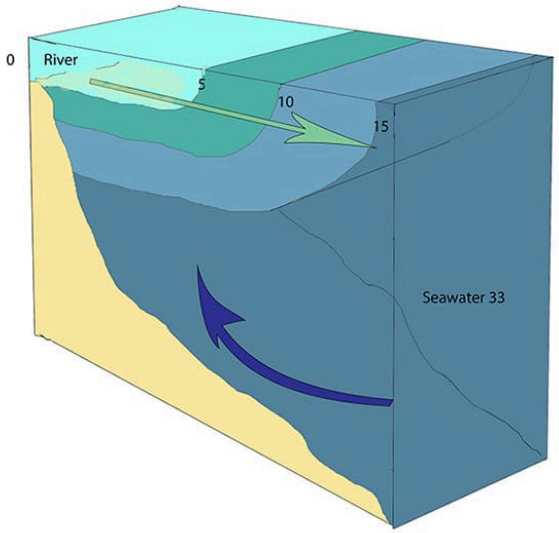


Figure 3.20.8 A highly stratified estuary. Strong river outflow and a deep basin prevent mixing between surface and bottom water, creating an estuary that is vertically stratified. Salinities are represented in ppt (JR).

Estuaries are very important commercially, as they are home to the majority of the world's metropolitan areas, they serve as ports for industrial activity, and a large percentage of the world's population lives near estuaries. Estuaries are also very important biologically, especially in their role as the breeding grounds for many species of fish, birds, and invertebrates.

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3.21: Sea Level Change

Sea level change has been a feature on Earth for billions of years, and it has important implications for coastal processes, estuaries, and both erosional and depositional features. There are two main mechanisms of sea level change, eustatic and isostatic, as described below.

Eustatic sea level changes are global sea level changes related to changes in the volume of water in the ocean. These can be due to changes in the volume of glacial ice on land, thermal expansion of the water, or to changes in the shape of the seafloor caused by plate tectonic processes. For example, seafloor spreading widens an ocean basin, thus changing its volume and affecting sea level.

Over the past 20,000 years, there has been approximately 125 m of eustatic sea level rise due to glacial melting. Most of that took place between 15,000 and 7,500 years ago during the major melting phase of the North American and Eurasian Ice Sheets (Figure 3.21.1). At around 7,500 years ago, the rate of glacial melting and sea level rise decreased dramatically, and since that time, the average rate has been in the order of 0.7 mm/year.

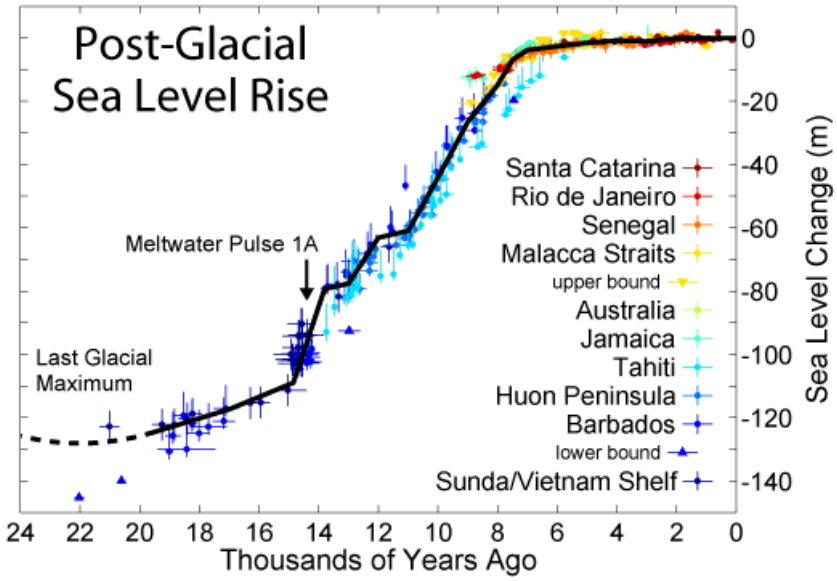


Figure 3.21.1 Sea level rise resulting from the melting of glacial ice over the past 24,000 years (Robert A. Rhode, CC BY-SA 3.0, via Wikimedia Commons).

Anthropogenic climate change led to accelerating sea level rise starting around 1870. Since that time, the average rate has been 1.1 mm/year, but it has been gradually increasing. Since 1992, the average rate has been 3.2 mm/year (Figure 3.21.2). Much of this is due to increased glacial melting as the global climate gets warmer (section 14.3), but a large part is due to **thermal expansion** of the water. As water warms, the molecules gain more kinetic energy and move faster and farther apart; the result is that the same amount of water now takes up more space. So even without the input of new water from melting ice, warming ocean temperatures will cause sea level to rise.

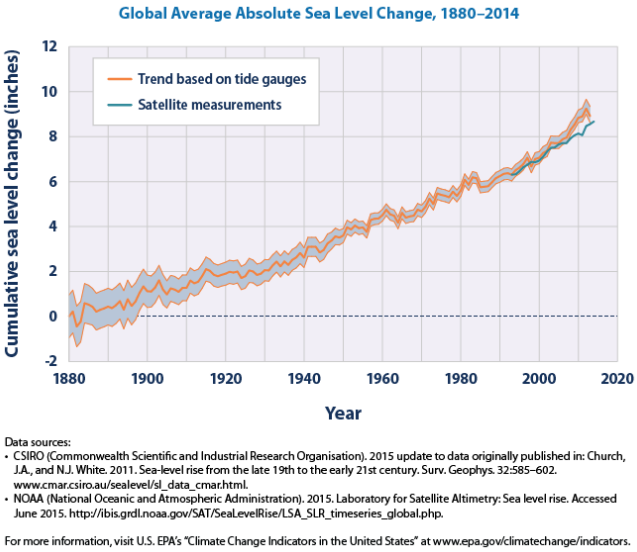


Figure 3.21.2 Average absolute sea level change, which refers to the height of the ocean surface, regardless of whether nearby land is rising or falling. Satellite data are based solely on measured sea level, while the long-term tide gauge data include a small correction factor because the size and shape of the oceans are changing slowly over time (US EPA [Public domain], via Wikimedia Commons).

Isostatic sea level changes are local changes caused by subsidence or uplift of the crust related either to changes in the amount of ice on the land, or to growth or erosion of mountains. Almost all of Canada and parts of the northern United States were covered in thick ice sheets at the peak of the last glaciation. Following the melting of this ice, there has been an isostatic rebound of continental crust in many areas. This ranges from several hundred meters of rebound in the central part of the Laurentide Ice Sheet (around Hudson Bay) to 100 m to 200 m in places such as Vancouver Island and the mainland coast of British Columbia. In other words, although global sea level was about 130 m lower during the last glaciation, the glaciated regions were depressed at least that much in most places, and more than that in places where the ice was thickest. Tectonic processes, such as the uplift of crust, can also cause localized changes in sea level.

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3.22: Tides

Learning Objectives

After reading this chapter you should:

- understand that tides are just very long waves, with crests and troughs
- understand Newton's Law of Universal Gravitation and how it applies to tides
- understand why most places on Earth experience two tides per day, not just the one predicted from gravitational attraction between the Earth and moon (i.e. inertial force)
- understand how the Earth, sun and moon interact to create spring and neap tides
- understand why the gravitational pull of the sun on tides is less than the pull of the moon
- understand why tides do not occur at the same time every day
- understand why amphidromic circulation occurs as a result of tides
- know the difference between diurnal, semi-diurnal, and mixed tides
- know the phases of a tidal current
- know what causes a tidal bore

The previous chapter discussed various types of waves at sea and along the shore. However, at least in terms of wavelength the largest waves in the ocean are the tides, where one wavelength stretches halfway around the Earth. The crests of these long waves represent the high tides, while the troughs create low tides.

You probably learned when you were younger that the basic cause of the tides is the gravitational attraction between the Earth and moon. This is a very old idea, as the Greek scientist Pytheas first made the connection between the tides and the moon back in 300 B.C. However, we now know that the tides involve a lot more than just the Earth and the moon, and it was Isaac Newton's work with gravitational forces in the 1600s that led to our modern understanding of tidal cycles.



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3.23: Tidal Forces

Our modern understanding of tide formation stems from Isaac Newton'sLaw of Universal Gravitation, which states that any two objects have a gravitational attraction to each other. The magnitude of the force is proportional to the masses of the objects, and inversely proportional to the square of the distance between the objects, according to the equation in Figure 3.23.1.

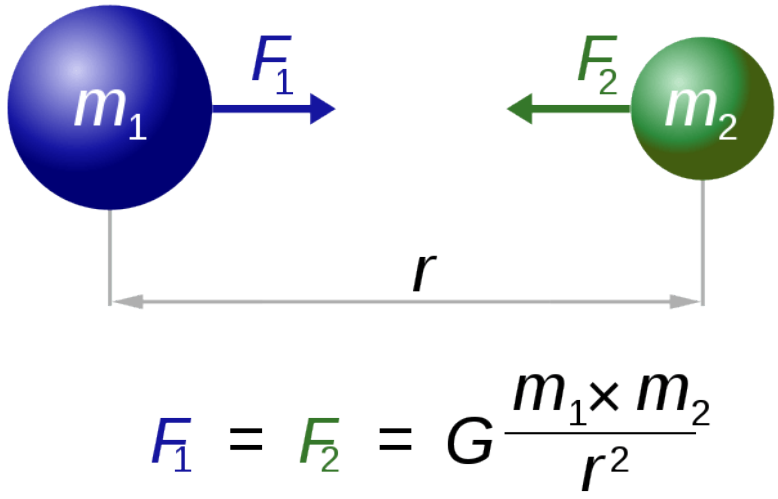


Figure 3.23.1 Newton's Law of Universal Gravitation. The gravitational force between two objects (F) is calculated as the product of the two masses (m_1 and m_2) divided by the distance between them (r) squared. G is the universal gravitational constant; 6.67408×10^{-11} m^3 kg^{-1} s^{-2} (By I, Dennis Nilsson [CC BY 3.0], via Wikimedia Commons).

In the case of tides, there are a few other factors that modify this equation so that the distance (r) is cubed rather than squared, giving distance an even greater impact on tidal forces. But for our purposes, the important lesson is that the greater the masses of the objects, the greater the gravitational force, and the farther the objects are from each other, the weaker the force.

Such a gravitational force exists between the Earth and moon, attempting to pull them towards each other. Since the water covering Earth is fluid (unlike the solid land that is more resistant to tidal forces), this gravitational force pulls water towards the moon, creating a "bulge" of water on the side of the Earth facing the moon (Figure 3.23.2). This bulge always faces the moon, while the Earth rotates through it; the regions of Earth moving through the bulge experience a high tide, while those parts of the Earth away from the bulge experience a low tide.

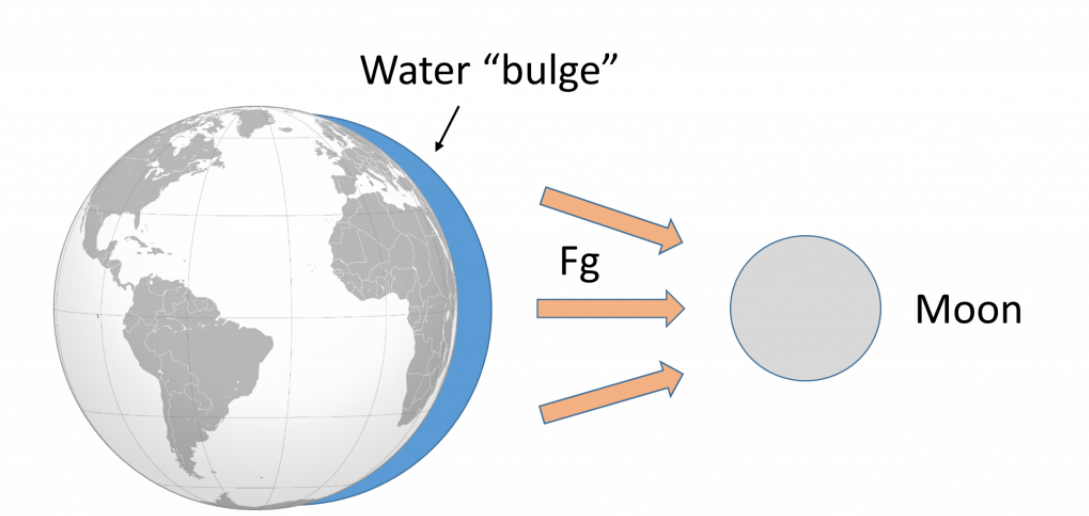


Figure 3.23.2 Gravitational forces between the Earth and moon cause a bulge of water to appear on the side of the Earth facing the moon (PW).

the tides were this simple, everywhere on Earth would see one high tide per day, as there would only be a bulge of water on the side closest to the moon. However, if you have ever looked at tide charts, or lived near the ocean, you probably know that in most places there are two high tides and two low tides per day. Where is this second high tide “bulge” coming from?

The gravitational force between the Earth and moon might be expected to draw the two objects closer together, however, this is not happening. This is because the inward gravitational force is opposed by outward forces that keep the Earth and moon apart. The outward force is an **intertial force** created by the rotation of the Earth and moon. Contrary to popular belief, the moon is not simply rotating around the Earth; in fact, the Earth and moon are both rotating around each other. Imagine the Earth and moon as equal-sized objects revolving around a point at their center of mass. If both objects had the same mass, the center of rotation would be a point equidistant between the two objects. But since the mass of the Earth is 82 times greater than the mass of the moon, the center of revolution must be closer to the Earth. As an analogy, think about two people on a see-saw. If the people are of roughly equal size, they can sit on either end of the see-saw at it will rotate around a point at equal distance between them. But if the two people have very different masses, such as a large adult and a small child, the larger person must move closer to the pivot point for the see-saw to rotate effectively. In the same way, the center of rotation between the Earth and the moon (the **barycenter**) must be located closer to the Earth. In fact, the center of rotation lies *within* the Earth, about 1600 km below the surface. As the Earth and moon rotate around the barycenter, the moon travels much farther than the Earth, giving the impression that the moon is rotating around Earth (Figure 3.23.3).

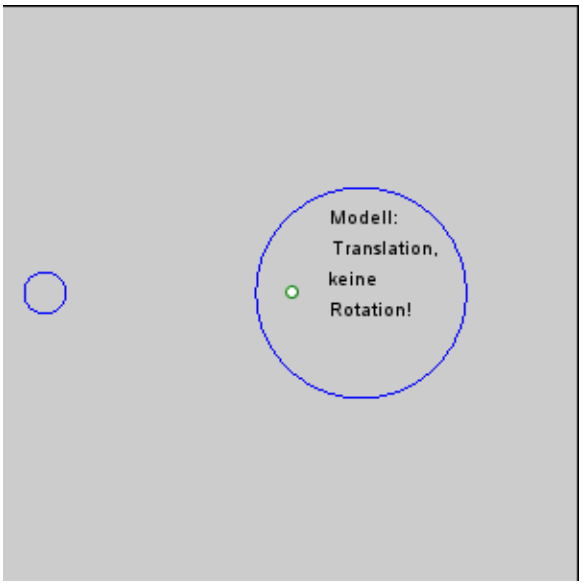


Figure 3.23.3 Rotation of the Earth and moon around the barycenter (white dot). Because of its larger mass, the center of rotation lies closer to the Earth than to the moon (By Modalanalytiker (Own work) [CC BY-SA 3.0 or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons).

The rotation of the Earth-moon system creates an outward inertial force, which balances the gravitational force to keep the two bodies in their orbits. The inertial force has the same magnitude everywhere on Earth, and is always directed away from the moon. Gravitational force, on the other hand, is always directed towards the moon, and is stronger on the side of the Earth closest to the moon. Figure 3.23.4 describes how these forces combine to create the tidal forces. At point O in the center of the Earth, the gravitational force (F_g) and the inertial force (F_r) are equal, and cancel each other out. On the side of Earth closest to the moon, the inward gravitational force (F_g) is greater than the outward inertial force (F_r); the net resulting force (A) is directed towards the moon, and creates a bulge of water on the side facing the moon. On the side of Earth opposite the moon, the outward inertial force is greater than the inward gravitational force; the net resulting force (C) is directed away from the moon, creating a water bulge directed away from the moon.

Now, as the Earth rotates through a 24 hour day, each region passes through two bulges, and experiences two high tides and two low tides per day. This represents Newton's **Equilibrium Theory of Tides,** where there are two high tides and two low tides per day, of similar heights, each six hours apart. But as with everything else in oceanography, reality is much more complex than this idealized situation.

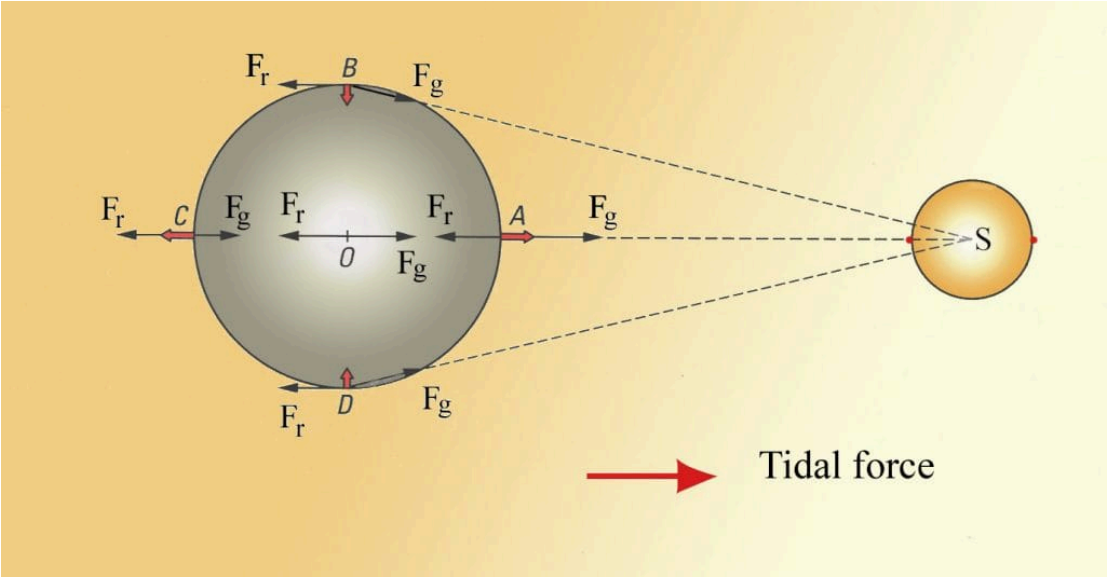


Figure 3.23.4 Gravitational force (F_g) are strongest closer to the moon and weaker opposite the moon. Inertial forces (F_r) are equal throughout the Earth and directed away from the moon. The tidal forces A and C are the result of the interaction between F_g and F_r and create water bulges on both sides of the Earth, leading to two high tides per day (Vitold Muratov (Own work) [CC BY-SA 3.0], via Wikimedia Commons).

Some of the additional complexity is because in addition to the moon, the sun also exerts tide-affecting forces on Earth. The solar gravitational and inertial forces arise for the same reasons described above for the moon, but the magnitudes of the forces are different. The sun is 27 million times more massive than the moon, but it is 387 times farther away from the Earth. Despite its larger mass, because the sun is so much farther away than the moon, the sun's gravitational forces are only about half as strong as the moon's (remember that distance is cubed in the gravity equation). The sun thus creates its own, smaller water bulges, independent of the moon's, that contribute to the creation of tides.

When the sun, Earth and moon are aligned, as occurs during new and full moons, the solar and lunar bulges are also aligned, and add to each other (constructive interference; see section 10.2) creating an especially high tidal range; high high tides and low low tides (Figure 3.23.5). This period of maximum tidal range is called a **spring tide**, and they occur every two weeks.

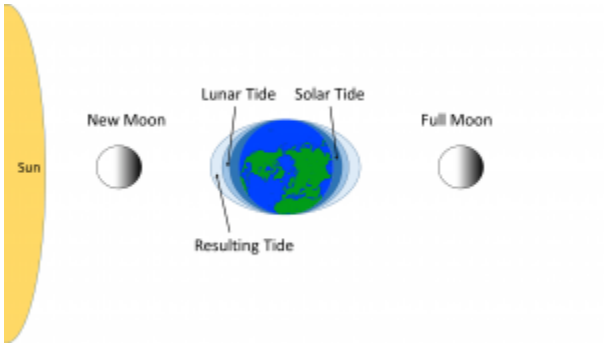


Figure 3.23.5 Spring tides with high tidal ranges occur when the solar and lunar tides are added together during full and new moons when the Earth, sun and moon are aligned (PW).

When the sun, Earth and moon are at 90° to each other, the solar and lunar bulges are out of phase, and cancel each other out (destructive interference). Now the tidal range is small, with low high tides and high low tides (Figure 3.23.6). These are **neap tides**, and occur every two weeks, when the moon is in its 1/4 and 3/4 phases (Figure 3.23.7).

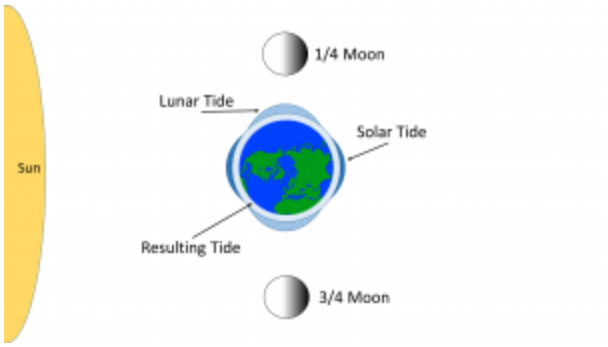


Figure 3.23.6 Neap tides are created during 1/4 and 3/4 moons when the Earth, sun and moon are perpendicular to each other. The solar and lunar tides cancel each other out, resulting in a small tidal range (PW).

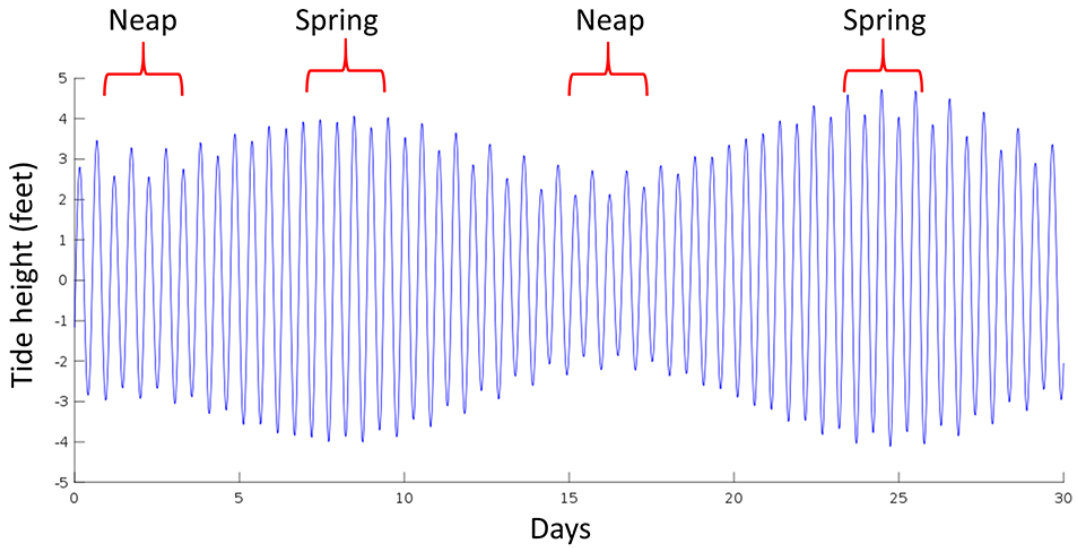


Figure 3.23.7 30 days of tidal data from Bridgeport, CT, USA, showing spring and neap tidal ranges (Modified by PW from Cody Logan (clpo13), Public Domain via Wikimedia Commons).

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3.24: Dynamic Theory of Tides

The Equilibrium Theory of tides predicts that each day there will be two high and two low tides, each one occurring at the same time day after day, with each pair producing tides of similar heights. While this view provides a basic explanation for the primary forces that generate the tides, it does not take into account such variables as the effects of the continents, the depth of the water, and many other factors. In all, there are almost 400 variables that must be incorporated into predicting the tides! The **Dynamic Theory** of tides takes these other factors into account, and shows that the tides are much more complicated and variable from place to place than the Equilibrium Theory would suggest. For example, some areas receive only one high and one low tide per day (see section 11.3). Furthermore, the tidal range varies greatly across the globe; in the Mediterranean Sea, there can be a difference of only 10 cm between high and low tides, while the Bay of Fundy in Canada experiences a tidal range of up to 17m (56 ft) every day (Figure 3.24.1).



Figure 3.24.1 Tidal range in the Bay of Fundy, Canada. Both photographs were taken on the same day in July 2003 (By Dylan Kereluk from White Rock, Canada (Flickr) [CC BY 2.0], via Wikimedia Commons).

Examination of any tide chart will show that the tides don't occur at same time each day; in fact, each tidal peak occurs about 50 minutes later than it did in the previous day. This is due to the orbit of the moon around the Earth. Imagine a high tide that occurs at a particular location (X) at 1:00 pm (Figure 3.24.2). The high tide occurs as location X moves through the bulge of water facing the moon. It will take the Earth 24 hours to complete one revolution, to bring location X back to site of the water bulge that caused that high tide. However, during those 24 hours, the moon has also moved as it orbits the Earth, so the high tide bulge has moved beyond its original location. The Earth thus has to rotate an additional distance for location X to reach the bulge and experience that same high tide. Because it takes the moon about 28 days to orbit the Earth, the moon gets "ahead" of the Earth's rotation by about 50 minutes per day. Therefore, it takes location X 24 hours and 50 minutes to rotate through the same tidal bulge, and as a result, the tidal peaks occur about 50 minutes later each day. In our example, an afternoon high tide at 1:00 pm on one day would be followed by a high tide at about 1:50 pm the following day. This 24 hour and 50 minute cycle is referred to as a **tidal day**.

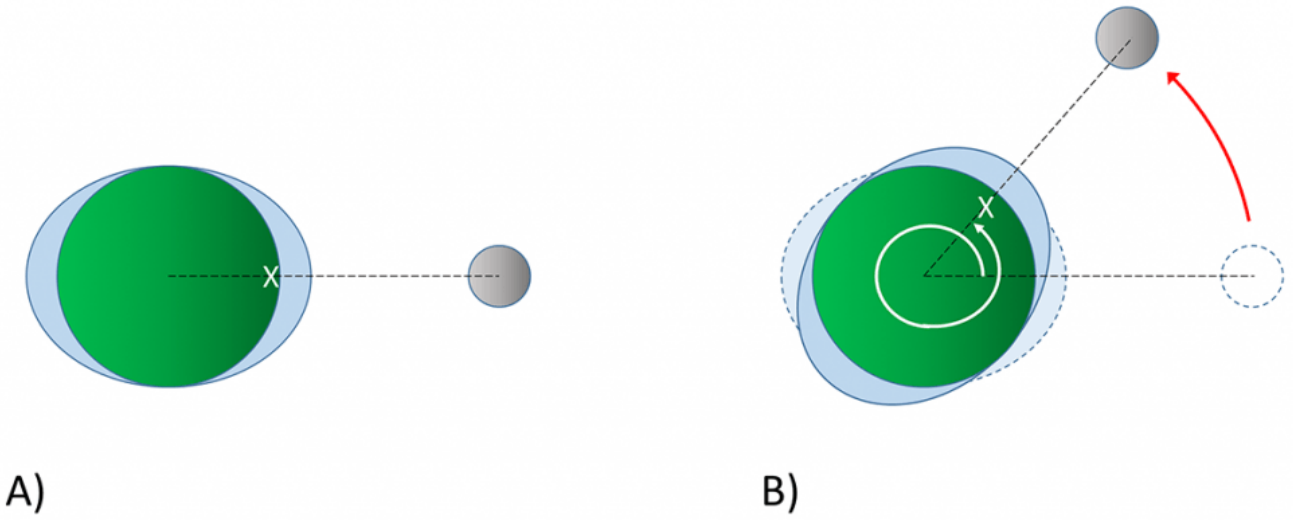


Figure 3.24.2 In A) a high tide is occurring at point X on Earth's surface. 24 hours later, X has made a complete rotation and is back in its original position. However, the moon has moved during that time (B), so X must travel an additional distance (white arrow) to once again become aligned with the moon and experience a high tide. For this reason, corresponding tides occur approximately 60 minutes later each day (PW).

The motion of the moon impacts the tidal cycles in other ways. As the moon orbits the Earth, its orbital plane is at an angle relative to the rotational plane of Earth. This angle, or **declination**, means than the moon fluctuates between an angle of 28.5° north of the equator, to 28.5° south of the equator roughly every two weeks (the cycle from maximum to minimum and back takes about 27 days). Figure 3.24.3 illustrates a case where the moon is at its maximum declination 28.5° north of the equator, creating its corresponding tidal maxima. A point on the Earth at the latitude indicated by the red line would experience two high tides as it rotated through 24 hours, at points A and B. But the two high tides would not be of equal heights; the high tide at A would be higher than the high tide at B. This helps create a mixed semi-diurnal tide; two high tides of different heights per day (see section 11.3).

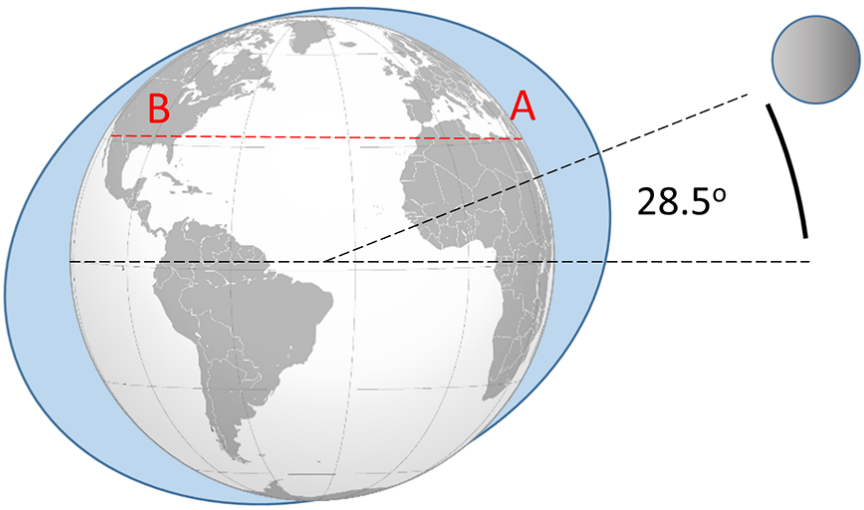


Figure 3.24.3 The effect of the moon declination on tide heights. The moon oscillates between 28.5° north and 28.5° south of the equator every two weeks, leading to uneven tidal heights each day at a particular latitude (PW).

Finally, the continents and the bottom topography of the oceans have an impact on the tides that are experienced in an area. Because the tides are essentially waves with extremely long wavelengths extending halfway across the Earth, they behave as shallow water waves, and they are influenced and refracted by the bottom contours, leading to regional tidal variations. When the

tidal crests encounter land, they are are reflected, and the wave moves back out to sea, theoretically until it encounters another continent on the opposite side of the ocean basin. The crest is once again reflected, and the water oscillates back and forth as a standing wave across the ocean basin. However, because of the scale over which these tidal waves move, we must take into account the influence of the Coriolis Effect. As the tidal crest is reflected back across the ocean basin, its path is deflected by the Coriolis force; to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere (see section 9.1). Using the Northern Hemisphere as an example, imagine a tidal crest that has reached land on the western side of an ocean basin. It would have a tendency to be reflected and move across the basin towards the east. But the Coriolis force deflects the movement to the right, causing the crest to instead head south. When the crest hits land in the south, it would now tend to reflect towards the north, but once again the Coriolis deflection to the right kicks in, and the wave instead moves to the east. From the east the reflected wave is deflected to the north, and so on. The result of all of this is that instead of a simple standing wave moving back and forth across the ocean, the tidal crest follows a circular pattern around the ocean basin, counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. This is analogous to shaking a pan full of water in a circular manner, and watching the water follow a similar circular path as it sloshes around inside. This large scale circular rotation pattern of tides is called **amphidromic circulation** (Figure 3.24.4). The rotation occurs around a central **amphidromic point** or **node**, that shows little tidal variation, while the largest tidal ranges occur on the edges of the circulation pattern. In Figure 3.24.4 the amphidromic points are indicated by the dark blue areas where the white lines converge, like spokes from a bicycle wheel, and the dark red and brown areas show the regions of maximum tidal heights. The tidal maxima will rotate around the amphidromic points, taking about 12 hours for a complete rotation, leading to two high and two low tides per day in many places. If a tidal maximum is occurring along one of the white lines in Figure 3.24.4 at a certain time in the Northern Hemisphere, one hour later that high tide will have moved to the white line to the left (counterclockwise), and so on until it completes a rotation. In the Southern Hemisphere, the tide will move to the line to the right for clockwise rotation.

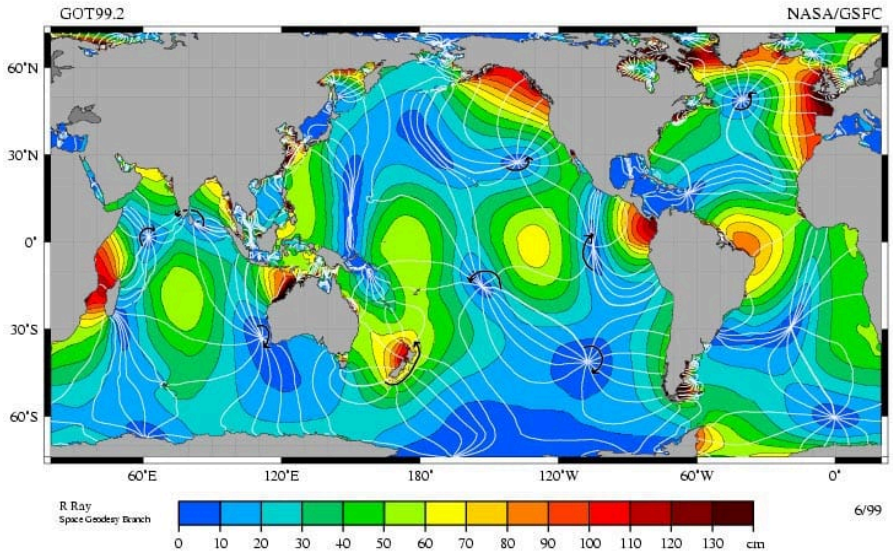


Figure 3.24.4 Amphidromic circulation. Amphidromic points are represented where the white lines converge in areas of minimal tidal range. Tidal crests rotate around the amphidromic points, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. See text for details (NASA, Public Domain via Wikimedia Commons).

The result of all of these variables is that the tides will not always occur twice each day, at the same time and with equal heights as the Equilibrium Theory of tides may suggest. Instead, each region of the oceans has a unique set of factors that contribute to the types of tides it will experience. The major types of tides are discussed in the next section.

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3.25: Tide Classification

With so many variables playing a role in the production of tides, it is understandable that not every place on Earth will experience exactly the same tidal conditions. There are three primary classifications for tides, depending on the number and relative heights of tidal cycles per day.

A **diurnal tide** consists of only one high tide and one low tide per day (Figure 3.25.1). “Diurnal” refers to a daily occurrence, so a situation where there is only one complete tidal cycle per day is considered a diurnal tide. Diurnal tides are common in the Gulf of Mexico, along the west coast of Alaska, and in parts of Southeast Asia.

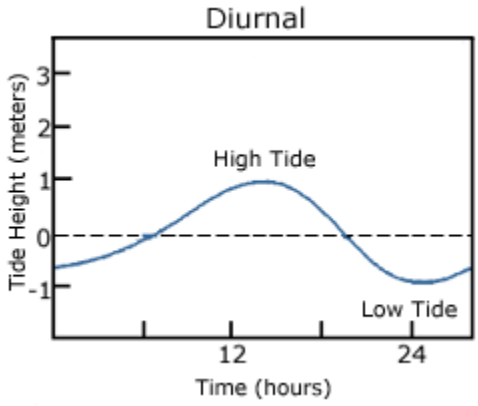


Figure 3.25.1 A diurnal tide, with one high and one low tide per day (By NOAA [Public domain], via Wikimedia Commons).

A **semidiurnal tide** exhibits two high and two low tides each day, with both highs and both lows of toughly equal height (Figure 3.25.2). “Semidiurnal” means “half of a day”; one tidal cycle takes half of a day, therefore there are two complete cycles per day. Semidiurnal tides are common along the east coasts of North America and Australia, the west coast of Africa, and most of Europe.

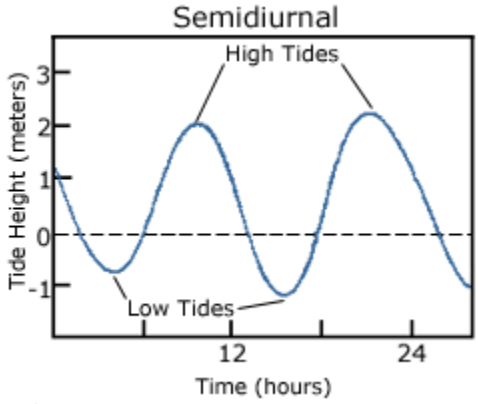


Figure 3.25.2 A semi-diurnal tide, with two high and two low tides per day, each of roughly equal heights (By NOAA [Public domain], via Wikimedia Commons).

Mixed semidiurnal tides (or **mixed tides**), have two high tides and two low tides per day, but the heights of each tide differs; the two high tides are of different heights, as are the two low tides (Figure 3.25.3). The differences in height may be the result of amphidromic circulation, the angle of the moon, or any of the other variables discussed in section 11.2. Mixed semidiurnal tides are found along the Pacific coast of North America.

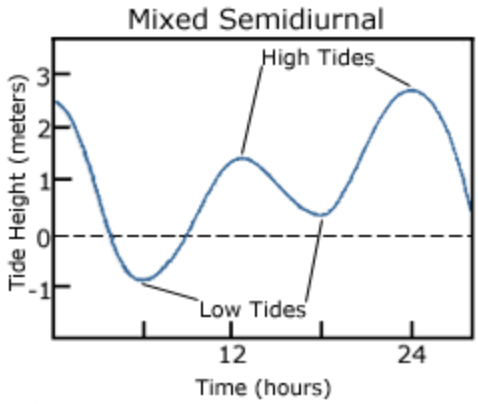


Figure 3.25.3 A mixed semi-diurnal tide, with two high and two low tides per day, each with a different height (By NOAA [Public domain], via Wikimedia Commons).

Figure 3.25.4 shows the distribution of the various tide types throughout the world.

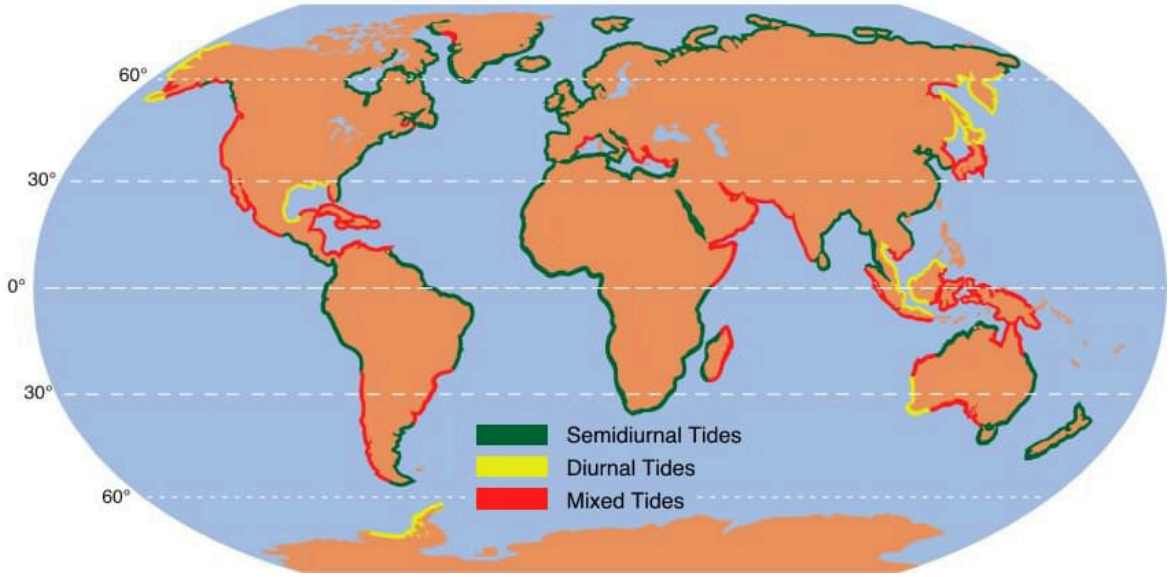


Figure 3.25.4 Global distribution of the different types of tides (By KVDP (Own work) [Public domain], via Wikimedia Commons).

Tidal Currents

The movement of water with the rising and falling tide creates tidal currents. As the tide rises, water flows into an area, creating a **flood current**. As the tide falls and water flows out an **ebb current** is created. **Slack water**, or **slack tides** occur during the transition between incoming high and outgoing low tides, when there is no net water movement.

The strength of a tidal current depends on the volume of water that enters and exits with each tidal cycle (the **tidal volume** or **tidal prism**), and the area through which the water flows. A large tidal volume moving through a large area may create only a weak tidal current, as the volume is spread over a wide area. On the other hand, a narrow area may produce a strong tidal current even if the tidal volume is small, as all of the water is forced through a small area. It follows that the strongest tidal currents will result from a large tidal range moving through a narrow area.

Tidal bores occur where rivers meet the ocean. If the incoming tidal current is stronger than the river outflow, the tidal bore appears as a wave, or moving wall of water that moves up the river as the tide comes in (Figure 3.25.5).



Figure 3.25.5 A tidal bore near Silverdale in the United Kingdom (Arnold Price [CC BY-SA 2.0], via Wikimedia Commons).

In many cases these tidal bores may move through a river or inlet for many kilometers, and if they are large enough they can form continually breaking waves that surfers can ride much farther and longer than a traditional ocean wave, such as the Severn Bore in England, shown in the video below.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Incredible Severn Bore Wave: https://www.youtube.com/watch?v=IKA3...ature=youtu.be

Additional links for more information

- For an even more dramatic tidal bore, watch this video of the "Silver Dragon" on China's Qiantang River

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3.26: Surface Water

A **stream** or **river** is a body of flowing surface water confined to a channel. Terms such as creeks and brooks are social terms not used in geology. Streams are the most important agents of erosion and transportation of sediments on the earth's surface. They create much of the surface topography and are an important water resource. Most of this section will focus on stream location, processes, landforms, and flood hazards. Water resources and groundwater processes will be discussed in later sections.

Discharge

Several factors cause streams to erode and transport sediment, but the two main factors are stream channel gradient and velocity. The stream **gradient** is the slope of the river channel. A steeper gradient promotes downward stream erosion. When tectonic forces lift up a mountain, the increased stream gradient causes the stream to erode downward and make a valley. Stream velocity is the speed of the flowing water in the channel. Velocity can increase by increasing the gradient, decreasing cross-sectional area (narrowing) of the channel (reducing friction), or by increasing the discharge.

Stream size is measured in terms of **discharge,** i.e. the volume of water flowing past a point in the stream over a defined time interval. Smaller streams have a smaller discharge, therefore generally stream discharge increase downstream**.** Volume is commonly measured in cubic feet (length x width x depth), shown as feet^3 or ft^3. Therefore, the units of discharge are cubic feet per second (ft^3/sec or cfs). Smaller streams have less discharge than larger streams. For example, the Mississippi River is the largest river in North America, with an average flow of about 600,000 cfs [19]. For comparison, the average discharge for the Jordan River at Utah Lake is about 574 cfs [20] and for the Amazon River (the world's largest river), annual discharge is about 6,200,000 cfs [21].

Discharge can be expressed by the following equation:

$Q = V A$

- Q = discharge (ft^3/sec),
- A = cross-sectional area of the stream channel [width times average depth] (in ft^2),
- V = average velocity (ft/sec).

When the channel narrows but discharge remains constant, the same volume of water flows through a narrower space causing the velocity to increase, similar to putting a thumb over the end of a backyard water hose. In addition, during rainstorms or heavy snowmelt, runoffs will increase which increases stream discharge and thus velocity.

Velocity varies within the stream channel as well. Generally, when the channel is straight and uniform in-depth, the highest velocity is in the center of the channel along the top of the water where it is the farthest from frictional contact with the channel bottom and sides. When the channel curves, the highest velocity will be on the outside of the bend.

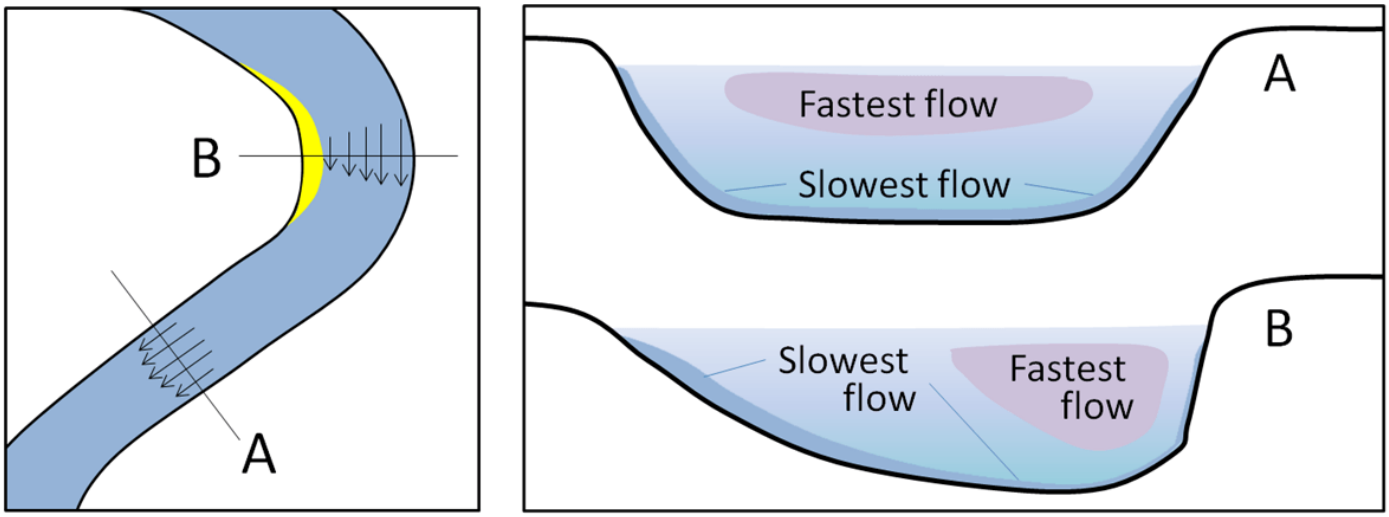


Figure 3.26.1: Thalweg of a river. In a river bend, the fastest moving particles are on the outside of the bend, near the cutbank. Stream velocity is higher on the outside bend and the surface which is farthest from the friction of the stream bed. Longer arrows indicate faster velocity (Earle 2015).

Runoff vs. Infiltration

There are many factors dictating whether water will infiltrate into the ground or runoff over the land after precipitation. These include but are not limited to the amount, type, and intensity of precipitation, the type and amount of vegetative cover, the slope of the land, the temperature and aspect of the land, preexisting conditions, and the type of soil in the area of infiltration. High-intensity precipitation as rain will cause more runoff than the same amount of rain spread out over a longer duration. If the rain falls faster than the properties of the soil allow it to infiltrate, then the water that cannot infiltrate becomes runoff. Dense vegetation can increase infiltration, as the vegetative cover slows the overland flow of water particles, giving them more time to infiltrate. If a parcel of land has more direct solar radiation and/or higher seasonal temperatures, there will likely be less infiltration and runoff, as evapotranspiration rates will be higher. As the slope of the land increases, so does runoff, as the water is more inclined to move downslope than infiltrate into the ground. Extreme examples are a basin and a cliff, where water infiltrates much quicker into a basin than a cliff having the same soil properties. Because saturated soil does not have the capacity to take more water, runoff is generally greater over-saturated soil. Clay rich soil cannot accept infiltration as quickly as gravel-rich soil.

Drainage Patterns

The pattern of tributaries within a region is called a **drainage pattern**. They depend largely on the type of rock beneath, and on structures within that rock (such as folds and faults). The main types of drainage patterns are dendritic, trellis, rectangular, radial, and deranged. **Dendritic patterns** are the most common and develop in areas where the underlying rock or sediments are uniform in character, mostly flat-lying, and can be eroded equally easily in all directions. Examples are alluvial sediments or flat-lying sedimentary rocks. **Trellis patterns** typically develop where sedimentary rocks have been folded or tilted and then eroded to varying degrees depending on their strength. The Appalachian Mountains in the eastern United States have many good examples of trellis drainage. **Rectangular patterns** develop in areas that have very little topography and a system of bedding planes, joints, or faults that form a rectangular network. A **radial pattern** forms when streams flow away from a central high point such as a mountain top or volcano, with the individual streams typically having dendritic drainage patterns. In places with extensive limestone deposits, streams can disappear into the groundwater via caves and subterranean drainage and this creates a **deranged pattern**.

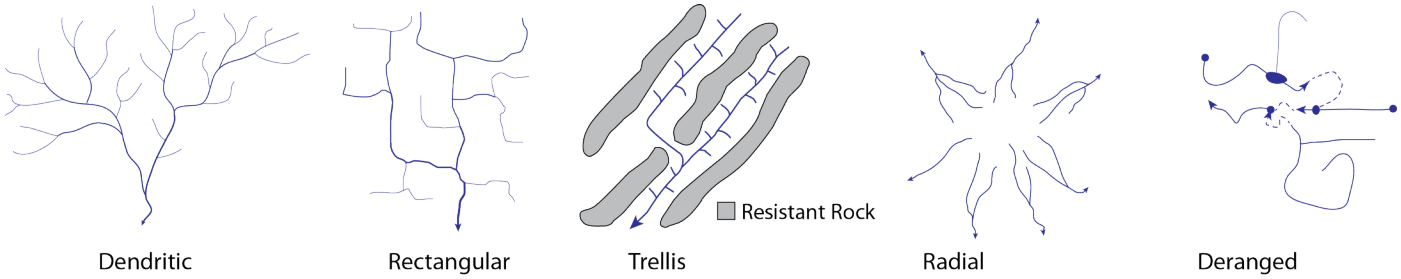


Figure 3.26.1: Various stream drainage patterns.

Fluvial Processes

Fluvial processes are the mechanisms that dictate how a stream functions and include factors controlling fluvial sediment production, transport, and deposition. Fluvial processes include velocity, slope and gradient, erosion, transportation, deposition, stream equilibrium, and base level.

Streams can be divided into three main sections: the many smaller tributaries in the source area, the main trunk stream in the floodplain and the distributaries at the mouth of the stream. These can be defined as zones of sediment production (erosion), transport, and deposition. The zone of sediment production is located in the headwaters of the stream. Downstream of the **headwaters**, the stream erodes less sediment but transports the sediment provided from the headwaters in the zone of sediment transfer. Lastly, most streams eventually flow into the ocean by a delta which is a zone of sediment deposition located at the **mouth** of a stream [6]. The **longitudinal profile** of a stream is a plot of the elevation of the stream channel at all points along its course and illustrates the location of the three zones [22].

Zone of Sediment Production (Erosion)

The zone of sediment production is located in the headwaters of a stream where rills and gullies erode sediment and contribute to larger tributary streams. These tributaries carry sediment and water further downstream to the main trunk of the stream. Tributaries at the headwaters have the steepest gradient and most sediment production and erosion, especially downward erosion, occur in the headwaters zone. Headwater streams tend to be narrow and straight with small or non-existent floodplains adjacent to the channel. Since the zone of sediment production is generally the steepest part of the stream, many headwaters are located in relatively high elevations. For example, the Rocky Mountains of Wyoming and Colorado contain much of the headwaters for the Colorado River which then flows from Colorado through Utah, Arizona, to Mexico.

Zone of Sediment Transfer (Transportation)

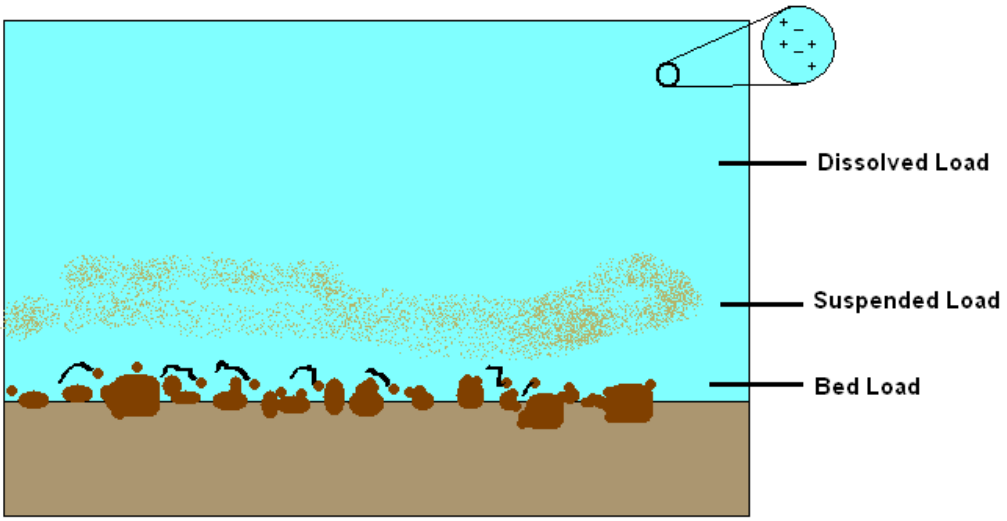


Figure 3.26.1: A stream carries dissolved load, suspended load, and bedload.

Streams transport sediment great distances from the headwaters to the ocean, the ultimate depositional basins. Sediment transportation is directly related to stream gradient and velocity. Faster and steeper streams can transport larger sediment grains. When velocity slows down, larger sediments settle to the channel bottom. When the velocity increases, those larger sediments are entrained and move again.

Transported sediments are grouped into bedload, suspended load, and dissolved load. Sediments moved along the channel bed are the **bedload** and typically are the largest and densest. Bedload is moved by saltation (bouncing) and traction (being pushed or rolled along by the force of the flow). When stream velocity increases, smaller bedload sediments can be picked up by flowing water and held in suspension as **suspended load**. The faster streams can carry larger grains as suspended load. **Dissolved load** in a stream is the sum of the ions in solution from chemical weathering. The dissolved load includes ions such as bicarbonate (HCO_3^-), calcium (Ca^{2+}), chloride (Cl^-), potassium (K^+), and sodium (Na^+). The solubility of these ions is not affected by flow velocity.

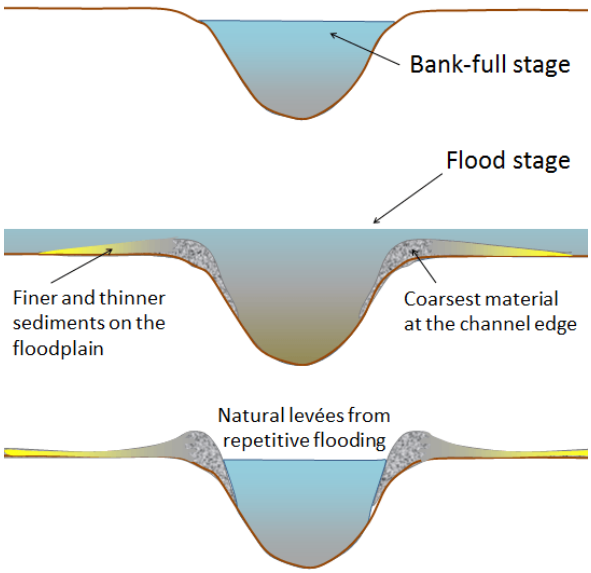


Figure 3.26.1: Profile of stream channel at bank-full stage, flood stage, and deposition of natural levee

Stream flooding is a natural process that adds sediment to floodplains. A **floodplain** is the generally flat area of land located adjacent to a stream channel that is inundated with floodwater on a regular basis. A stream typically reaches its greatest velocity when it is close to flooding, known as the **bank-full stage**. As soon as the flooding stream overtops its banks and occupies the wide area of its floodplain, the velocity decreases. At this point, sediment that was being carried by the swiftly moving water is deposited near the edge of the channel, forming a low ridge or **natural levée.** In addition, sediments are added to the floodplain during this flooding process.

Zone of Disposition

The process of **deposition** occurs when bedload and suspended load come to rest on the bottom of the water column in a stream channel, lake, or ocean. The two major factors causing deposition are the decrease in stream gradient and the reduction in velocity. These can be associated with a decrease in discharge or increased in cross-sectional area. Deposition occurs temporarily in the zone of transportation such as along meandering stream point bars, floodplains, and alluvial fans (discussed later), however, ultimate deposition occurs at the mouth of the stream where it reaches a lake or ocean. These deposits at the mouth of a stream form landforms called **deltas**. Deposition at the mouth of a stream is generally of the finest sediment such as fine sand, silt, and clay, because as the stream exits its channel, the energy of the water is completely dispersed, causing the deposition of all particles in the stream.

Equilibrium and Base Level

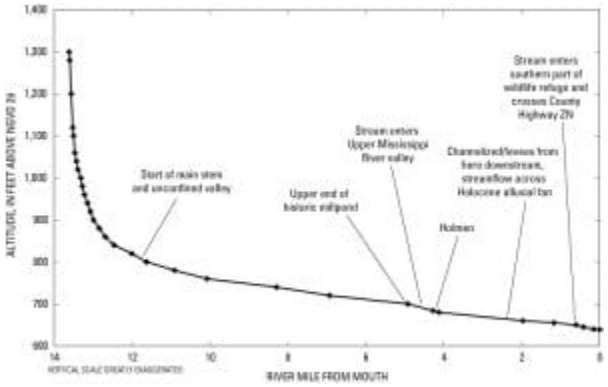


Figure 3.26.1: Example of a longitudinal profile of a stream; Halfway Creek, Indiana

All three stream zones are present in the typical **longitudinal profile** of a stream which plots the elevation of the channel at all points along its course (see figure). All streams have a long profile, some of which have been measured, plotted, and published. The long profile shows the stream gradient from headwater to mouth and represents the balance among erosion, transport, gradient, velocity, discharge, and channel characteristics at each point along the stream's course. This balance is called **equilibrium**. When mountains are uplifted, streams become steeper which erodes downward cutting a valley. This uplift is balanced against downward erosion of the stream. Eventually, streams erode enough downward that the gradient is reduced, downward erosion slows, and the river starts to erode from side to side. This point is generally characterized by a stream with a **floodplain** [6].

Another factor influencing equilibrium is the **base level**, the elevation of the stream's mouth. The base level represents the lowest level to which a stream can erode. The ultimate base level is, of course, sea-level. A lake or reservoir may also represent the base level for a stream entering it. The Great Basin of western Utah, Nevada, and parts of some surrounding states contains no outlets to the sea and provides internal base levels for streams within it. The base level for a stream entering the ocean can change if sea-level rises or falls or if a natural or human-made dam is added along its profile. When base level is lowered, a stream will downcut and deepen its channel, perhaps into a canyon. When base level is raised, deposition increases along the stream profile as the river adjusts to the change and establishes a new state of equilibrium. River equilibrium is dynamic as the river adjusts to changes in base level, tectonics, climate, precipitation, sea level, and human activities along its course.

Landforms

Stream landforms are the land features formed on the surface by either erosion or deposition. The primarily stream-related landforms described here are related to channel types.

Channel Types



Figure 3.26.1: Braided stream pattern on the Waimakariri River in New Zealand.



Figure 3.26.1: Air photo of the meandering river, Río Cauto, Cuba.

Stream channels can be straight, braided, meandering, or entrenched. The gradient, sediment load, discharge, and location of the base level all influence channel type.

Straight channels are relatively straight, located near the headwaters, have steep gradients, low discharge, and narrow V-shaped valleys. Good examples of these are located in mountainous areas. Anastomosing streams, forming a network of branching and reconnecting channels are a variety of straight channels, formed in areas of high vegetation where the plant growth keeps the channel straight.

Braided channels have multiple smaller channels splitting and recombining downstream creating numerous mid-channel bars. These are found in broad terrain with low gradients near sediment source areas such as mountains or in front of glaciers, for example in Alaska.

Meandering channels are composed of a single channel that curves back and forth like a snake within its floodplain. Meandering channels tend to have a wide floodplain, high discharge, natural levees, and flood regularly. Meandering channels are usually located on low gradient slopes where the stream emerges from its headwaters into the zone of transportation and extends close to the zone of deposition at the stream's mouth. In areas of uplift, like has occurred on the Colorado Plateau, meanders that

formed on the upland can become entrenched or incised as the stream cuts its meandering pattern down into bedrock.



Figure 3.26.1: Panoramic view of incised meanders of the San Juan River at Gooseneck State Park, Utah.

Alluvial Fans



Figure 3.26.1: Alluvial fan in Iraq seen by a NASA satellite. A stream emerges from the canyon and creates this cone-shaped deposit.

Alluvial fans are a depositional landform created where streams emerge from mountain canyons into a valley. The channel that had been confined by the canyon walls and suddenly is no longer confined slows down and spreads out, dropping its bedload of all sizes, forming a delta in the air of the valley. As distributary channels fill with sediment, the stream is diverted laterally, and the alluvial fan develops into a cone shape with distributaries radiating from the canyon mouth. Alluvial fans are common in the dry climates of the West where ephemeral streams emerge from canyons in the ranges of the Basin and Range.

Floodplains, Meandering Levels, and Natural Levees

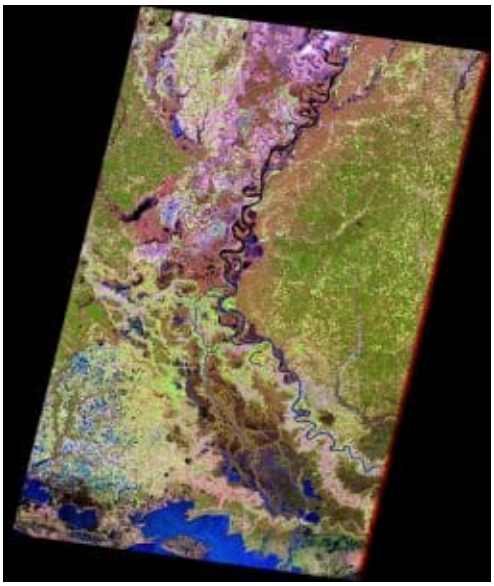


Figure 3.26.1: Landsat image of lower Mississippi River floodplain

Many fluvial landforms occur in a floodplain near a meandering stream. A **floodplain** is the broad, mostly flat area next to a meandering river that is regularly flooded. A stream creates its floodplain as the channel meanders back and forth over thousands, even millions of years. Regular flooding contributes to creating the floodplain by eroding uplands next to the floodplain. The stream channels are confined by small **natural levees** that have been built up over many years of regular flooding. Natural levees can isolate flow from contributing channels from immediately reaching the main channel on the floodplain. The smaller isolated streams, called **yazoo streams**, will flow parallel to the main trunk stream until there is an opening in the levee to allow for a belated confluence [23].

The location and width of floodplains naturally vary, however, humans build artificial levees on flood plains to limit flooding. Sediment that breaches the levees during flood stage is called **crevasse splays** delivering silt and clay into the floodplain. Floodplains are nutrient-rich from the fine-grained deposits and thus often make good farmland. Floodplains are also easy to build on due to their flat nature, however, when floodwaters crest over human-made levees, the levees quickly erode with potentially catastrophic impacts. Because of the good soils, farmers regularly return after floods and rebuild year after year.



Figure 3.26.1: Point bar and cut bank on the Cirque de la Madeleine in France.

Meandering rivers create additional landforms as the channel migrates within the floodplain. Meandering rivers erode side-to-

side because the highest velocity water having the most capacity to erode is located on the outside of the bend. Erosion of the outside of the bend of a stream channel is called a **cut bank** and the meander extends its loop by this erosion. The **thalweg** of the stream is the deepest part of the stream channel. In the straight parts of the channel, the thalweg and highest velocity are in the center of the channel. But at the bend of a meandering stream, the thalweg moves to the cut bank. Opposite the cut bank on the inside bend of the channel is the lowest stream velocity and therefore becomes an area of deposition call a **point bar**.



Figure 3.26.1: Meander nearing cutoff on the Nowitna River in Alaska

Through erosion on the outsides of the meanders and deposition on the insides, the channels of meandering streams move back and forth across their floodplain over time. Sometimes on very broad floodplains with very low gradients, the meander bends can become so extreme that they cut across themselves at a narrow neck (see figure). The former channel becomes isolated from streamflow and forms an **oxbow lake** seen on the right of the figure. Eventually, the oxbow lake fills in with sediment and becomes a wetland and eventually a **meander scar**. Stream meanders can migrate and form oxbow lakes in a relatively short amount of time. Where stream channels form geographic and political boundaries, this shifting of channels can cause conflicts.

Deltas



Figure 3.26.1: Location of the Mississippi River drainage basin and Mississippi River delta.

When a stream reaches a low energy body of water such as a lake or some parts of the ocean, the velocity slows and the bedload and suspended load sediment come to rest, forming a **delta**. If wave erosion from the water body is greater than deposition from the river, the deposition will not occur and a delta will not form. The largest and most famous delta in the United States is the Mississippi River delta formed where the Mississippi River flows into the Gulf of Mexico. The Mississippi River drainage basin is the largest in North America, draining 41% of the contiguous U.S. [24]. Because of the large drainage area, the river carries a large amount of sediment that is supplied to the delta. The Mississippi River is a major shipping route and human engineering has ensured that the channel no longer meanders significantly within the floodplain. In addition, the river has been artificially

straightened so that it meanders less and is now 229 km shorter than it was before humans began engineering it [24]. Because of these restraints, the delta is now solely focused in one area and thus has created a “bird’s foot” pattern. These two NASA images of the delta (follow the link) show how the shoreline has retreated and the land was inundated with water while deposition of sediment was located at end of the delta. These images have changed over a 25 year period from 1976 to 2001. These are stark changes illustrating sea level rise and land subsidence from the compaction of peat due to the lack of sediment resupply [25].

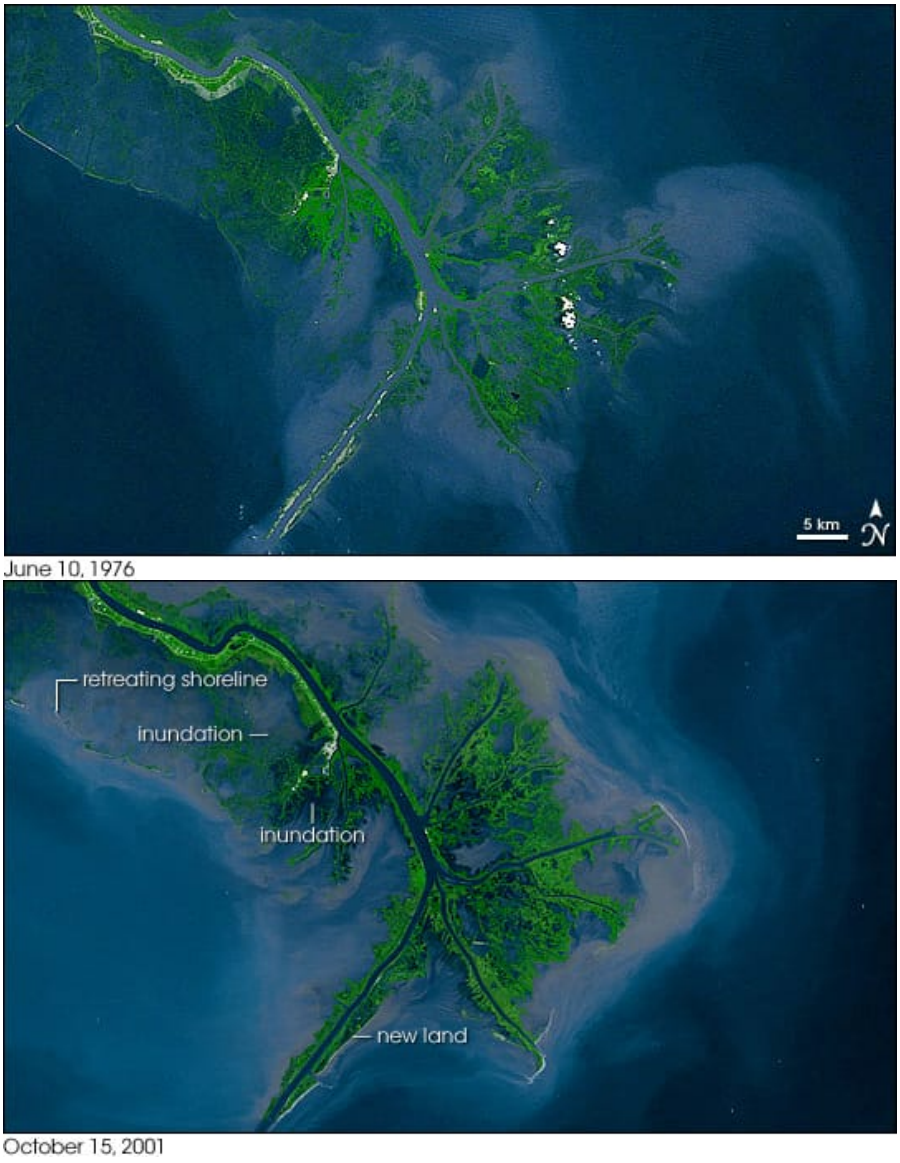


Figure 3.26.1: Before (left) vs. After (right)

The formation of the Mississippi River delta started about 7500 years ago when postglacial sea level stopped rising. In the past 7000 years, prior to anthropogenic modifications, the Mississippi River delta had several lobes that were sequentially created by the river, abandoned for a shorter route to the Gulf of Mexico, then reworked by the ocean waves of the Gulf of Mexico [26]. After the lobes were abandoned by the river, isostatic depression and compaction of the sediments caused basin subsidence (e.g. the mass and compaction of the new sediments caused the land to sink).

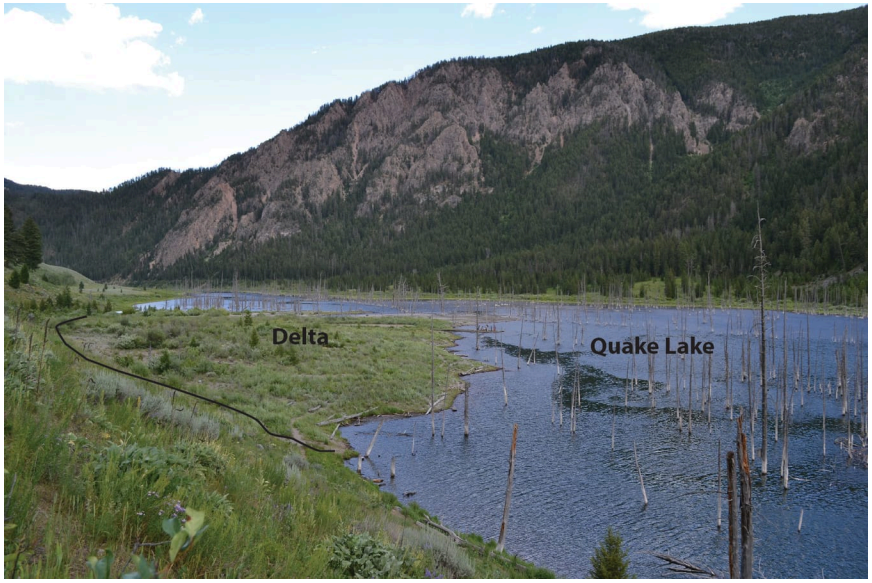


Figure 3.26.1: Delta in Quake Lake Montana. The deposition of this delta began in 1959 when the Madison River was dammed by the landslide caused by the 7.5 magnitude earthquake.

A clear example of how deltas form came from an unlikely source, an earthquake. During the 1959 Madison Canyon 7.5 magnitude earthquake in Montana, a large landslide dammed the Madison River forming Quake Lake [27], which is still there today. A small tributary stream that once flowed into the Madison River now flows into Quake Lake where a delta has been forming since. This a modern example of a Gilbert-type delta, which is a delta composed primarily of coarse material actively eroded from the mountainous upthrown block to the north.

Deltas represent stream deposits protruding into a quiet water body and can be further categorized as wave-dominated or tide-dominated. Wave-dominated deltas occur where the tides are small and wave energy dominates. An example is the Nile River delta in the Mediterranean Sea that has the classic shape like the Greek character (Δ) from which the landform is named. A tide-dominated delta is when ocean tides are powerful and influence the shape of the delta. For example, Ganges-Brahmaputra Delta in the Bay of Bengal (near India and Bangladesh) is the world's largest delta and mangrove swamp called the Sundarban.



Sundarban Delta in Bangladesh, a tide-dominated delta of the Ganges River Tidal forces creates linear segments in the delta shoreline by ocean intrusion into the delta deposits. This delta also holds the world's largest mangrove swamp, and incidentally is the only place where the Bengal tiger still actively hunts humans as prey.



Figure 3.26.1: Nile Delta showing its classic “delta” shape.

Special Topic: Ancient Deltas in Lake Bonneville

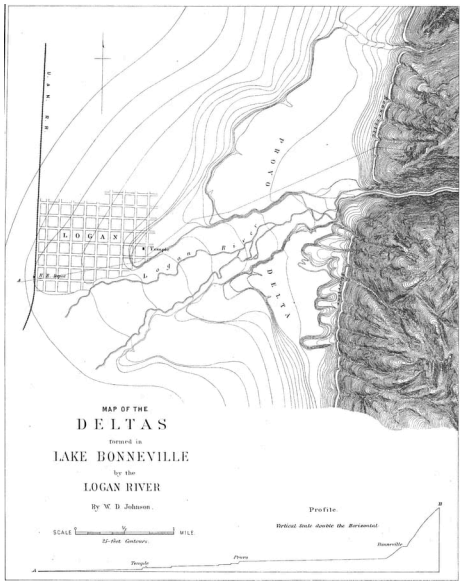


Figure 3.26.1: Map of the Logan Delta

Lake Bonneville was a large, pluvial lake that occupied the western half of Utah and parts of eastern Nevada from about 30,000 to 12,000 years ago [30]. The lake filled to a maximum elevation as great as approximately 5100 feet above the mean sea level, covering the basins, leaving the mountains exposed, many as islands. The presence of the lake allowed for deposition of fine-grained lake mud and silt, as well as coarse gravels entrained by mountain streams that lost their sediment load and energy to the open water of the lake. The lake’s average surface elevation varied over its existence. The variations in lake level were controlled by regional climate and a catastrophic failure of Lake Bonneville’s main outlet, Red Rock Pass [31]. Extended periods of time where the lake level remained stable caused wave-cut terraces that can be seen today on the flanks of many mountains in the region and allowed for the development of large deltaic deposits at the mouths of major canyons in Salt Lake, Cache, and other valleys. As the lake regressed to its remnant, the Great Salt Lake, the rivers that created the deltaic deposits incised stream valleys through the same deposits.



Figure 3.26.1: Deltaic deposits of Lake Bonneville near Logan, Utah.

Entrenched Meanders



Figure 3.26.1: Entrenched meander of the Colorado River, downstream of Page, Arizona.

In some rare cases, uplift will occur on a low-gradient landscape with a meandering river. This effectively increases the gradient of the stream causing it to erode downward instead of side-to-side. An example of this process is where the Colorado River and other streams crossed the Colorado Plateau as meandering streams. As the Colorado Plateau has uplifted over the past several million years, the Colorado River has incised into the flat-lying rocks of the plateau by hundreds of feet.

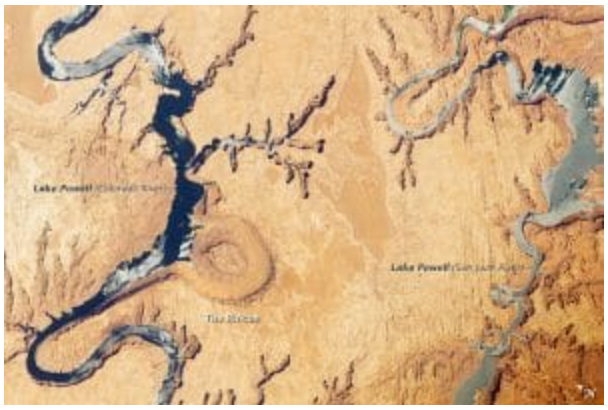


Figure 3.26.1: The Rincon is an abandoned meaner loop on the entrenched Colorado River in Lake Powell.

The entrenched meanders continue to experience lateral erosion. The Rincon on the entrenched Colorado River at Lake Powell is an incised oxbow lake. Another excellent example of entrenched meanders is Goosenecks State Park, Utah, where the San Juan River is deeply entrenched into the Colorado Plateau.

To summarize, an **entrenched channel** occurs when a meandering channel rapidly down cuts due to a drop in base level. This causes the original meandering shape to be preserved within a deeply entrenched channel. This channel type is rare worldwide but is common in the Colorado Plateau region which is a broad flat area near four-corners where Utah, Colorado, Arizona, and New Mexico meet. For example, the Green, Colorado, and San Juan Rivers famously form entrenched channels.

A winding river cut deep through hundreds of feet of rock. The San Juan River incised the flat Colorado Plateau at Goosenecks State Park, southeastern Utah.
CC BY 3.0], via Wikimedia Commons" width="1067px" height="359px" src="/@api/deki/files/7708/11.6_USA_Utah_316_Goosenecks_SP.jpg">

Figure 3.26.1: The San Juan River has incised meanders into the flat Colorado Plateau at Goosenecks State Park, southeastern Utah.

Terraces

Stream terraces are remnants of older floodplains located above the existing floodplain and river. Like entrenched meanders, stream terraces form when uplift occurs or base level drops and streams erode downward, leaving behind their old floodplains. In other cases, stream terraces can form from extreme flood events associated with retreating glaciers. A classic example of multiple stream terraces is along the Snake River in Grand Teton National Park in Wyoming [32, 33].



Figure 3.26.1: Terraces along the Snake River, Wyoming.



Figure 3.26.1: Terraces in Glen Roy, Scotland

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3.27: Groundwater

Groundwater is an important source of freshwater. It can be found in all places under the ground but is limited by extractable quantity and quality.

Properties

Permeability and Porosity

Most rocks are not entirely solid and contain a certain amount of open space between grains or crystals, known as pores. **Porosity** is a measure of the open space in rocks –expressed as the percentage of open space that makes up the total volume of the rock or sediment material. Porosity can occur as primary porosity, which represents the original pore spaces in the rock (e.g. space between sand grains, vesicles in volcanic rocks), or secondary porosity which occurs after the rock forms (e.g. fractures, dissolved portions of rock). Lithification of unconsolidated sediments will reduce porosity because it compacts grains and adds cement (see chapter 5.3). Water trapped in the unconnected pores of the rock during the processes of deposition and lithification is called **connate water**.

Permeability is a measure of the interconnectedness of pores in a rock or sediment. The connections between pores allows for that material to transmit water. A combination of a place to put water (porosity) and the ability to move water (permeability) makes a good **aquifer**—a rock unit or sediment that contains extractable groundwater. Well-sorted sediments have higher porosity because there are not smaller sediment particles filling in the spaces between the larger particles. Clays generally have very high porosity, but the pores are poorly connected, thereby causing low permeability.

While permeability is important as a measure of the ability to transmit fluids, it is generally not the most commonly used descriptor among geologists for this property. **Hydraulic conductivity** is another common measure of the connectedness of pore spaces and is a function of both permeability and fluid properties. Because it considers fluid properties, hydraulic conductivity is used by both petroleum geologists and hydrogeologists to describe the production capability of oil reservoirs and aquifers. A high hydraulic conductivity indicates a rapid transmission of fluid through an aquifer. Unconsolidated gravels, highly fractured and dissolved rocks, and well-sorted sandstones have high hydraulic conductivities.

Aquifers and Confining Layers

An **aquifer** is a geologic material capable of delivering water in usable quantities. Geologic material includes any rock or sediment. In order for a geologic material to be considered an aquifer, it must be at least partially saturated, where its open spaces are filled with water, and be permeable, i.e. able to transmit water. For drinking water aquifers, the water must also be **potable**. Aquifers can vary dramatically in scale, from spanning several formations to being limited to a small area on the side of a hill. Aquifers adequate for water supply are both permeable and porous.

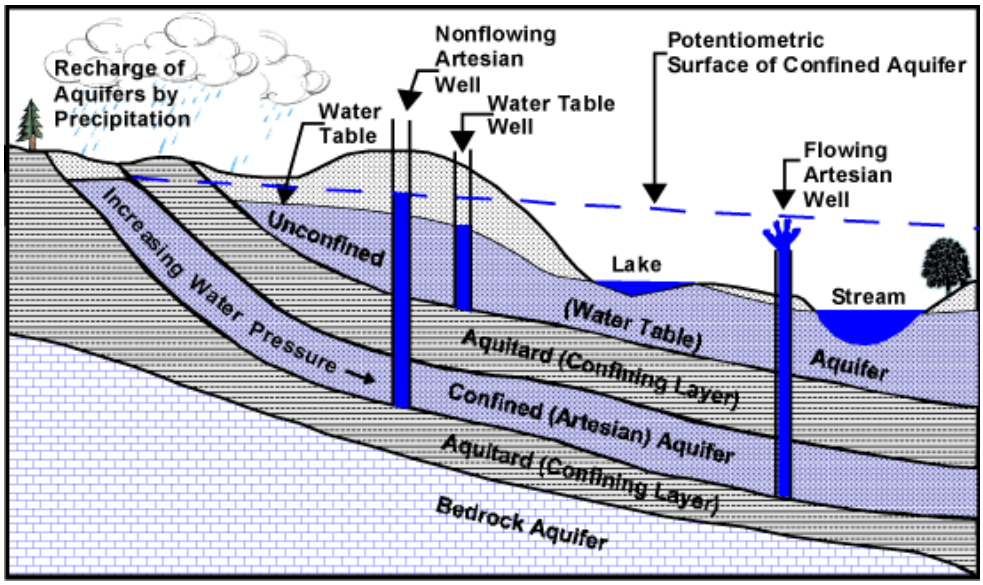


Figure 3.27.1: Potentiometric surface and water table in an aquifer system.

A good aquifer will provide a sufficient quantity of water to meet demand. The quantity of water that an aquifer can hold and transmit is governed by its physical properties. Most simply, the aquifer's porosity and permeability (defined above) are variables that govern its hydraulic conductivity and **storativity**.

A **confining layer** is a layer of low permeability geologic material that restricts the flow of water to or from the aquifer. Confining layers include **aquicludes** (a.k.a. aquifuges), which are so impermeable that no water travels through them, and **aquitards**, which significantly decrease the speed at which water travels through them due to their low permeability.

Groundwater Flow

From the Surface into the Ground

The groundwater table is where the pores in an aquifer are completely saturated.
via Wikimedia Commons" width="397px" height="302px" src="/@api/deki/files/7684/Vadose_zone.gif">

Figure 3.27.1: Zone of saturation.

When surface water infiltrates or seeps into the ground, it usually enters the unsaturated zone (a.k.a. vadose zone, a.k.a. zone of aeration). The **vadose zone** is the volume of material between the land surface and the zone of saturation, which consists of geologic materials in which the pore spaces are not completely filled with water [34]. Plants' roots inhabit the upper vadose zone. In the vadose zone, fluid pressure in the pores is less than atmospheric pressure. Below the vadose zone is the capillary fringe. The capillary fringe is the usually thin zone below the vadose zone where the pores are completely filled with water (saturation), but the fluid pressure is less than atmospheric pressure. The pores in the capillary fringe are filled because of capillary action, described in the Properties of Water section above. Below the capillary fringe is the saturated zone (a.k.a. phreatic zone), where the pores are completely saturated and the fluid in the pores is at or above atmospheric pressure [34]. The interface between the capillary fringe and the saturated zone marks the location of the water table.

Water Table

Wells are conduits that extend into the ground with openings to the aquifers, to extract from, measure, and sometimes add water to the aquifer. Wells are generally the way that geologists and hydrologists measure the depth to groundwater from the land surface as well as withdraw water from aquifers.

Water is found throughout porosity in sediments and bedrock. The **water table** is the area at which the pores are fully saturated with water. The most simple case of a water table is when the aquifer is unconfined, meaning it does not have a confining layer above it. Confining layers can pressurize aquifers by trapping water that is recharged at a higher elevation underneath the confining layer, allowing for a potentiometric surface higher than the top of the aquifer, and sometimes higher than the land

surface. The **potentiometric surface** represents the height that water would rise in a well penetrating the pressurized aquifer system. Breaches in the pressurized aquifer system, like faults or wells, can cause **springs** or **flowing wells**, also known as **artesian wells**.

The water table will generally mirror surface topography, though more subdued because hydrostatic pressure is equal to atmospheric pressure along the surface of the water table. If the water table intersects the ground surface the result will be water at the surface in the form of a gaining stream, spring, lake, or wetland. The water table intersects the channel for **gaining streams** which then gains water from the water table. The channels for **losing streams** lie below the water table, thus losing streams lose water to the water table. Losing streams may be seasonal during a dry season or **ephemeral** in dry climates where they may normally be dry and carry water only after rainstorms. Ephemeral streams pose a serious danger of flash flooding in dry climates.

Mentioned in the video is the USGS Groundwater Watch site. Here is the link to that site: groundwaterwatch.usgs.gov/

Geologists measure the height of the water table and potentiometric surface using wells. Graphs of the depth to groundwater over time are known as **hydrographs**. Hydrographs can indicate changes in the water table over time. The water level in a well can change very frequently (every minute), seasonally, and over long periods of time, and is controlled by many forces.

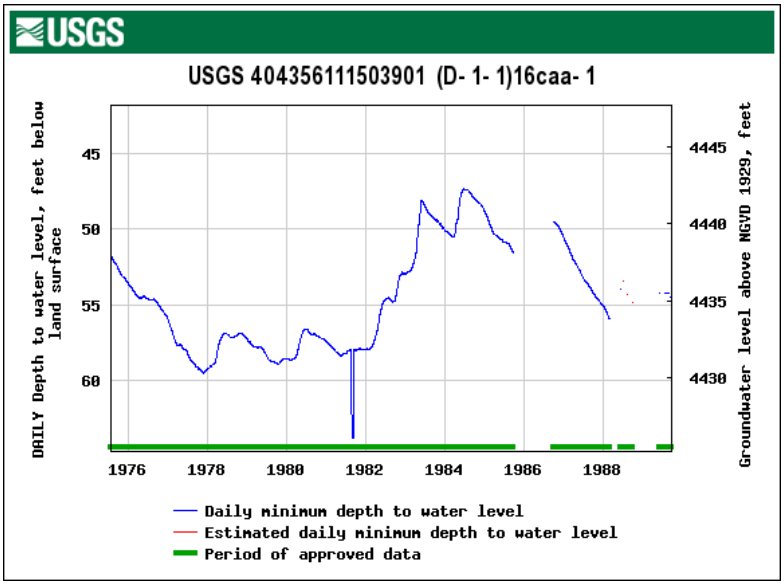


Figure 3.27.1: Example of a hydrograph.

Darcy's Law

Darcy's Law was an empirical relationship established by Henry Darcy in 1856 showing how to discharge through a porous medium is controlled by permeability, pressure, and cross-sectional area. In his experiment, Darcy used tubes of packed sediment with water running through them. The relationships described by Darcy's Law have close similarities to Fourier's law in the field of heat conduction, Ohm's law in the field of electrical networks, or Fick's law in diffusion theory. Darcy's Law provides a quantitative measure of hydraulic conductivity and discharge.

$$Q = K * A * \frac{\Delta h}{L} \tag{3.27.1}$$

Cylinder with a length (L), cross-sectional area (A), which is filled with a material of a specific hydraulic conductivity. CC BY-SA 2.5], via Wikimedia Commons" width="431" src="/@api/deki/files/7682/Darcys_Law.png">

Figure 3.27.1: Pipe showing apparatus that would demonstrate Darcy's Law. Δh would be measured across L from a to b.

- Q = flow (volume/time)
- K = hydraulic conductivity (length/time)
- A = cross-sectional area of flow (area)
- Δh = change in pressure head (pressure difference)
- L = distance between pressure (h) measurements (length)
- Δh/L is commonly referred to as the hydraulic gradient

Cone of Depression

Pumping water from an aquifer lowers the water table or potentiometric surface around the well. In an unconfined aquifer, the water table is lowered as water is removed from the aquifer near the well. In a confined aquifer, the pressure around the well is reduced. The amount of change from before pumping to pumping level is termed drawdown. Drawdown is the greatest nearest the well, resulting in a concentric pattern of drawdown termed the **cone of depression**.

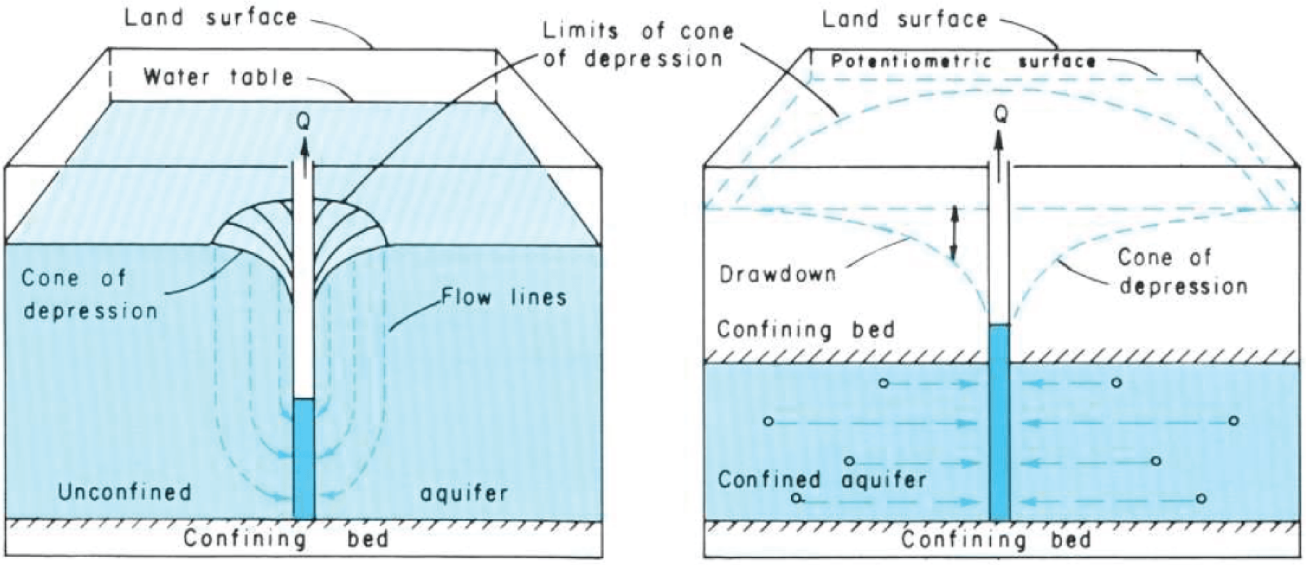


Figure 3.27.1: Cones of depression (Heath 1983).

When one cone of depression intersects another cone of depression or a barrier feature like an impermeable mountain block, drawdown is intensified. When a cone of depression intersects a recharge zone, the cone of depression is lessened.

Recharge

The **recharge** area is where surface water enters an aquifer through the process of infiltration. Recharge areas are generally the topographically highest location of an aquifer. They are characterized by losing streams and sediment or rock that allows infiltration into the subsurface. Recharge areas mark the beginning of groundwater flow paths.

In the Basin and Range region, the recharge zones for the unconsolidated aquifers of the valley areas are along the valley margins, near the foothills of the mountains. In Salt Lake Valley, as mountain streams leave the mountainous areas, they lose water to the gravel-rich deltaic deposits of ancient Lake Bonneville.

Recharge can be induced through the aquifer management practice of aquifer storage and recovery. Injection wells and infiltration galleries (basins) allow for humans to increase the rate of recharge into an aquifer system [35]. Injection wells pump water into an aquifer. Injection wells are regulated by state and federal governments to ensure that the injected water is not negatively impacting the quality or supply of the existing groundwater in the aquifer. Some aquifers are capable of storing significant quantities of water, allowing water managers to use the aquifer system like a surface reservoir. Water is stored in the aquifer during periods of low water demand and high water supply and later extracted during times of high water demand and low water supply.

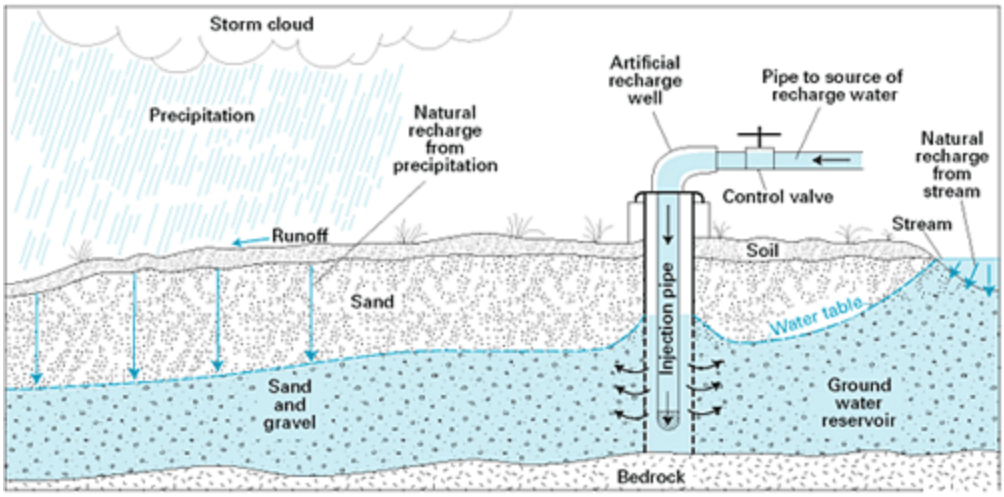


Figure 3.27.1: Different ways an aquifer can be recharged.

Discharge

Discharge areas are where groundwater emerges at the land surface. Groundwater emerges at the land surface when the potentiometric surface or water table intersects the land surface. These areas are characterized by springs, flowing (artesian) wells, gaining streams, and playas. Discharge areas mark the end of groundwater flow paths. In the Basin and Range of the western United States, discharge zones are typically in the middle of the valley basins, where playa lakes, springs, and gaining streams signify groundwater emerging at the land surface.

Groundwater Mining and Subsidence

Groundwater as a Limited Resource

Like other natural resources on our planet, the quantity of fresh and potable water is finite. The only natural source of water on land is from the sky in the form of precipitation. Because of a slow rate of travel, limited recharge areas, and intensifying extraction and demand, in many places groundwater is being extracted faster than it is being replenished. When groundwater is extracted faster than recharge can renew it, groundwater levels (potentiometric surfaces) decline and areas of discharge can diminish or dry up completely. Regional pumping-induced groundwater decline is known as **groundwater mining** or groundwater overdraft. Groundwater mining can lead to dry wells, reduced spring and streamflow, and subsidence. Where there is a continual lowering of the water table in an area, e.g. extraction by pumping is greater than replenishment by precipitation, groundwater mining is happening.

Subsidence



Figure 3.27.1: Example of an earth fissure in Cedar City.

In many places, water actually helps hold up the skeleton of the aquifer by the water pressure exerted on the grains in an aquifer. If pore pressure decreases because of groundwater mining, the aquifer can compact, causing the surface of the ground to sink. Areas especially susceptible to this effect are aquifers made of unconsolidated sediments. Unconsolidated sediments with multiple layers of clay and other fine-grained material are at higher risk because clay can compact considerably when drained of water [36, 37].



Figure 3.27.1: The pole shows subsidence from groundwater pumping for irrigation in the San Joaquin Valley of California.

In many cases, the amount of compaction in one area will be greater than the amount of compaction in an adjacent area. The different amounts of compaction in areas that are next to each other can cause the land to offset and develop cracks and fissures.

Subsidence from groundwater mining has been documented in southwestern Utah, notably Cedar Valley, Iron County, Utah. Groundwater levels have declined more than 100 feet in certain parts of Cedar Valley, causing earth fissures and measurable amounts of land subsidence.

The photo shows documentation of subsidence from the pumping of groundwater for irrigation in the Central Valley in California. The dates marked on the pole show land elevation in the past.

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3.28: Prelude to Galciers

The hydrosphere, liquid water, is the single most important agent of erosion and deposition. The cryosphere, the solid state of water in the form of ice also has its own unique erosional and depositional features. Large accumulations of year-round ice on the land surface are called **glaciers**. Masses of ice floating on the ocean as sea ice or icebergs are not glaciers, although they may have had their origin in glaciers.



Figure 3.28.1: Avalanche Lake in Glacier National Park, Montana is an example of a glacially-carved cirque basin.

Glaciers cover about 10% of the surface of the Earth, and are powerful erosional agents that sculpt the planet's surface. Glaciers form when more snow accumulates over a long span of time than melts and eventually turns into ice. This usually occurs in mountainous areas that have both cold temperatures and high precipitation. But snow can also accumulate and turn into ice in extremely cold low lying areas such as Greenland and Antarctica. This chapter focuses on types of glaciers, how glaciers function, erosional and depositional landforms created by glaciers, and how glaciers are connected to past climates and modern day climate change.

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3.29: Types of Glaciers



Figure 3.29.1: Glacier in the Bernese Alps.

There are two general types of glaciers – alpine glaciers and ice sheets. **Alpine glaciers** form in mountainous areas either at high elevations or near cool and wet coastal areas like the Olympic Peninsula of Washington. A common type of alpine glacier is a **valley glacier** which is confined to a long, narrow valley located in mountainous areas especially at higher latitudes (closer to either the north or south pole). Most alpine glaciers are located in the major mountain ranges of the world such as the Andes, Rockies, Alps, and Himalayas.



Figure 3.29.1: Greenland ice sheet.

The other major glacier type is **ice sheets** (also called **continental glaciers**). These are thick accumulations of ice that occupy a large geographical area. The main ice sheets on the earth today are located on Greenland and Antarctica. The Greenland Ice Sheet has an extensive surface area and thickness up to 3,300 meters (10,800 feet or two miles) and has a volume estimated at nearly 3 million cubic kilometers (~102 billion cubic feet) [1].

The Antarctic Ice Sheet is much larger and covers almost the entire continent. The thickest parts of this massive ice sheet are

over 4,000 meters thick (>13,000 feet or 2.5 miles) and its weight depresses the Antarctic bedrock to below sea level in many places beneath the ice [2]. The Antarctic Ice Sheet contains the most ice as illustrated by the figure below comparing cross-sectional views of both ice sheets.

Former ice sheets, present during the last glacial maximum event (also known as the last ice age) in North America, are called the Laurentide Ice Sheet.



Figure 3.29.1: Thickness of Greenland ice sheet in meters (Source: Eric Gaba).

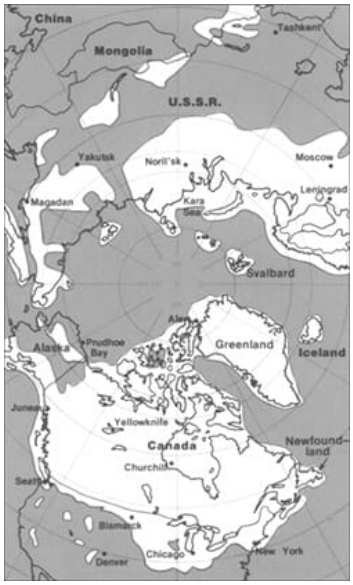


Figure 3.29.1: Maximum extent of Laurentide Ice Sheet

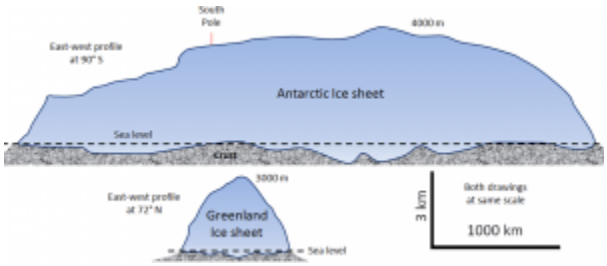


Figure 3.29.1: Cross-sectional view of both Greenland and Antarctic ice sheets drawn to scale for size comparison (Source: Steve Earle)

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3.30: Glacier Formation and Movement

Glaciers form when accumulating snow compresses into firn and eventually turns into ice. In some cases, perennial snow accumulates on the ground and lasts all year. This makes a snowfield and not a glacier since it is a thin accumulation of snow. Snow and glacial ice actually have a fair amount of void space (porosity) that traps air. As the snow settles, compacts, and bonds with underlying snow, the amount of void space diminishes. When the snow gets buried by more snow, it compacts into granular **firn** (or névé) with less air and it begins to resemble ice more than snow. Continual burial, compression, and recrystallization make the firn denser and more ice-like. Eventually, the accumulated snow turns fully to ice, however, small air pockets remain trapped in the ice and form a record of the past atmosphere.



Figure 3.30.1: Glacial crevasses.



Figure 3.30.1: Cravasse on the Easton Glacier in the North Cascades

As the ice accumulates, it begins to flow downward under its own weight. An early study of glacier movement conducted in 1948 on the Jungfraufirn Glacier in the Alps installed hollow vertical rods in the ice and measured the tilt over two years. The study found that the top part was fairly rigid and the bottom part flowed internally. A P-T diagram of ice shows that ice actually melts under pressure (one of the unique properties of water) so ice at the base of a typical glacier is actually melting. About half of the overall glacial movement was from sliding on a film of meltwater along the bedrock surface and a half from internal flow [3].

These studies show that the ice near the surface (about the upper 165 feet [50 meters] depending on location, temperature, and flow rate) is rigid and brittle [4]. This upper zone is the **brittle zone**, the portion of the ice in which ice breaks when it moves to form large cracks along the top of a glacier called **crevasses**. These crevasses can be covered and hidden by a snow bridge and thus are a hazard for glacier travelers.

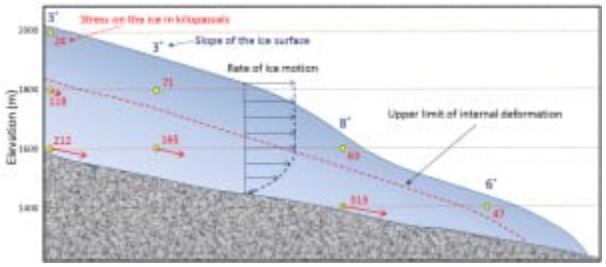


Figure 3.30.1: Cross-section of a valley glacier showing stress (red numbers) increases with depth under the ice. The ice will deform and flow where the stress is greater than 100 kilopascals, and the relative extent of that deformation is depicted by the red arrows. Downslope movement is shown with blue arrows. The upper ice above the red dashed line does not flow but is pushed along en masse. (Source: Steve Earle)

Below the brittle zone, there is so much weight of the overlying ice (typically exceeding 100 kilopascals-approximately 100,000 times atmospheric pressure) that it no longer breaks when force is applied to it but rather it bends or flows. This is the **plastic zone** and, within this zone, the ice flows. The plastic zone represents the great majority of the ice of a glacier and often contains a fair amount of sediment from as large as boulders and as small as silt and clay which act as grinding agents. The bottom of the plastic zone slides and grinds across the bedrock surface and represents the zone of erosion.

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3.31: Glacial Budget

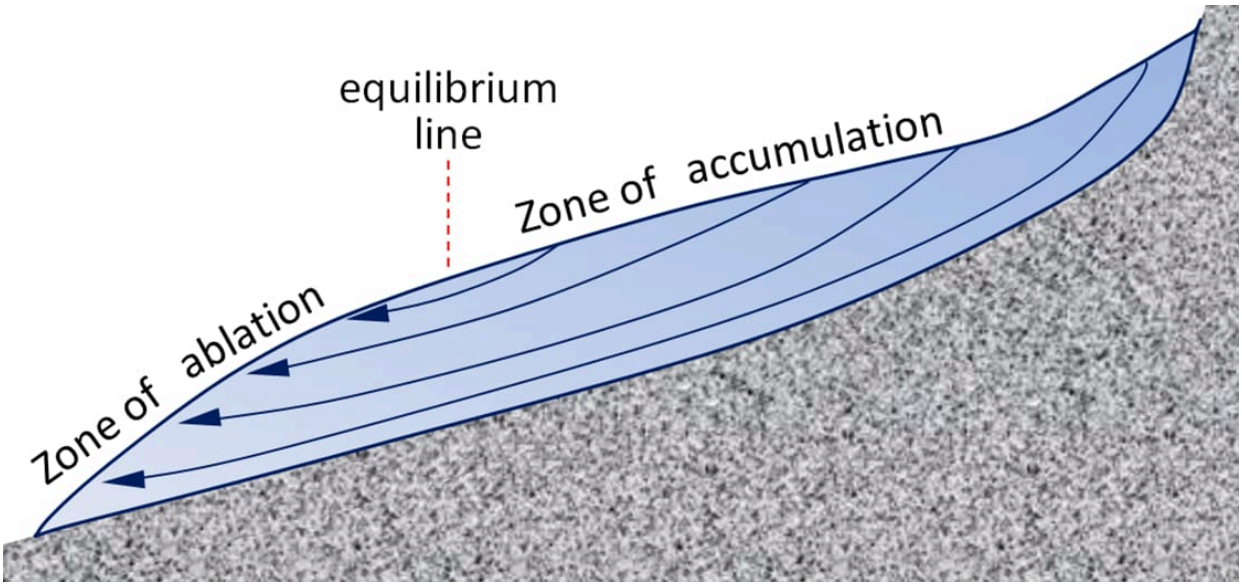


Figure 3.31.1: Cross-sectional view of an alpine glacier showing internal flow lines, zone of accumulation, snow line, and zone of melting.

Glaciers gain mass during the winter as snow accumulates. During summer the snow melts. The glacier is like a bank account, if more money is coming in (snow accumulating in winter) than going out (snow melting in summer), then the bank account grows. The glacial budget works in a similar way. The **glacial budget** describes how ice accumulates and melts on a glacier which ultimately determines whether a glacier advances or retreats. The balance of accumulating ice (**zone of accumulation**) is weighed against melting ice (**zone of melting** or **zone of ablation**), and whichever is greater determines whether the glacier will advance or retreat. In the zone of accumulation, the rate of annual snowfall is greater than the rate of melting. In other words, not all of the snow that falls each winter melts during the following summer, and the ice surface is always covered with snow. In the zone of melting or ablation, more ice melts then accumulates as snow during the year. The equilibrium line (or **snowline**, also called the **firnline**) marks the boundary between the zones of accumulation and ablation. Below the equilibrium line, in the zone of melting, bare ice is exposed because last winter's snow has all melted; above that line, the ice is still mostly covered with snow from last winter. The position of the equilibrium line changes from year to year as a function of the balance between snow accumulation in the winter and snowmelt during the summer. More winter snow and less summer melting obviously favors the advance of the equilibrium line (and of the glacier's leading-edge (or **terminus**), but of these two variables, it is the summer melt that matters most to a glacier's budget. Cool summers promote glacial advance and warm summers promote glacial retreat [5].

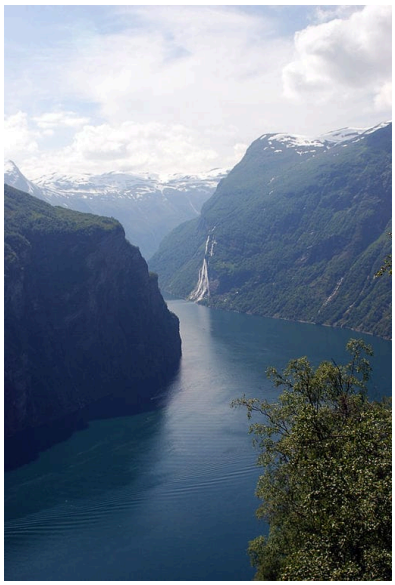


Figure 3.31.1: Fjord

If warmer summers promote glacial retreat, then overall climate warming over many decades and centuries causes the glacier to melt and retreat significantly. Since the global climate has been warming due to human burning of fossil fuels [6], this warming is likely causing the ice sheets to melt (or lose mass) at an increasing rate over years and decades rather than over centuries [7]. This means that as time goes on, the glaciers are melting faster and contributing more to rising sea-level than expected based on the previous history.

When ice sheets start to melt, such as those in Antarctica and Greenland, their flow into the ocean speeds up eventually creating floating ice sheets. The edges of the glacier or its extension as floating ice break off in a process called **calving**. In cases like these, the end of the glacier in the fjord may retreat but it will also lose thickness or deflate [8; 9]. A **fjord** is a narrow ocean-flooded valley with steep walls that were carved by a recent glacier. The retreating glacier or glaciers may add to sea level, and this increased sea level can also add to the flooding of the former glacially-carved valleys. Glacial retreat and deflation are well-illustrated in the 2009 TED Talk by James Balog.

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3.32: Glacial Landforms

Glacial landforms are of two kinds, erosional and depositional landforms. Erosional landforms are formed by removing material. The internal pressure and movement within glacial ice cause some melting and glaciers to slide over bedrock on a thin film of water. Glacial ice also contains a large amount of sediments such as sand, gravel, and boulders. Together, the movement plucks off bedrock and grinds the bedrock producing a polished surface and fine sediment called rock flour as well as other poorly-sorted sediments. Characteristic depositional landscapes are produced when the ice melts and retreats and leaves behind these sediments with distinct shapes and compositions. Because glaciers are among the earliest geological processes studied by geologists whose studies were in Europe, the terminology applied to glaciers and glacial features contains many terms from European languages.

Erosional Glacial Landforms

Both alpine and continental glaciers erode bedrock and create erosional landforms. Glaciers are heavy masses of abrasive ice that grind over the surface. Elongated grooves are created by fragments of rock embedded in the ice at the base of a glacier scraping along the bedrock surface called **glacial striations**. In addition, rock flour as fine grit in the ice can polish a hard granite or quartzite bedrock to a smooth surface called **glacial polish**. This figure illustrates these glacial landforms.



Figure 3.32.1: A polished and striated rock in Yosemite.



Figure 3.32.1: Glacial striations in Mt. Rainier National Park.

Following is a description of erosional landforms produced by alpine glaciers. Since glaciers are typically much wider than rivers of similar length, and since they tend to erode more at their bases than their sides, they transform former V-shaped stream valleys into broad valleys that have relatively flat bottoms and steep sides with a distinctive “U” shape [5]. Little Cottonwood Canyon near Salt Lake City, Utah was occupied by a large glacier that extended down to the mouth of the canyon and into Salt Lake Valley [10]. Today, that canyon is the location of many erosional landforms including the U-shaped valley, as well as polished and striated rock surfaces. In contrast, river-carved canyons have a V-shaped profile when viewed in cross-section. Big Cottonwood Canyon, its neighbor to the north, has that V-shape in its lower parts, indicating that its glacier did not extend clear to its mouth but was confined to its upperparts.

A valley with a u shape that shows steep cliffs on the sides and a wide-flat bottom
via Wikimedia Commons" width="483" src="/@api/deki/files/8177/UshapedValleyUT.jpg">

Figure 3.32.1: The U-shape of the Little Cottonwood Canyon, Utah, as it enters into the Salt Lake Valley.



Figure 3.32.1: V-shaped Big Cottonwood Canyon, carved by a stream.

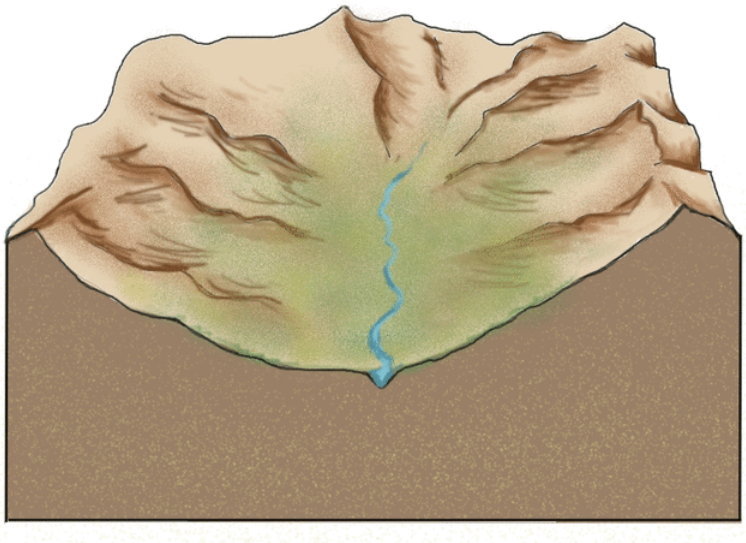


Figure 3.32.1: Formation of a glacial valley. Glaciers change the shape of the valley from a “V” shape to a “U”.

When two U-shaped valleys are adjacent to each other, the ridge between them can be carved into a sharp ridge called an **arête**. Since glaciers erode a broad valley, the arêtes are left behind with steep walls separating them. At the head of a glacially carved valley is a bowl-shaped feature called a **cirque** representing where the head of the glacier is eroding against the mountain by plucking rock away from it and the weight of the thick ice is eroding out a bowl. After the glacier is gone, the bowl at the bottom of the cirque is often occupied by a lake called a **tarn.** Headward cirque erosion by three or more mountain glaciers produces **horns,** which are steep-sided, spire-shaped mountains with pronounced cirques on three or more sides. Low points along arêtes or between horns (also mountain passes) are termed **cols**. When a smaller tributary glacier intersects a larger trunk glacier, the smaller glacier erodes down less. Therefore, once the ice has been removed, the tributary valley is left as a **hanging valley**, sometimes with a waterfall. Where the trunk glacier straightens and widens the former V-shaped valley and erodes the ends of

side ridges, the result is a steep triangle-shaped cliff called a **truncated spur**.

A circular area near the top of a mountain that looks as if it had been scooped out.
GFDL, CC-BY-SA-3.0 or CC BY 2.5], via Wikimedia Commons" width="556" src="/@api/deki/files/8182/Thornton_Lakes_25929.jpg">

Figure 3.32.1: Cirque with Upper Thornton Lake in the North Cascades National Park, Washington. Photo by Walter Siegmund.

A large and very pointy (almost pyramid-like) mountain
via Wikimedia Commons" width="473" src="/@api/deki/files/8183/14.4_Kinnerly_Peak-e1496423758756.jpg">

Figure 3.32.1: An example of a horn, Kinnerly Peak, Glacier National Park, Montana. Photo by USGS.

U-shaped valley feeding into another, lower u-shaped valley. A waterfall forms where the higher valley meet the lower valley.
CC BY-SA 1.0, GFDL or CC-BY-SA-3.0], via Wikimedia Commons" width="508" src="/@api/deki/files/8185/Closeup_of_Bridalveil_Fall_seen_from_Tunnel_View_in_Yosemite_NP.jpg">

Figure 3.32.1: Bridalveil Falls in Yosemite National Park, California, is a good example of a hanging valley.

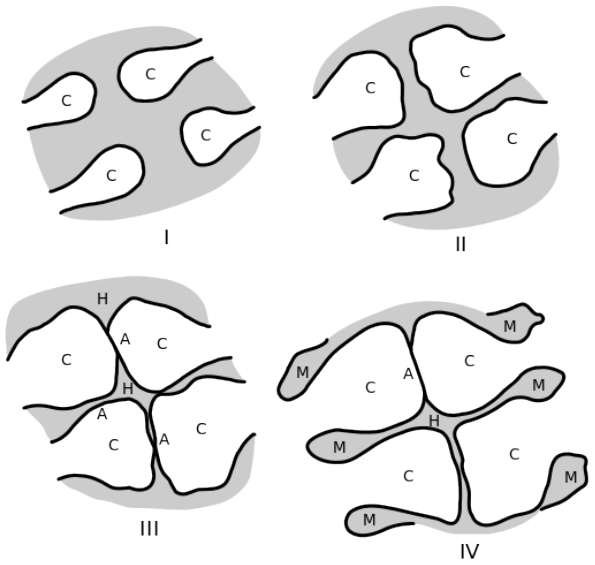


Figure 3.32.1: Key: **A** = Arête, **C** = Cirque, **H** = Horn, **M** = Monument, Preglacial surface shaded

Stage Number	Stage Name	Description
I	Grooved Upland	Early-stage. Only cirques (C) developed at this point.
II	Early-Fretted Upland	Cirque (C) development moves headward, very much like a stream and headward erosion. Still no ridge-like glacial features.
III	Mature-Fretted Upland	Classic mountain glacial landscape. Horns (H) and Arêtes (A) have developed.
IV	Monumented Upland	Final stage of mountain glacial erosion. Erosion so extensive that monuments (M) of the mountain and knife-like ridges are some of the only features remaining.

Depositional Glacial Landforms

Very large boulder, dark in color, with smaller boulders "floating" inside of it.
via Wikimedia Commons" width="390" src="/@api/deki/files/8187/Diamictite_Mineral_Fork.jpg">

Figure 3.32.1: Boulder of diamictite of the Mineral Fork Formation, Antelope Island, Utah, United States.

Sediment is deposited by glaciers in both alpine and continental environments. Since ice is responsible for a large amount of erosion, there is a lot of sediment in glacial ice. When sediment is left behind by a melting glacier, it is called **till** and is characteristically poorly sorted with grain sizes ranging from clay and silt to subrounded pebbles and boulders, possibly striated.

Many of the depositional landforms described in this section are composed of till. Lithified rocks of this type are sometimes referred to as **tillites**, though that implies an interpretation of glacial origin. A more objective and descriptive term is **diamictite**, meaning a rock with a wide range of clast sizes.

Material carried by the glacier is called **moraine**, which is an accumulation of glacial till produced by the grinding and erosive effects of a glacier. In valley glaciers, moraine also includes material falling on the sides of the glacier by mass wasting from the valley walls. The glacier acts like a conveyor belt, carrying sediment inside and on the ice and depositing it at the end and sides of the glacier. Because ice in the glacier is always flowing downslope, the deposited moraines build up even if the end of the glacier doesn't advance. The type of moraine depends on its location. A **terminal moraine** is a ridge of unsorted till at the maximum extent of a glacier or the farthest extent of a glacier [11]. When glaciers retreat in episodes, they may leave behind deposits called **recessional moraines**. The recessional moraines look similar to terminal moraines but are formed when the glacier retreat pauses. Moraines located along the side of a glacier are called **lateral moraines** and mostly represent material that fell on the sides of the glacier from the mass wasting of the valley walls. When two tributary glaciers join together, the two lateral moraines combine to form a **medial moraine**. Behind the terminal and recessional moraines is a veneer (or thin sheet) of till on top of bedrock called the **till sheet** (or **ground moraine**).



Figure 3.32.1: Lateral moraines of Little Cottonwood and Bell canyons, Utah.



Figure 3.32.1: Medial moraines where tributary glaciers meet. At least seven tributary glaciers from upstream have joined to form the trunk glacier flowing on out of the upper left of the picture.

In addition to moraines, as glaciers melt they leave behind other depositional landforms. The intense grinding process creates a lot of silt. Streams of water melting from the glacier carry this silt (along with sand and gravel) and deposit it in front of the glacier in an area called an **outwash plain**. In addition, when glaciers retreat, they may leave behind large boulders of a type of rock that doesn't match the local bedrock. These are called **glacial erratics**. When continental glaciers melt, large blocks of ice can be left behind to melt within the impermeable till and can create a depression called a **kettle** that can be later filled with surface water like a **kettle lake**. As glaciers melt, the meltwater flows over the ice surface until it descends into crevasses, perhaps finding channels within the ice or continuing to the base of the glacier into channels along the bottom. Such streams located under continental glaciers carry sediment in a sinuous channel within or under the ice, similar to a river. When the ice recedes, the sediment remains as a long sinuous ridge known as an **esker**. Meltwater descending down through the ice or along the margins of the ice may deposit mounds of sediment that remain as hills called **kames**.



Figure 3.32.1: A small group of Ice Age drumlins in Germany.

Also common in continental glacial areas of New York state and Wisconsin are drumlins. A **drumlin** is an elongated asymmetrical drop-shaped hill with its steepest side pointing upstream to the flow of ice and streamlined side (low angle side) pointing in the direction the ice is flowing.

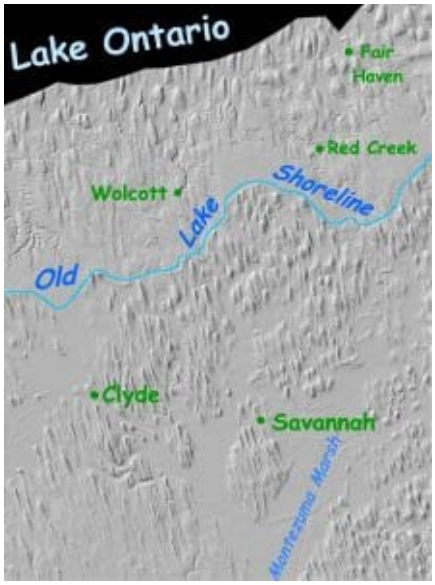
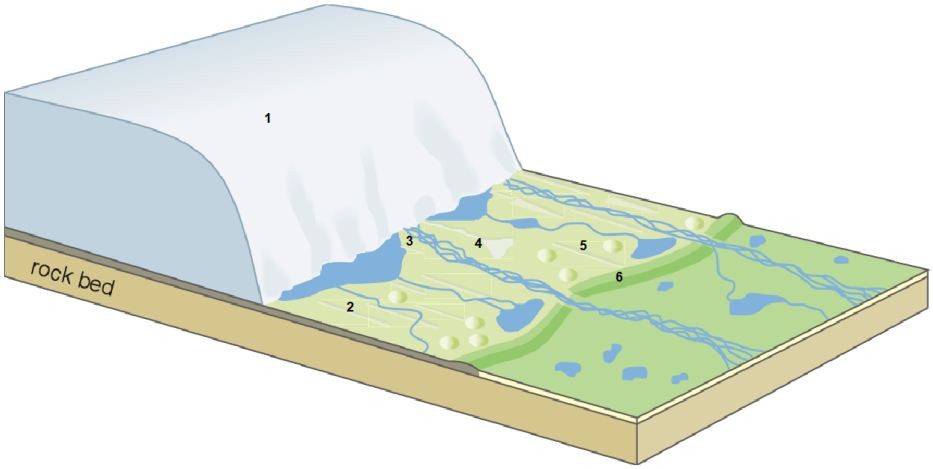


Figure 3.32.1: Drumlin field in Wayne County, New York. Their shape indicates the glacier moved in a NNW to SSE direction.

Drumlins can occur in great numbers in drumlin fields. The origin of drumlins is still debated and some leading ideas are the incremental accumulation of till under the glacier, large catastrophic meltwater floods located under the glacier, and surface deformation by the weight of the overlying glacial ice [12; 13].



Number	Name	Note
1	Receding Glacier	Sheet of ice with a terminus that is moving back with time.
2	Ground Morraine	N/A
3	Esker	N/A
4	Esker	
5	Drumlin	N/A

Number	Name	Note
6	Terminal Morraine	

Glacial Lakes

A mountainous area with a circular bowl filled with a lake.
CC BY-SA 4.0], via Wikimedia Commons" width="291" src="/@api/deki/files/8197/Verdi_Leak_in_The_Ruby_Mountains-e1496442171386.jpg">

Figure 3.32.1: Tarn in a cirque.

Lakes are common features in alpine glacial environments. A lake that is confined to a glacial cirque is known as a **tarn** such as Silver Lake near Brighton Ski resort located in Big Cottonwood Canyon or Avalanche Lake in Glacier National Park. Tarns are common in areas of alpine glaciation because the thick ice that carves out a cirque also typically hollows out a depression in bedrock that after the glacier is gone, fills with precipitated water.



Figure 3.32.1: Paternoster lakes

In some cases, recessional moraines may isolate a series of basins within a glaciated valley, and the resulting chain of lakes is called **paternoster lakes**.



Figure 3.32.1: Satellite view of Finger Lakes region of New York

Lakes that occupy long glacially carved depressions are known as **finger lakes** [5].

In areas of continental glaciation, the crust is depressed isostatically by crustal loading from the weight of thick glacial ice. Basins are formed along the edges of continental glaciers (except for those that cover entire continents like Antarctica and Greenland), and these basins fill with glacial meltwater forming **proglacial lakes**. The classic example of a proglacial lake is Lake Agassiz, located mostly in Manitoba, Canada, with Lake Winnipeg serving as the remnant of the lake. Many such lakes, some of them huge, existed at various times along the southern edge of the Laurentide Ice Sheet.

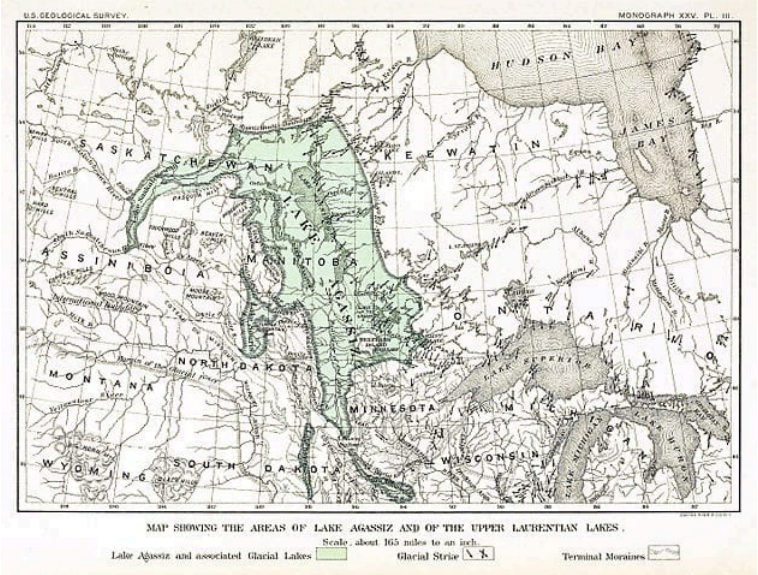


Figure 3.32.1: Extent of Lake Agassiz

Other proglacial lakes formed when glaciers dammed rivers causing the valley to be flooded. The classic example is Glacial Lake Missoula, which formed in Idaho and Montana when the Clark Fork River was dammed by the ice sheet. During the latter part of the last glaciation about 18,000 years ago, the ice holding back Lake Missoula was breached enough to allow some of the lake water to start flowing out, which escalated into a massive and rapid outflow (over days to weeks) during which much of the volume of the lake drained along the valley of the Columbia River to the Pacific Ocean. The ice dam and the lake then formed again. It is estimated that this process of massive flooding happened at least 25 times over that span. In many cases, the rate of outflow was equivalent to the discharge of all of Earth's current rivers combined.



Figure 3.32.1: View of Channeled Scablands in eastern Washington showing huge potholes and massive erosion

The landscape produced by these massive floods is preserved in the Channelled Scablands of Idaho, Washington, and Oregon [5].

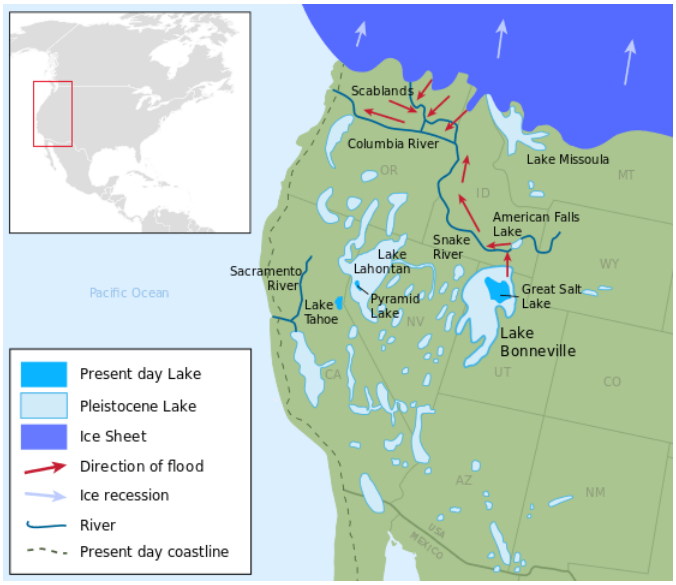


Figure 3.32.1: Pluvial lakes in the western United States

During the last glaciation, most of the western United States had a cooler and wetter climate. Due to less evaporation and more precipitation, many large lakes formed in the basins of the Basin and Range Province called **pluvial lakes**. Two of the largest pluvial lakes were Lake Bonneville and Lake Lahontan. Lake Bonneville occupied much of western Utah and eastern Nevada (Figure from Miller et al 2013) and filled Salt Lake Valley, which is densely urbanized today, with water hundreds of feet deep. During the last glaciation, the level of the lake fluctuated many times leaving several pronounced old shorelines in the western portion of Utah including Salt Lake Valley identified by wave-cut terraces. Lake level peaked around 18,000 years ago [14] and spilled over Red Rock Pass in Idaho into the Snake River causing rapid erosion and a very large flood that rapidly lowered the lake level and scoured the land in Pocatello Valley, Snake River Plain, and Twin Falls Idaho. The flood ultimately flowed into the Columbia River across part of the scablands area and had an incredible discharge of about 4,750 km^3 [15] which is about the volume of Lake Michigan. This would be as if one of the Great Lakes completely emptied within days. Lake Lahontan existed at about the same time mostly in northwestern Nevada.



Figure 3.32.1: The great lakes

The five great lakes in the upper Midwest of North America occupy five basins carved by the ice sheet in a large depression during the Ice Age and were exposed as the ice retreated about 14,000 years ago. They form a naturally interconnected body of freshwater that drains into the Atlantic through the St. Lawrence River. Emergent coastline features are forming on the lakes due to isostatic rebound since the ice retreated (see Chapter 12).

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3.33: Ice Age Glaciations

A **glaciation** (or ice age) occurs when the Earth's climate is cold enough that large ice sheets grow on continents. There have been four major, well-documented glaciations in Earth's history: one during the Archean-early Proterozoic (~2.5 billion years ago), another in late Proterozoic (~700 million years ago), another in the Pennsylvanian (323 to 300 million years ago), and the most recent Pliocene-Quaternary glaciation (Chapter 15). A minor glaciation that occurred around 440 million years ago in modern-day Africa is also mentioned by some authors. The best-studied glaciation is, of course, the most recent. The Pliocene-Quaternary glaciation is a series of many glacial cycles, possibly 18, during the last 2.5 million years. There is especially strong evidence for eight glacial advances within the last 420,000 years as recorded in the Antarctic ice core record [16]. The last of these, known in popular media as "The Ice Age" but known by geologists as the last glacial maximum, reached its height between 26,500 and 19,000 years ago [10; 17]. Follow this link to an **infographic** that illustrates the glacial and climate changes over the last 20,000 years ending with the human influences since the Industrial Revolution.

Causes of Glaciations

Why do glaciations occur? The causes include both long-term and short-term factors. In the geologic sense, long-term means a scale of 10's to 100's of millions of years and short-term means a 100 to 200,000-year scale. Ideas about long-term causes of glaciations over geologic time include the positioning of continents near poles by plate tectonics and the Wilson Cycle and changes in ocean circulation due to re-positioning of the continents such as the closing of the Panama Strait. Short-term factors are more recognizable for the most recent Pliocene-Quaternary Glaciation and are most relevant to today's anthropogenic climate change, but may have taken place in the earlier glaciations.

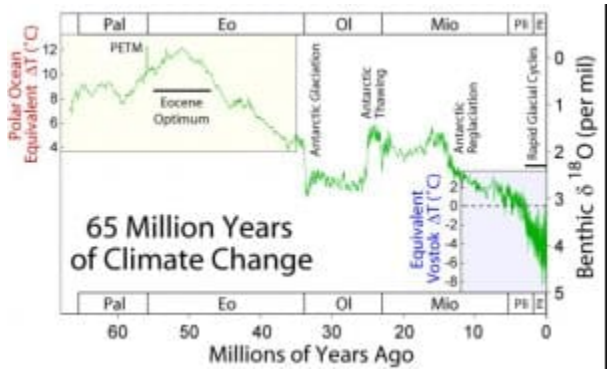
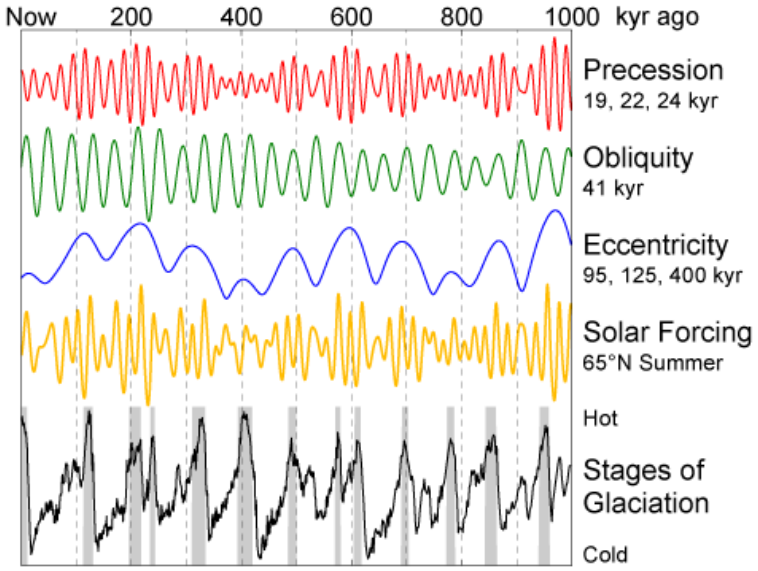
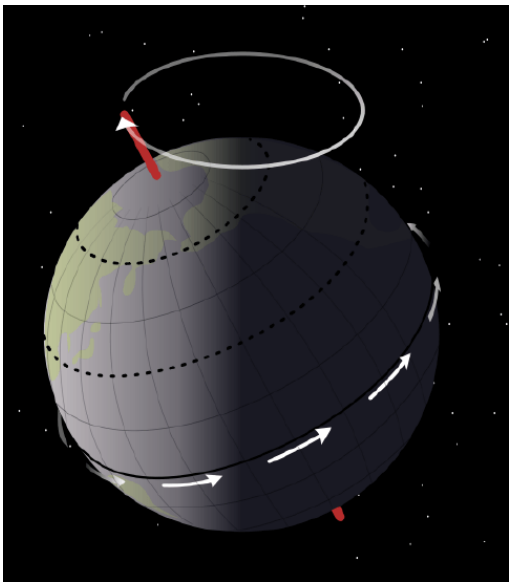


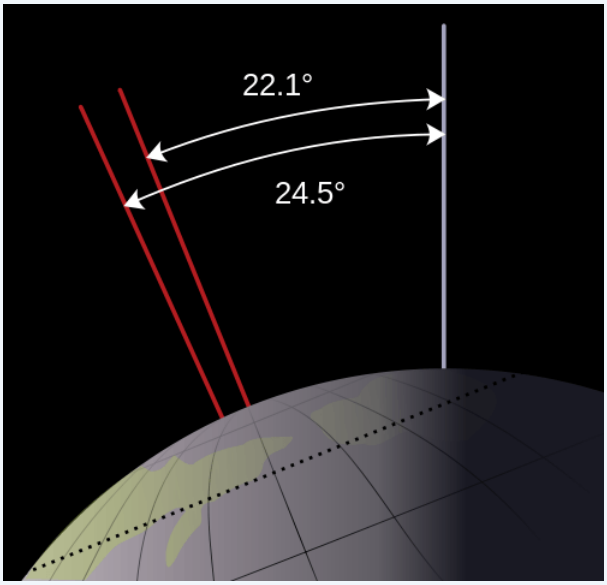
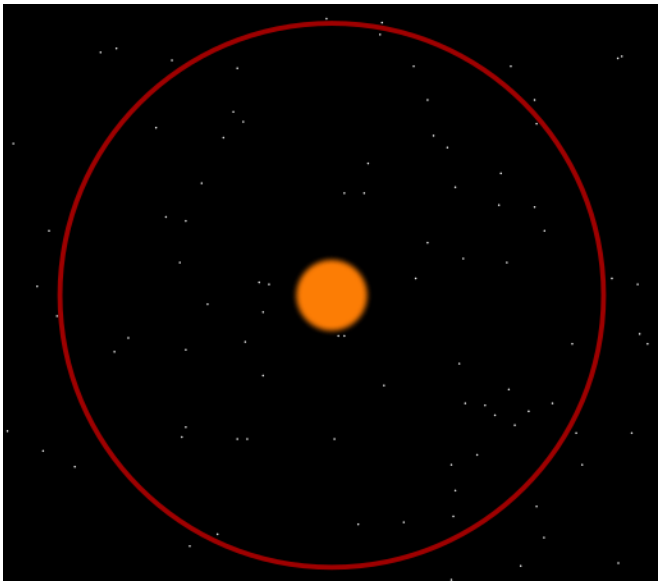
Figure 3.33.1: Atmospheric CO_2 has declined during the Cenozoic from a maximum in the Paleocene-Eocene to its dramatic rise since the Industrial Revolution.

Short-term causes of glacial fluctuations are attributed to cycles in the rotational axis of the Earth and in Earth-Sun relations due to variations in the earth's orbit called **Milankovitch Cycles**. These cycles affect the amount of incoming solar radiation, and changes in carbon dioxide in the atmosphere. During the Cenozoic, carbon dioxide levels steadily decreased from a maximum in the Paleocene causing a gradual climatic cooling [18]. As the climate cooled, the effects of the Milankovitch Cycles began to influence climate with regular cycles of warming and cooling. Milankovitch Cycles are three orbital changes named after the Serbian astronomer Milutin Milankovitch. The three orbital changes are the wobbling of Earth's axis called **precession** with a span of 21,000 years, the angle of Earth's axis called **obliquity** with a span of about 41,000 years, and variations of the distance from the sun in Earth's orbit around the sun referred to as **eccentricity** with a span of 93,000 years [19]. These orbital changes created a glacial-interglacial cycle of 41,000 years from 2.5 to 1.0 million years ago and a longer cycle of ~100,000 years from 1.0 million years ago to today (for detail, see this **chart**). The combination of these three Milankovitch Cycles changes the angle at which the sun's energy strikes the surface of the earth near the poles and the amount of energy (insolation) received by Earth (for detail, see this **chart**). As the climate cooled during the Cenozoic Era, the subtle changes in energy received by the planet were expressed as a warmer and cooler climate cycle, thus the glacial-interglacial cycles.

This chart illustrates the effect of the Milankovitch Cycles.



Name	Illustration
Precession	

Name	Illustration
Obliquity	
Eccentricity	

This video summarizes ice ages: their characteristics and causes.

Sea-Level Change and Isostatic Rebound

Since glaciers are ice located on land (not floating in the ocean), when glaciers melt and retreat two things happen, sea-level rises globally and the land rises locally due to isostatic rebound. Melting glacial water runs off into the ocean and sea-level worldwide will rise. For example, since the last glacial maximum about 19,000 years ago [17] sea-level has risen about 400 feet (125 meters) [20]. An overall global change in sea level is called **eustatic** sea-level change. More water in the ocean causes a eustatic sea-level rise. Another important factor causing eustatic sea-level rise is thermal expansion. According to basic physics, thermal expansion occurs when a solid, liquid, or gas expands in volume when the temperature increases. Watch this **30-second video** demonstrating thermal expansion with the classic brass ball and ring experiment. About half of the eustatic sea-level rise during the last century has been the result of thermal expansion, the rest from the melting of glaciers [21; 22].

However, tectonics and isostatic rebound can move the land up and down. The change of sea level as it relates to a more local continental landscape is called relative sea-level change. The relative sea-level change includes both the vertical movement of the eustatic sea-level and the vertical movement of land, so that the sea-level change is measured *relative* to the land. Therefore,

if the land rises a lot and sea-level rises only a little, then the sea-level would appear to go down.

The lithosphere can move vertically as a result of two main processes, tectonics, and isostatic rebound. Tectonic uplift occurs when tectonic plates collide as discussed in the Plate Tectonics chapter. **Isostasy** describes the equilibrium that exists for the earth's lithosphere, where denser lithosphere "sinks" lower on top of the asthenosphere and less dense lithosphere "floats" higher on the asthenosphere. **Isostatic rebound** is when some weight is removed from the continental lithosphere causing it to "float" higher on the asthenosphere. Erosion can remove this weight very slowly or the relatively rapid removal of glaciers can remove a lot of weight in a short amount of time. Melting glaciers removes weight from the continental lithosphere causing it to rise or "rebound" from being previously depressed. Most glacial isostatic rebound is occurring where glaciers recently melted (19,000 years ago) such as Canada and Scandinavia. Glacial isostatic rebound causes the relative sea-level to fall or rise less quickly as seen from the land. Isostatic rebound also occurred in Utah when the water from Lake Bonneville was removed [23]. Isostatic rebound is still taking place wherever Ice Age ice or water bodies were present on continental surfaces. Its effects can be seen in terraces forming on river floodplains that cross these areas.

This map shows the rates of vertical crustal movement worldwide. Note that the greatest upward movement occurs in regions affected by recent glaciation, isostatic rebound. Also, note that crustal depression has also occurred in adjacent regions as subcrustal material displaced by isostatic lowering from the weight of the ice has flowed back in under the rebound.

World map showing greatest rebound rates in the areas of recent glaciation.

via Wikimedia Commons" width="716px" height="554px" src="/@api/deki/files/8202/
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Rates of isostatic rebound worldwide, greatest in regions of recent glaciation.

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3.34: Anthropogenic Effects on Water Quality

Human activities are common causes of water-supply problems, and, in this regard, the most important activities are agriculture, industry, landfills, sewage, and anything that can lead to elevated turbidity. Anthropogenic sources are divided into two types, nonpoint sources where the effect is distributed over a large area such as agriculture or logging, and point sources, like factories, landfills or mines, where the effect is localized to a specific site.

By a wide margin, agriculture represents the greatest threat to water quality. Agriculture is everywhere, and it occupies more land than all other uses combined. There is currently 30% more agricultural land than forested land. Modern agriculture, while very efficient in terms of production per input dollar, is also intensively dependent on the use of chemicals (fertilizers and pesticides) and a significant proportion of the chemicals applied either run off the surface into streams and lakes, or seep into aquifers.

A two-decade study by the US Geological Survey has shown that the water in over 50% of wells tested in agricultural regions has detectable amounts of pesticides, that the issue is also prevalent in urban areas (because of pesticide use on golf courses and lawns) and that it was worse during the period from 2002 to 2011 than it was from 1993 to 2001 (Figure 3.33.1). Although the figure doesn't show levels of pesticides in these wells, another study has shown that over 1000 wells in Florida have been closed because of pesticide levels above acceptable limits.[1]

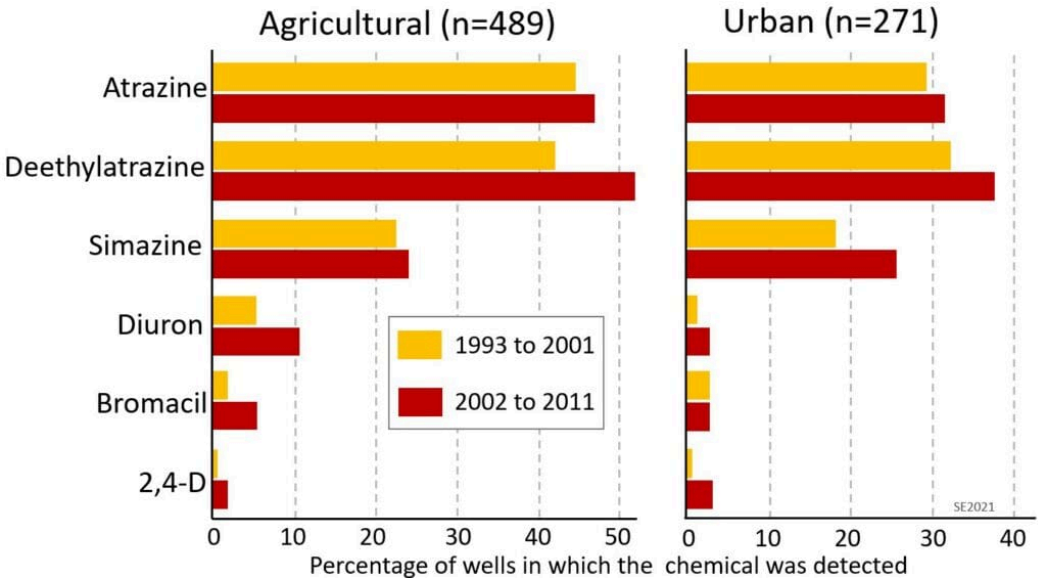


Figure 3.34.1 Pesticide Incidence in Groundwater in the United States, 1993 to 2011

Large amounts of nitrogen, phosphorous and potassium fertilizers are applied to fields all over the world. These nutrients help the crops to grow, but if more fertilizer is applied that is really needed, then the excess will end up making its way into the environment. Nitrogen from fertilizers can volatilize into the air, to come down within rainfall somewhere else. Nitrogen, phosphorous and potassium can run off fields into surface water bodies. They can also infiltrate down into the soil, and move downwards out of reach of the plant roots where they are added to the groundwater. That groundwater may discharge to a surface water body. In lakes and streams these excess nutrients help algae to thrive, and that can create significant problems for aquatic life and human water supplies and is also an issue for anyone who likes to be in or near the water.

Lake Erie has long been the poster child for algal blooms related to excess nutrients, as is illustrated in a satellite image from 2011 (Figure 3.34.2). Erie is the shallowest of the Great Lakes (average depth is only 19 m, compared with 147 m for Lake Superior) and so has the greatest potential to warm up in the summer. The Erie drainage basin is also the most heavily populated of the Great Lakes (home to 12.4 million people) and the lake is entirely surrounded by farmland and cities and industry, with very little remaining forest. The western part of Lake Erie has a springtime phosphorous level of over 12 µg/L, whereas Lakes Superior and Huron are in the range of 2 to 3 µg/L, and Lake Ontario is just over 6 µg/L.[2]



Figure 3.34.2 Algal Growth in Lake Erie in 2011

Agriculture is a major source of the phosphorous that leads to excess algal growth in Lake Erie, but not the only one. Other important sources include municipal sewage effluent, industrial effluent, urban storm water runoff, and atmospheric deposition.[3] Runoff from fields is not only laced with excess nutrients and pesticides, it is also rich in suspended matter that contributes to the turbidity of surface water, degrading aquatic ecosystems, and potentially endangering human water supplies (Figure 3.34.3). The risk of turbid runoff is greatest when fields have been left unprotected by vegetation following harvesting or tillage.



Figure 3.34.3 Turbid Runoff From a Field in Iowa Following a Rainstorm

Nearly 80% of global farmland is dedicated to livestock, either for grazing or for growing animal feed (although livestock farming accounts for only 18% of the caloric output from farming)[4] and farm animals produce manure—lots of it. Manure from all livestock is rich in nitrogen, potassium and phosphorous, and so contributes to the surface water algae problem described above, and to elevated levels of nitrogen in groundwater.

The Abbotsford-Sumas Aquifer of southwestern British Columbia and northwestern Washington provides a good example of how agriculture can affect groundwater quality. The area is intensively farmed with row crops (mostly raspberries and blueberries), large-scale poultry production and pastured livestock. In the past, manure from poultry operations was spread on raspberry fields. A 1992 study on the Canadian side of the border showed that 60% of 125 wells had nitrate levels above the 10 mg/L MAC for drinking water.[5] The Abbotsford-Sumas Aquifer slopes towards the south and crosses into northwestern Washington. A 1999

report[6] shows that the nitrogen contamination extended south across the border, although similar farming activities on the US side are responsible for much of that contamination. The extent of the nitrate contamination in the Abbotsford-Sumas Aquifer is shown on Figure 3.34.4.

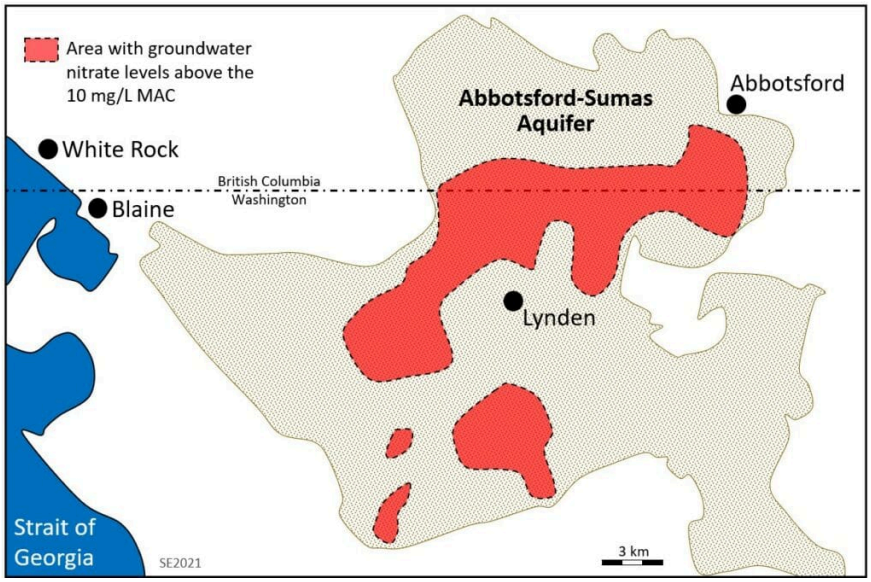


Figure 3.34.4 Extent of Elevated Nitrate Levels in the Abbotsford-Sumas Aquifer, British Columbia and Washington

In addition to nitrates and other nutrients, animal manure also contains bacteria, and while most of those bacteria are harmless to humans, some present a serious risk.

Walkerton Ontario, a town of about 5000 residents situated 150 km northwest of Toronto, has a water supply system sourced by wells in a fractured bedrock aquifer. One of those wells (Well 5) was shallow, drawing water from a depth of only 6 m. A heavy rainstorm in early May 2000 soaked a pasture that had been fertilized with cattle manure a few weeks earlier. Some of that water was introduced into the Walkerton water system from Well 5, situated 80 metres away from the pasture. In the following week 2300 residents became ill with gastroenteritis from the bacterium Escherichia coli in the water supply, and seven people died. Although Walkerton's Public Utility Commission did routine tests for bacterial contamination, the testing protocols were not always followed nor were they as frequent as prescribed, monitoring records were falsified, and the utility's chlorination system was set to a level below that stipulated by the Ontario Clean Water Agency. A public inquiry concluded that much of the blame for the Walkerton disaster can be traced back to provincial government cuts to funding for programs that had been established to protect citizens and ensure safe water supplies.[7] The Walkerton disaster spurred increased efforts to protect groundwater across Canada.

Logging, like agriculture, is a nonpoint source of pollution because it is carried out over wide areas, and it involves the application of fertilizers and pesticides and the removal of vegetation. But logging differs because it is often carried out on steep slopes—in the remaining forested areas that are too rugged for farming or urbanization—(Figure 3.34.5) and so the issue with erosion and turbid runoff is exacerbated. Most logging also operations also involve the construction of temporary roads on steep terrain. Road construction amplifies the risk of slope failure and that increases the likelihood of damage to surface water habitat and supplies.



Figure 3.34.5 A Clear Cut in the Coquille River Basin of Southwestern Oregon

Point sources of pollution include mines, petroleum extraction operations, plants for extracting and refining ores and petroleum, chemical works, manufacturing plants, sewage treatment systems, landfills and underground storage tanks (USTs) at filling stations. Some of these are discussed in other chapters and therefore won't be considered here.

Throughout the history of industrialization, owners and operators all of these types of facilities have failed catastrophically and repeatedly to protect the environment, water supplies, ecosystems and the lives and health of workers and innocent people. One of the most notorious examples was in the city of Niagara Falls, New York. In the 1920s the city set aside an abandoned canal—Love Canal—as a dump site for municipal waste. In 1942 the Hooker Chemical Company was given permission to dispose of chemical by-products from the manufacture of dyes, perfumes and rubber goods into the dump. From then until 1952 Hooker dumped nearly 20,000 tonnes of chemical wastes at the site, most of it in 200-litre metal drums, which they eventually covered up with clay. In 1952 they sold the site (which they had purchased from the city in 1947), along with the liability for the dumped chemicals, to the Niagara Falls Board of Education. A 400-student elementary school was built on top of the old dump and it was in use from 1955 to 1978. Soon after construction of the school, toxic chemicals started coming to surface, parts of the clay cover collapsed, and some of the metal drums were exposed at surface.[8] During heavy storms contaminated surface water ran off the site and into the Niagara River (and then over the falls). Contaminated groundwater also migrated offsite and into the basements of neighboring homes. The Love Canal site was eventually cleaned up, and the school and surrounding homes abandoned, but there are lingering health issues amongst those who lived in the area.

There are industrial sites like Love Canal all over the world and their contamination legacies will be with us for decades, even centuries. Increasingly however, corporations and individuals are being held to account for making the assumption that they can dump whatever waste they need to get rid of onto the ground and into water and the air.

But it isn't just large operations that are problematic. In virtually every village, town and neighborhood in North America (and elsewhere as well) there are abandoned sites surrounded by chain link fences and dotted with the plastic pipes of monitoring wells. Many of these are the remains of gas stations with underground storage tanks (USTs) that had leaked so badly that the operation was forced to close. If you think you haven't seen one, you probably just haven't realized what they are. Some UST sites have been cleaned up and rehabilitated. The one illustrated on Figure 3.34.6 has been vacant for over 20 years, possibly because the value of the land is less than the cost of removing the contamination and making the site usable for some other purpose.



Figure 3.34.6 The Site of a Filling Station With Leaking Underground Storage Tanks. The white pipes are groundwater monitoring wells.

A leaking fuel UST is at least three problems in one (Figure 3.34.7). Some components of the fuel are volatile, and so will form a vapor phase that rises to surface and may enter nearby buildings. Most fuels used for vehicles like cars, trucks and planes are lighter than water and so will float along the surface of the saturated zone (the water table). Some components of the fuel are soluble in water and so will mix with groundwater and be dispersed in that way. Some components of the fuel may be heavier than water so will sink through the saturated zone. The aquifer water will eventually come to surface somewhere and will bring some of those dissolved and heavy constituents with it.

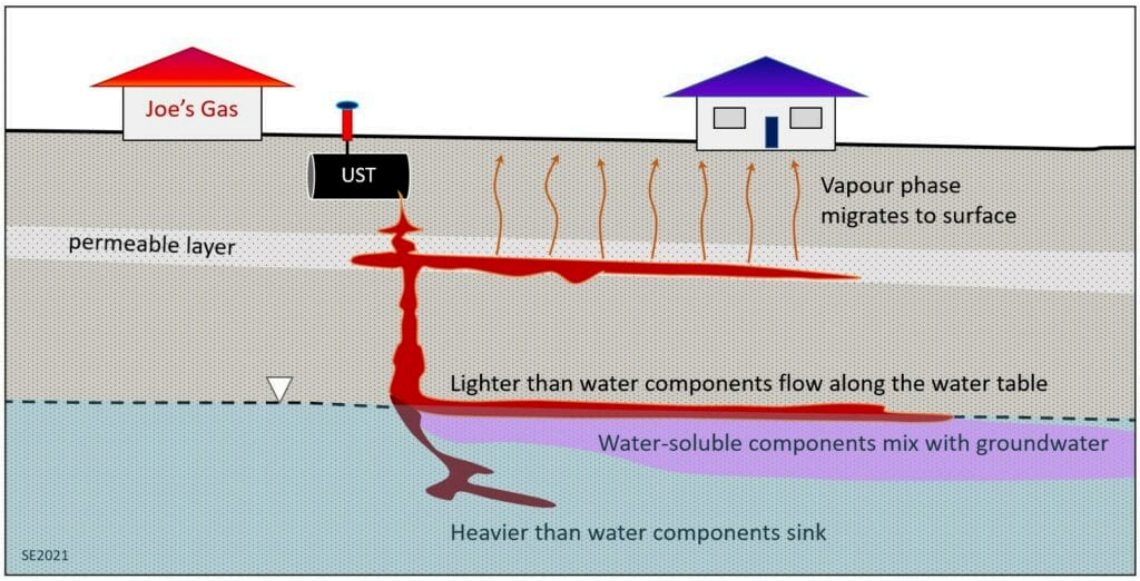


Figure 3.34.7 Illustration of the Fate of Petroleum That Has Leaked from a UST

Exercise 3.34.1 Find a Leaking UST in Your Community

Most the USTs installed at gas stations in the past were made of steel with single walls and no corrosion protection, and so there is a very high probability that they have corroded and started to leak. Take a look around your community for abandoned gas stations (many of which are now just empty lots) that are surrounded by chain-link fences, like the one on Figure 3.34.6. Many will be at busy intersections. There is a good chance that over half of the gas stations that were established in your community prior to 2000 have compromised USTs and are now abandoned. Some may still be leaking fuel into the nearby aquifers.

Media Attributions

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4: THE ATMOSPHERE

4.1: Introduction to the Atmosphere and Objectives
4.2: Atmosphere- Composition and Properties
4.3: Atmospheric Circulation
4.4: Atmospheric Pollution

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4.1: Introduction to the Atmosphere and Objectives

Introduction to the Atmosphere

This chapter will explore the Earth's atmosphere, a dynamic layer of gases that envelops our planet and plays a crucial role in sustaining life. We will examine its composition, structure, and the processes that drive weather patterns and climate. Understanding the atmosphere's functions and interactions with the geosphere, hydrosphere, and biosphere is essential for addressing global environmental challenges.

We'll delve into the composition and properties of the atmosphere, from the life-sustaining oxygen we breathe to the greenhouse gases that regulate our climate. Discover the mechanisms of atmospheric circulation that transfer heat from the equator poleward, create wind patterns, influence ocean currents, and shape our weather systems. We will also tackle the pressing issue of atmospheric pollution, exploring its sources, impacts, and strategies to mitigate its effects. Prepare to be captivated by the complexities of the atmosphere, where every gust of wind and every raindrop tells a story of Earth's interconnected systems.

Learning Objectives

1. Describe the composition and structure of Earth's atmosphere, including the roles of major and trace gases.
2. Explain the processes driving atmospheric circulation and their effects on global weather patterns and climate.
3. Analyze the interactions between the atmosphere and other Earth systems, such as the geosphere, hydrosphere, and biosphere.
4. Evaluate the sources and impacts of atmospheric pollution, and discuss strategies for reducing its harmful effects.
5. Understand the scientific principles behind weather phenomena and climate change, and apply this knowledge to address global environmental challenges.



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4.2: Atmosphere- Composition and Properties

Atmospheric Circulation

Our **atmosphere** is the gaseous mass or envelope surrounding the Earth, and retained by the Earth's gravitational field. Other planets and moons in the Solar System have atmospheres. The atmosphere plays many important roles in moving water in the world's ocean basins, and for supporting life on Earth!

Earth's atmosphere is:

- **Density stratified** - air is compressed and most dense near the surface and grows increasingly ***rarefied*** skyward.
- About **100 kilometers thick** between the ocean/land surface and the vacuum of space.
- **Composed mostly of gases,** mostly nitrogen (as N_2) and oxygen (as O_2), and trace amounts of other gases (including CO_2, argon, water vapor); **and traces of liquids and solids in suspension or falling as precipitation**: suspended water (clouds, water droplets and ice crystals), traces of organic compounds, and suspended particles of dust from a variety of sources.



Figure 8.1. Layers of the Earth's atmosphere as seen from space.

Structure of the Atmosphere

The Earth's atmosphere is subdivided into levels (Figure 8.2):

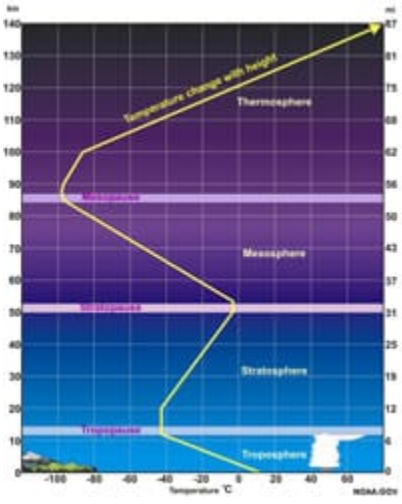


Figure 8.2. **Structure of Earth's atmosphere.**

* The **troposphere** is the lowest portion (**up to about 6-8 miles** [10-13 km]) where all weather takes place and contains about 80% of the air's mass and **99% of water vapor**.
* The overlying **stratosphere** contains an abundance of ozone which absorbs ultraviolet radiation, protecting life on land and in the shallow ocean extends **up to about 31 miles** (50 km).

*The **mesosphere** is the part of the earth's upper atmosphere above the stratosphere in which temperature decreases with altitude to the atmosphere's absolute minimum.

* The **thermosphere** the region of the atmosphere above the mesosphere and below the height at which the atmosphere ceases to have the properties of a continuous medium (about 60 miles [100 km]). The thermosphere is characterized throughout by an increase in temperature with height, where the charged atomic particles of the solar wind begins to interact with atmospheric gases.

Energy Transfer Through the Atmosphere

The amount of energy coming into the Earth from the Sun **is equal to** the energy **reflected** and **radiated** back into space. The atmosphere, oceans, and land **absorb and release energy**. Living things also absorb and release energy. Some of the energy stored in organic matter is preserved when it is buried in sediments. **Geothermal energy** is also a trace of the energy radiated into space. The rate of energy transfer also varies due to cloud cover and ice and snow coverage.

Incoming solar radiation involves all wavelengths of the **electromagnetic spectrum**. **Figure 8.3** shows the wavelengths and intensity of solar energy striking the top of the atmosphere and the energy reaching the surface. The atmosphere is transparent to most wavelengths, but part of the solar spectrum are absorbed by certain **greenhouse gases** in the atmosphere including water vapor, carbon dioxide, ozone, methane, and other gases. Shorter wavelengths (UV and blue light) is diffused in the air—making the sky blue. Longer wavelengths are less diffused—making sunsets and sunrises red (Figure 8.4).

Energy that is not reflected back into space is radiated back into space in wavelengths longer than visible light (mostly in the the**rmal infrared** portion of the electromagnetic spectrum).

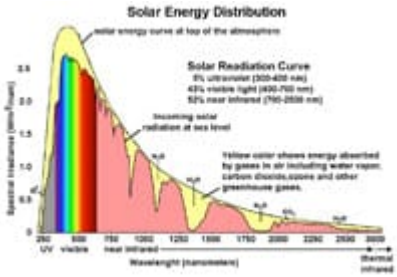


Figure 8.3. Wavelengths of solar energy transmitted and absorbed by the atmosphere.

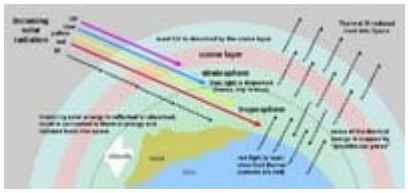


Figure 8.4. Energy transfer through the atmosphere

Composition of the Atmosphere

- **Nitrogen** (**N_2**) - 78%
- **Oxygen** (**O_2**) - 21%
- **Argon** - 0.9%
- **Carbon Dioxide** (**CO_2**) - 0.036%
- **Others** < 1 % - Neon, Helium, Methane (CH_4), Krypton, Hydrogen (H_2), traces of other compounds

Other trace gases in variable amounts include nitrogen oxides, ozone (O_3), sulfur dioxide, hydrocarbons, and more. These gases are released by volcanic eruptions, lightning, wildfires, erosion, and pollutants of many kinds from human activity. Major sources of air pollutants included gases and smoke released by fossil-fuel energy consumption, industrial releases, agriculture, and leaks of refrigerator and air conditioner coolant compounds.

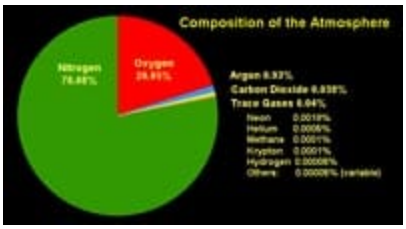


Figure 8.5. Chemical composition of the atmosphere (major and trace gases)

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4.3: Atmospheric Circulation

Atmospheric Circulation

Differential heating of the Earth's surface results in equatorial regions receiving more heat than the poles. As air is warmed at the equator it becomes less dense and rises, while at the poles the cold air is denser and sinks. If the Earth was non-rotating, the warm air rising at the equator would reach the upper atmosphere and begin moving horizontally towards the poles. As the air reached the poles it would cool and sink, and would move over the surface of Earth back towards the equator. This would result in one large atmospheric convection cell in each hemisphere (Figure 4.3.1), with air rising at the equator and sinking at the poles, and the movement of air over the Earth's surface creating the winds. On this non-rotating Earth, the prevailing winds would thus blow from the poles towards the equator in both hemispheres (Figure 4.3.1).

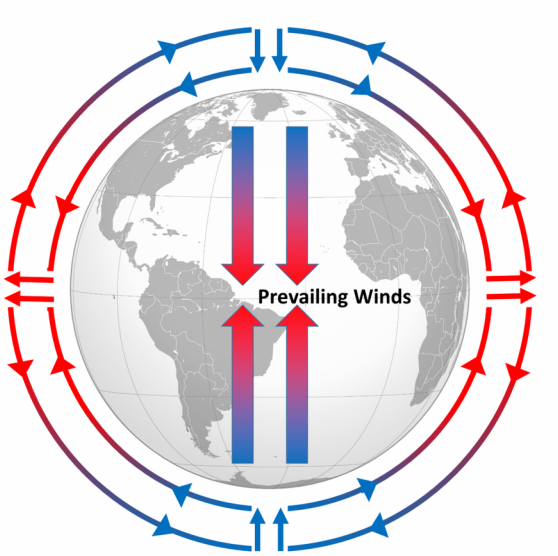


Figure 4.3.1: Hypothetical atmospheric convection cells on a non-rotating Earth. Air rises at the equator and sinks at the poles, creating a single convection cell in each hemisphere. The prevailing winds moving over the Earth's surface blow from the poles towards the equator in both hemispheres (Modified by Paul Webb from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

The non-rotating situation in Figure 4.3.1 is of course only hypothetical, and in reality the Earth's rotation makes this atmospheric circulation a bit more complex. The paths of the winds on a rotating Earth are deflected by the **Coriolis Effect**. The Coriolis Effect is a result of the fact that different latitudes on Earth rotate at different speeds. This is because every point on Earth must make a complete rotation in 24 hours, but some points must travel farther, and therefore faster, to complete the rotation in the same amount of time. In 24 hours a point on the equator must complete a rotation distance equal to the circumference of the Earth, which is about 40,000 km. A point right on the poles covers no distance in that time; it just turns in a circle. So the speed of rotation at the equator is about 1600 km/hr, while at the poles the speed is 0 km/hr. Latitudes in between rotate at intermediate speeds; approximately 1400 km/hr at 30° and 800 km/hr at 60°. As objects move over the surface of the Earth they encounter regions of varying speed, which causes their path to be deflected by the Coriolis Effect.

To explain the Coriolis Effect, imagine a cannon positioned at the equator and facing north. Even though the cannon appears stationary to someone on Earth, it is in fact moving east at about 1600 km/hr due to Earth's rotation. When the cannon fires the projectile travels north towards its target; but it also continues to move to the east at 1600 km/hr, the speed it had while it was still in the cannon. As the shell moves over higher latitudes, its momentum carries it eastward faster than the speed at which the ground beneath it is rotating. For example, by 30° latitude the shell is moving east at 1600 km/hr while the ground is moving east at only 1400 km/hr. Therefore, the shell gets "ahead" of its target, and will land to the east of its intended destination. From the point of view of the cannon, the path of the projectile appears to have been deflected to the right (red arrow, Figure 4.3.2). Similarly, a cannon located at 60° and facing the equator will be moving east at 800 km/hr. When its shell is fired towards the

equator, the shell will be moving east at 800 km/hr, but as it approaches the equator it will be moving over land that is traveling east *faster* than the projectile. So the projectile gets "behind" its target, and will land to the west of its destination. But from the point of view of the cannon facing the equator, the path of the shell still appears to have been deflected to the right (green arrow, Figure 4.3.2). Therefore, in the Northern Hemisphere, the apparent Coriolis deflection will *always* be to the **right**.

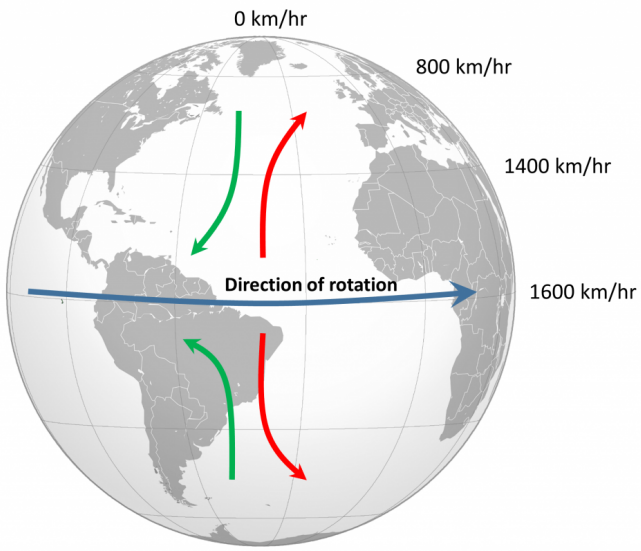


Figure 4.3.2: The Coriolis Effect. Objects moving from the equator towards the poles (red arrows) move into a region of slower rotational speed and their paths are deflected "ahead" of their point of origin. Movement from high latitudes to low latitudes (green arrows) goes from a region of low speed to a region of higher rotation speed, and there is deflection "behind" their point of origin. In the Northern Hemisphere this deflection is always to the right from the point of origin, and in the Southern Hemisphere the deflection is always to the left (Modified by Paul Webb from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

In the Southern Hemisphere the situation is reversed (Figure 4.3.2). Objects moving towards the equator from the south pole are moving from low speed to high speed, so are left behind and their path is deflected to the left. Movement from the equator towards the south pole also leads to deflection to the left. In the Southern Hemisphere, the Coriolis deflection is always to the **left** from the point of origin.

The magnitude of the Coriolis deflection is related to the difference in rotation speed between the start and end points. Between the poles and 60° latitude, the difference in rotation speed is 800 km/hr. Between the equator and 30° latitude, the difference is only 200 km/hr (Figure 4.3.2). Therefore the strength of the Coriolis Effect is stronger near the poles, and weaker at the equator.

Because of the rotation of the Earth and the Coriolis Effect, rather than a single atmospheric convection cell in each hemisphere, there are three major cells per hemisphere. Warm air rising at the equator cools as it moves through the upper atmosphere, and it descends at around 30° latitude. The convection cells created by rising air at the equator and sinking air at 30° are referred to as **Hadley Cells**, of which there is one in each hemisphere. The cold air that descends at the poles moves over the Earth's surface towards the equator, and by about 60° latitude it begins to rise, creating a **Polar Cell** between 60° and 90°. Between 30° and 60° lie the **Ferrel Cells**, composed of sinking air at 30° and rising air at 60° (Figure 4.3.3). With three convection cells in each hemisphere that rotate in alternate directions, the surface winds no longer always blow from the poles towards the equator as in the non-rotating Earth in Figure 4.3.1. Instead, surface winds in both hemispheres blow towards the equator between 90° and 60° latitude, and between 0° and 30° latitude. Between 30° and 60° latitude, the surface winds blow towards the poles (Figure 4.3.3).

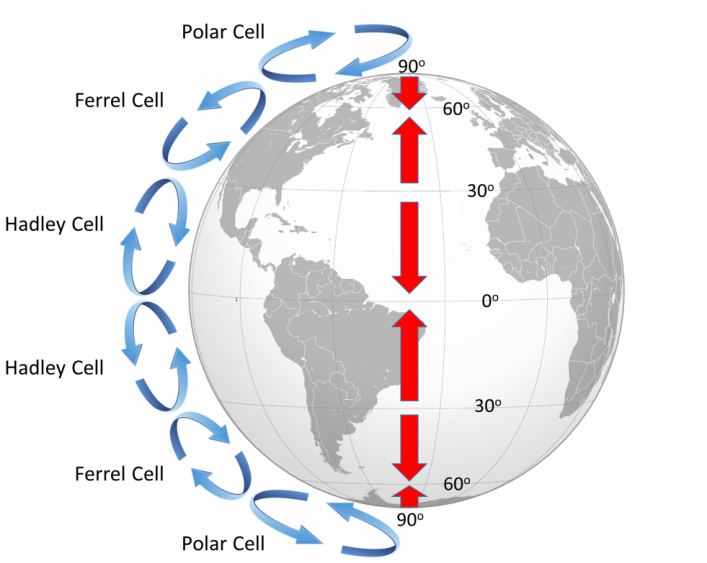


Figure 4.3.3: On a rotating Earth, there are three atmospheric convection cells in each hemisphere, leading to alternating bands of surface winds (red arrows)
(Modified by Paul Webb from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

The surface winds created by the atmospheric convection cells are also influenced by the Coriolis Effect as they change latitudes. The Coriolis Effect deflects the path of the winds to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Adding this deflection leads to the pattern of prevailing winds illustrated in Figure 4.3.4. Between the equator and 30° latitude are the **trade winds**; the northeast trade winds in the Northern Hemisphere and the southeast trade winds in the Southern Hemisphere (note that winds are named based on the direction from which they originate, not where they are going). The **westerlies** are the dominant winds between 30° and 60° in both hemispheres, and the **polar easterlies** are found between 60° and the poles.

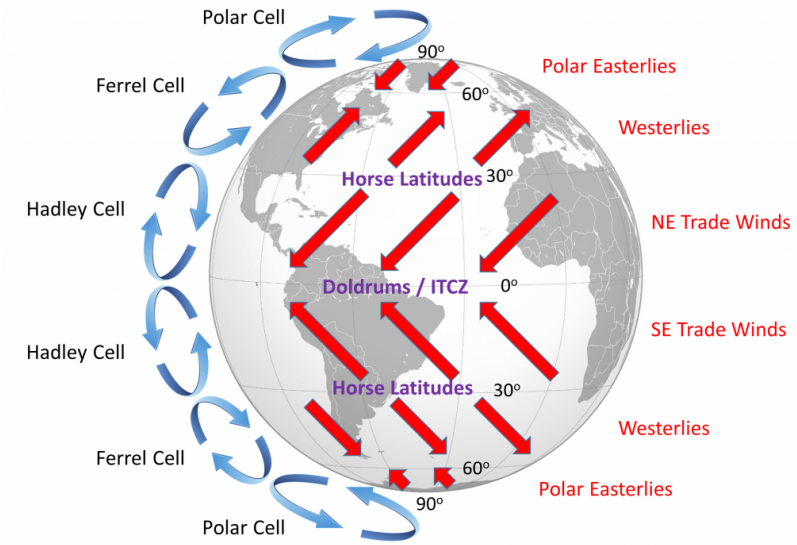


Figure 4.3.4: The prevailing wind patterns of Earth (Modified by PW from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

In between these wind bands lie regions of high and low pressure. High pressure zones occur where air is descending, while low pressure zones indicate rising air. Along the equator the rising air creates a low pressure region called the **doldrums**, or the **Intertropical Convergence Zone** (ITCZ) (convergence zone because this is where the trade winds converge). At 30° latitude there are high pressure zones of descending air known as the **horse latitudes**, or the subtropical highs. Finally, at 60° lies

another low pressure region called the **polar front**. It should be noted that these high and low pressure zones are not fixed in place; their latitude fluctuates depending on the season, and these fluctuations have important implications for regional climates.

Doldrums, horse latitudes, and trade winds may seem like some odd names for these atmospheric phenomena, but many of them can be traced back to maritime traditions and lore. The **doldrums** refer to regions of low pressure around the equator. In these areas, air is rising rather than moving horizontally, so these regions commonly encounter very light winds. The lack of wind could leave sailing ships becalmed for days or weeks at a time, which was not good for the morale of the ship's crew. Like the doldrums the **horse latitudes** are also areas with light winds, this time due to descending air, which could leave ships becalmed. The term **trade winds** may have originally derived from the terms for "track" or "path", but the term may have become more common during European exploration and commercialization of the New World. Mariners sailing from Europe to the New World could sail south until they reached the trade winds, which would then propel their ships across the Atlantic to the Caribbean. To return to Europe, ships could sail to the northeast until they entered the westerlies, which would then steer them back to Europe.

In addition to their role in creating the surface winds, these high and low pressure systems also influence other climatic phenomena (Figure 4.3.5. Along the equator air is rising as it is warmed by solar radiation. Warm air contains more water vapor than cold air, which is why we experience humidity during the summer and not during the winter. The water content of air roughly doubles with every 10° C increase in temperature. So the air rising at the equator is warm and full of water vapor; as it rises into the upper atmosphere it cools, and the cool air can no longer hold as much water vapor, so the water condenses and forms rain. Therefore, low pressure systems are associated with precipitation, and we see wet habitats like tropical rainforests near the equator (Figure 4.3.5.

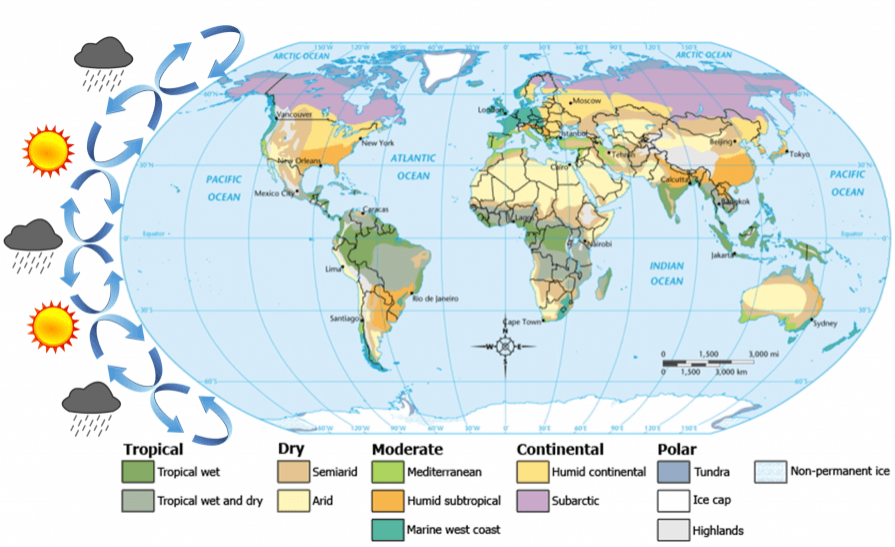


Figure 4.3.5: Major global climatic regions in relation to atmospheric convection cells. Rising air and low pressure creates rain and wet environments at 0° and 60° latitudes, while high pressure, sinking air creates drier conditions at 30° and 90° latitudes. (Modified by Paul Webb; Map by Waitak at en.Wikipedia Later version(s) were uploaded by Splette at en.Wikipedia; Sun by Inductiveload (Own work Based on File:Nuvola_apps_kweather.svg); Raincloud by Calusarul (Own work); all [CC BY-SA 3.0], via Wikimedia Commons).

After rising and producing rain near the equator, the air masses move towards 30° latitude and sink back towards Earth as part of the Hadley convection cells. This air has lost most of its moisture after producing the equatorial rains, so the sinking air is dry, resulting in arid climates near 30° latitude in both hemispheres. Many of the major desert regions on Earth are located near 30° latitude, including much of Australia, the Middle East, and the Sahara Desert of Africa (Figure 4.3.5. The air also becomes compressed and heats up as it sinks, absorbing any moisture from the clouds and creating clear skies. Thus high pressure systems are associated with dry weather and clear skies. This cycle of high and low pressure regions continues with the Ferrel and Polar convection cells, leading to rain and the boreal forests at 60° latitude in the Northern Hemisphere (there are no corresponding large land masses at these latitudes in the Southern Hemisphere). At the poles, descending, dry air produces little precipitation, leading to the polar desert climate.

The elevation of the land also plays a role in precipitation and climactic characteristics. As moist air moves over land and encounters mountains it rises, expands, and cools because of the declining pressure and temperature. The cool air holds less water vapor, so condensation occurs and rain falls on the windward side of the mountains (Figure 4.3.6. As the air passes over the mountains to the leeward side, it is now dry air, and as it sinks the pressure increases, it heats back up, any moisture revaporizes, and it creates dry, deserts regions behind the mountains (Figure 4.3.6. This phenomenon is referred to as a **rain shadow**, and can be found in areas such as the Tibetan Plateau and Gobi Desert behind the Himalayas, Death Valley behind the Sierra Nevada mountains, and the dry San Joaquin Valley in California.

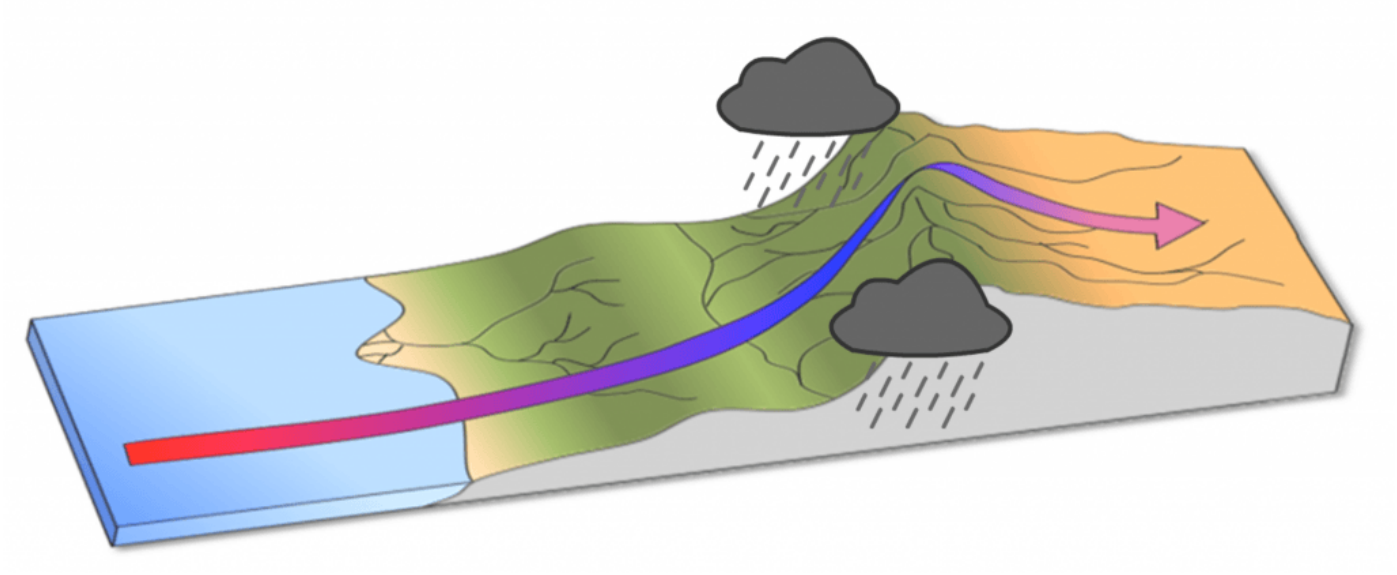


Figure 4.3.6: A rain shadow. Air rising over mountains cools and condenses and forms rain, leaving dry descending air and arid conditions on the other side of the mountain (Modified by Paul Webb from Thebiologyprimer, Public domain via Wikimedia Commons).

Ocean Circulation

Not unexpectedly, the oceans are warmest near the equator—typically 25° to 30°C—and coldest near the poles—around 0°C (Figure 4.3.7). (Sea water will remain unfrozen down to about -2°C.) Variations in sea-surface temperatures (SST) are related to redistribution of water by ocean currents, as we'll see below. A good example of that is the plume of warm Gulf Stream water that extends across the northern Atlantic. St. John's, Newfoundland, and Brittany in France are at about the same latitude (47.5° N), but the average SST in St. John's is a frigid 3°C, while that in Brittany is a reasonably comfortable 15°C.

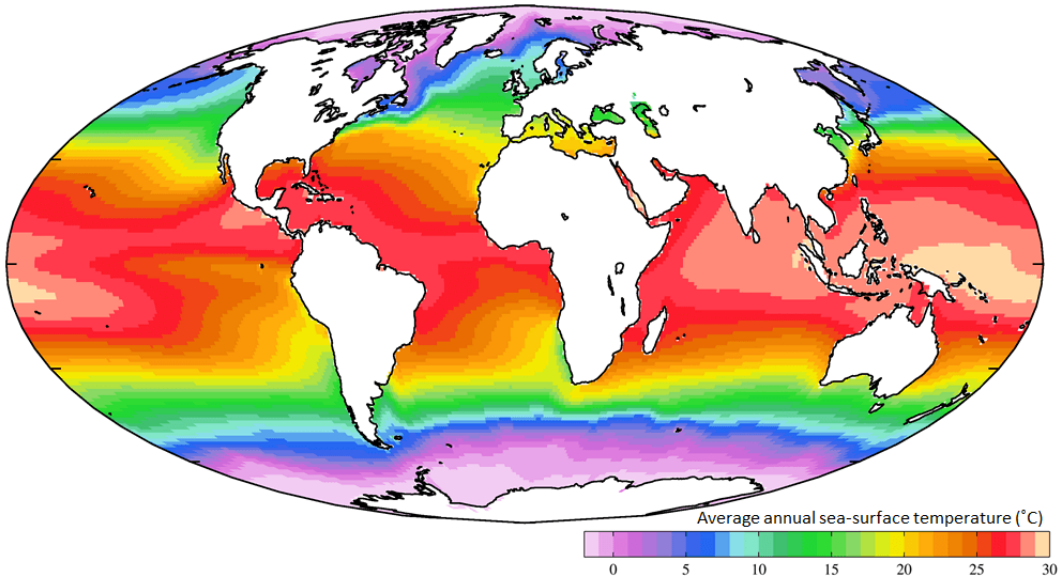


Figure 4.3.7: The global distribution of average annual sea-surface temperatures.
[© Plumbago. CC BY-SA. *https://upload.wikimedia.org/wikiped..._TMP_AYool.png*]

Currents in the open ocean are created by wind moving across the water and by density differences related to temperature and salinity. An overview of the main ocean currents is shown in Figure 4.3.8. As you can see, the northern hemisphere currents form circular patterns (**gyres**) that rotate clockwise, while the southern hemisphere gyres are counter-clockwise. This happens for the same reason that the water in your northern hemisphere sink rotates in a clockwise direction as it flows down the drain; this is caused by the **Coriolis effect**.

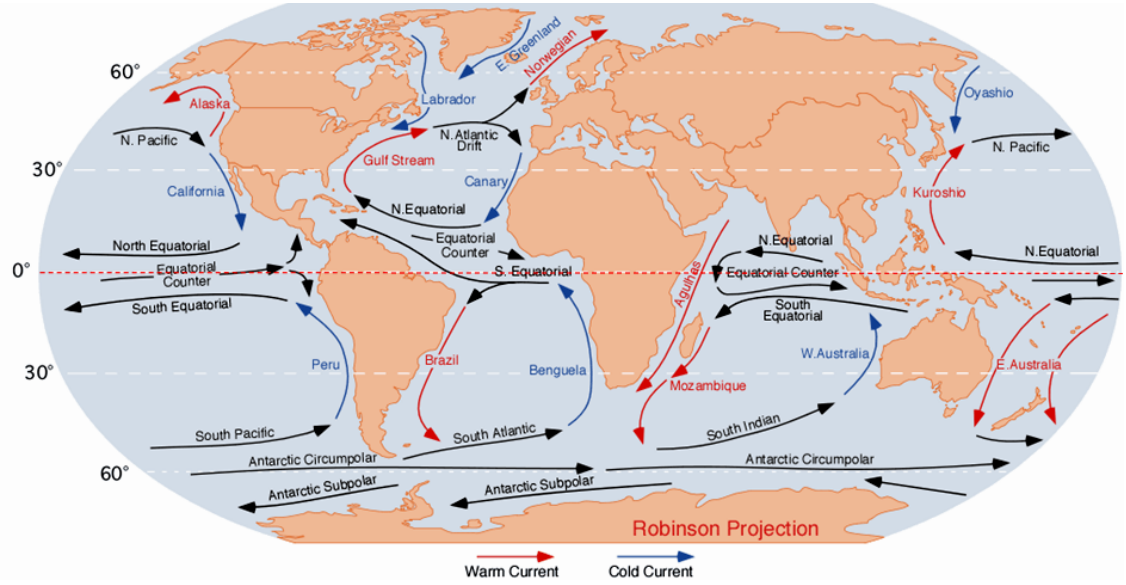


Figure 4.3.8: Overview of the main open-ocean currents. Red arrows represent warm water moving toward colder regions. Blue arrows represent cold water moving toward warmer regions. Black arrows represent currents that don't involve significant temperature changes.
["Corrientes Oceanicas" by Dr. Michael Pidwirny. Public domain. From: *https://upload.wikimedia.org/wikiped...-oceanicas.png*]

Because the ocean basins aren't like bathroom basins, not all ocean currents behave the way we would expect. In the North Pacific, for example, the main current flows clockwise, but there is a secondary current in the area adjacent to our coast—the Alaska Current—that flows counter-clockwise, bringing relatively warm water from California, past Oregon, Washington, and B.C. to Alaska. On Canada's eastern coast, the cold Labrador Current flows south past Newfoundland, bringing a stream of icebergs past the harbour at St. John's (Figure 4.3.9). This current helps to deflect the Gulf Stream toward the northeast, ensuring that Newfoundland stays cool, and western Europe stays warm.



Figure 4.3.9: An iceberg floating past Exploits Island on the Labrador Current.
"Newfoundland Iceberg just off Exploits Island" © Shawn. CC BY-SA.

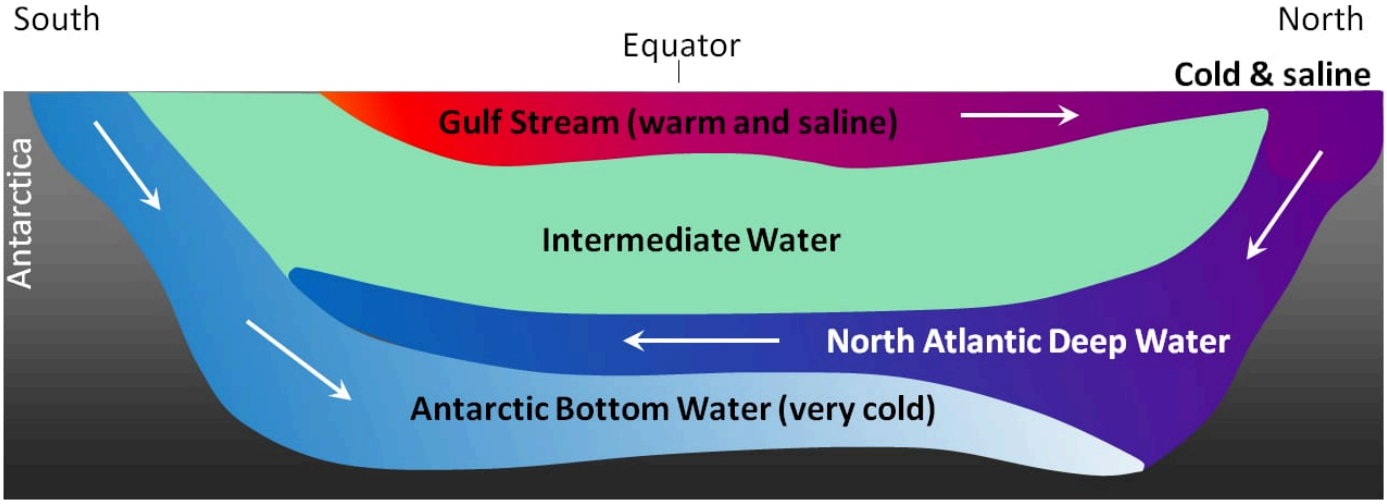


Figure 4.3.10: A depiction of the vertical movement of water along a north-south cross-section through the Atlantic basin.
© Steven Earle. CC BY.

The currents shown in Figure 4.3.8 are all surface currents, and they only involve the upper few hundred meters of the oceans. But there is much more going on underneath. The Gulf Stream, for example, which is warm and saline, flows past Britain and Iceland into the Norwegian Sea (where it becomes the Norwegian Current). As it cools down, it becomes denser, and because of its high salinity, which also contributes to its density, it starts to sink beneath the surrounding water (Figure 4.3.10). At this point, it is known as **North Atlantic Deep Water** (NADW), and it flows to significant depth in the Atlantic as it heads back south. Meanwhile, at the southern extreme of the Atlantic, very cold water adjacent to Antarctica also sinks to the bottom to become **Antarctic Bottom Water** (AABW) which flows to the north, underneath the NADW.

The descent of the dense NADW is just one part of a global system of seawater circulation, both at surface and at depth, as illustrated in Figure 4.3.11. The water that sinks in the areas of deep water formation in the Norwegian Sea and adjacent to Antarctica moves very slowly at depth. It eventually resurfaces in the Indian Ocean between Africa and India, and in the Pacific Ocean, north of the equator.

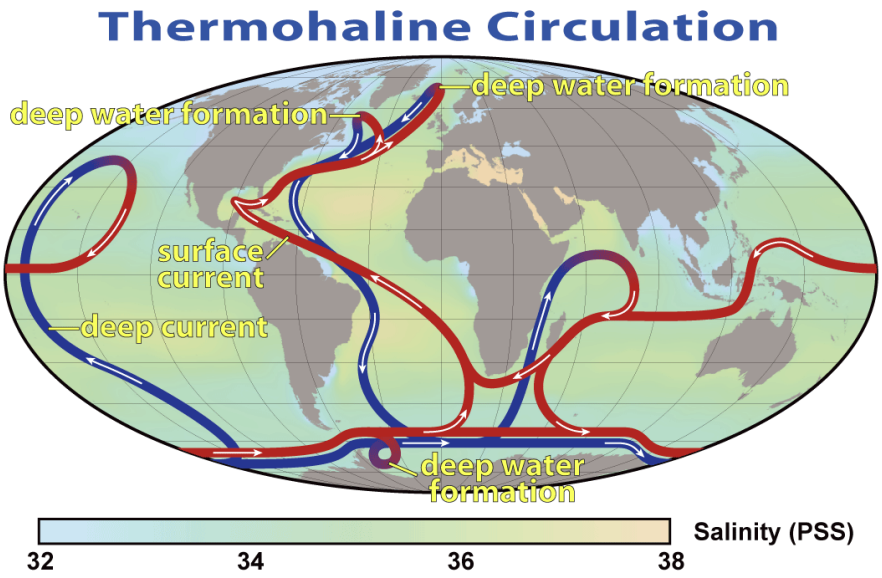


Figure 4.3.11: The thermohaline circulation system, also known as the Global Ocean Conveyor.
["Thermohaline Circulation" by NASA. Public domain from: *https://en.Wikipedia.org/wiki/Thermo...culation_2.png*]

The thermohaline circulation is critically important to the transfer of heat on Earth. It brings warm water from the tropics to the poles, and cold water from the poles to the tropics, thus keeping polar regions from getting too cold and tropical regions from getting too hot. A reduction in the rate of thermohaline circulation would lead to colder conditions and enhanced formation of sea ice at the poles. This would start a positive feedback process that could result in significant global cooling. There is compelling evidence to indicate that there were major changes in thermohaline circulation, corresponding with climate changes, during the Pleistocene Glaciation.

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4.4: Atmospheric Pollution

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**.

Air pollution is typically separated into two categories: outdoor air pollution and **indoor** air **pollution**. Outdoor air pollution involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide, ground-level ozone and tobacco smoke. Indoor air pollution involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include gases, household products and chemicals, building materials (asbestos, formaldehyde, lead, etc.) outdoor indoor allergens (cockroach and mouse dropping, etc.), tobacco smoke, mold and pollen.

Sources of Air Pollution

Stationary and Area Sources. A stationary source of air pollution refers to an emission source that does not move, also known as a point source. Stationary sources include factories, power plants, dry cleaners and degreasing operations. The term area source is used to describe many small sources of air pollution located together whose individual emissions may be below thresholds of concern, but whose collective emissions can be significant. Residential wood burners are a good example of a small source, but when combined with many other small sources, they can contribute to local and regional air pollution levels. Area sources can also be thought of as non-point sources, such as construction of housing developments, dry lake beds, and landfills.

Mobile Sources. A mobile source of air pollution refers to a source that is capable of moving under its own power. In general, mobile sources imply "on-road" transportation, which includes vehicles such as cars, sport utility vehicles, and buses. In addition, there is also a "non-road" or "off-road" category that includes gas-powered lawn tools and mowers, farm and construction equipment, recreational vehicles, boats, planes, and trains.

Agricultural Sources. Agricultural operations, those that raise animals and grow crops, can generate emissions of gases and particulate matter. For example, animals confined to a barn or restricted area (rather than field grazing), produce large amounts of manure. Manure emits various gases, particularly ammonia into the air. This ammonia can be emitted from the animal houses, manure storage areas, or from the land after the manure is applied. In crop production, the misapplication of fertilizers, herbicides, and pesticides can potentially result in aerial drift of these materials and harm may be caused.

Natural Sources. Although industrialization and the use of motor vehicles are overwhelmingly the most significant contributors to air pollution, there are important natural sources of "pollution" as well. Wildland fires, dust storms, and volcanic activity also contribute gases and particulates to our atmosphere.

Unlike the above mentioned sources of air pollution, natural "air pollution" is not caused by people or their activities. An erupting volcano emits particulate matter and gases; forest and prairie fires can emit large quantities of "pollutants"; plants and trees naturally emit VOCs which are oxidized and form aerosols that can cause a natural blue haze; and dust storms can create large amounts of particulate matter. Wild animals in their natural habitat are also considered natural sources of "pollution".

Six Common Air Pollutants

The commonly found air pollutants (also known as **criteria pollutants**) are *particle pollution* (often referred to as particulate matter), *ground-level ozone*, *carbon monoxide, sulfur oxides*, *nitrogen oxides*, and *lead*. These pollutants can harm health and the environment, and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. The U.S. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally-based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called **primary standards**. Another set of limits intended to prevent environmental and property damage is called **secondary standards**.

Ground level or "bad" **ozone** is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) in the presence of sunlight. Emissions from industrial facilities and electric utilities,

motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NOx and VOC. Breathing ozone can trigger a variety of health problems, particularly for children, the elderly, and people of all ages who have lung diseases such as asthma. Ground level ozone can also have harmful effects on sensitive vegetation and ecosystems.

Particulate matter, also known as particle pollution or PM, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

Carbon monoxide (CO) is a colorless, odorless gas emitted from combustion processes. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.

Nitrogen dioxide (NO_2) is one of a group of highly reactive gasses known as "oxides of nitrogen," or nitrogen oxides (NOx). Other nitrogen oxides include nitrous acid and nitric acid. EPA's National Ambient Air Quality Standard uses NO_2 as the indicator for the larger group of nitrogen oxides. NO2 forms quickly from emissions from cars, trucks and buses, power plants, and off-road equipment. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, NO2 is linked with a number of adverse effects on the respiratory system.

Sulfur dioxide (SO_2) is one of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment. SO_2 is linked with a number of adverse effects on the respiratory system.

Lead is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in on-road motor vehicles (such as cars and trucks) and industrial sources. As a result of regulatory efforts in the U.S. to remove lead from on-road motor vehicle gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent between 1980 and 1999. Today, the highest levels of lead in air are usually found near lead smelters. The major sources of lead emissions to the air today are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline.

Indoor Air Pollution (Major concerns in developed countries)

Most people spend approximately 90 percent of their time indoors. However, the indoor air we breathe in homes and other buildings can be more polluted than outdoor air and can increase the risk of illness. There are many sources of indoor air pollution in homes. They include biological contaminants such as bacteria, molds and pollen, burning of fuels and environmental tobacco smoke (see below), building materials and furnishings, household products, central heating and cooling systems, and outdoor sources. Outdoor air pollution can enter buildings and become a source of indoor air pollution.

Sick building syndrome is a term used to describe situations in which building occupants have health symptoms that are associated only with spending time in that building. Causes of sick building syndrome are believed to include inadequate ventilation, indoor air pollution, and biological contaminants.

Usually indoor air quality problems only cause discomfort. Most people feel better as soon as they remove the source of the pollution. Making sure that your building is well-ventilated and getting rid of pollutants can improve the quality of your indoor air.

Secondhand Smoke (Environmental Tobacco Smoke)

Secondhand smoke is the combination of smoke that comes from a cigarette and smoke breathed out by a smoker. When a non-smoker is around someone smoking, they breathe in secondhand smoke.

Secondhand smoke is dangerous to anyone who breathes it in. There is no safe amount of secondhand smoke. It contains over 7,000 harmful chemicals, at least 250 of which are known to damage human health. It can also stay in the air for several hours after somebody smokes. Even breathing secondhand smoke for a short amount of time can hurt your body.

> Over time, secondhand smoke can cause serious health issues in non-smokers. The only way to fully protect non-smokers from the dangers of secondhand smoke is to not allow smoking indoors. Separating smokers from nonsmokers (like “no smoking” sections in restaurants), cleaning the air, and airing out buildings does not completely get rid of secondhand smoke.
>
> Source: Smokefree.gov

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5: WEATHER

5.1: Introduction to Weather and Objectives
5.2: Weather Processes and Systems
5.3: Extreme Weather Events
5.4: Collecting Weather Data and Forecasting Weather

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5.1: Introduction to Weather and Objectives

Introduction to Weather

In this chapter, we focus on the processes and systems that shape our daily weather, beginning with a study of atmospheric pressure and temperature and the crucial role of humidity. As we dive deeper, we'll explore the awe-inspiring power of extreme weather events—thunderstorms, tornadoes, hurricanes—and understand their profound impacts on our lives and the environment.

We will also explore the methods and technologies meteorologists use to collect weather data, from high-flying satellites to ground-based radar. A secondary focus will be on global atmospheric circulation models, and the science of weather forecasting. This chapter will equip you with a comprehensive understanding of weather phenomena, the tools used to study them, and the vital importance of accurate weather forecasting in safeguarding our communities.

Learning Objectives

1. Describe the fundamental processes and systems that drive weather patterns, including the role of atmospheric pressure, temperature, and humidity.
2. Analyze the development and characteristics of extreme weather events, such as hurricanes, tornadoes, and thunderstorms, and their impacts on human and natural systems.
3. Explain the methods and technologies used in collecting weather data, including satellites, radar, and ground-based observations.
4. Evaluate the principles and techniques of weather forecasting, including the interpretation of meteorological data and the use of weather models.
5. Understand the challenges and limitations of weather prediction and the importance of accurate forecasting for public safety and planning.





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5.2: Weather Processes and Systems

LEARNING OUTCOMES

- Describe the various aspects and elements of weather and atmospheric water.
- Explain how air masses and weather fronts together form mid-latitude cyclones.
- Describe the three phases a thunderstorm goes through in it's life cycle.
- Determine the causes and geographic location of most tornadoes around the world.
- Describe the genesis of hurricanes formation
- Compare the difference between blizzards lake effects, and heat waves.

Weather and Atmospheric Water

ELEMENTS OF WEATHER

If someone across country asks you what the weather is like today, you need to consider several factors. Air temperature, humidity, wind speed, the amount and types of clouds, and precipitation are all part of a thorough weather report. In this chapter, you will learn about many of these features in more detail.

Weather is what is going on in the atmosphere at a particular place at a particular time. Weather can change rapidly. A location's weather depends on air temperature; air pressure; fog; humidity; cloud cover; precipitation; wind speed and direction. All of these are directly related to the amount of energy that is in the system and where that energy is. The ultimate source of this energy is the sun.

Climate is the average of a region's weather over time. The climate for a particular place is steady, and changes only very slowly. Climate is determined by many factors, including the angle of the Sun, the likelihood of cloud cover, and the air pressure. All of these factors are related to the amount of energy that is found in that location over time.

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HUMIDITY

Humidity is the amount of water vapor in the air in a particular spot. We usually use the term to mean **relative humidity**, the percentage of water vapor a certain volume of air is holding relative to the maximum amount it can contain. If the humidity today

is 80%, it means that the air contains 80% of the total amount of water it can hold at that temperature. What will happen if the humidity increases to more than 100%? The excess water condenses and forms precipitation.

Since warm air can hold more water vapor than cool air, raising or lowering temperature can change air's relative humidity. The temperature at which air becomes saturated with water is called the air's dew point. This term makes sense, because water condenses from the air as dew, if the air cools down overnight and reaches 100% humidity.



CLOUDS

Clouds have a big influence on weather by preventing solar radiation from reaching the ground; absorbing warmth that is re-emitted from the ground; and as the source of precipitation.

When there are no clouds, there is less insulation. As a result, cloudless days can be extremely hot, and cloudless nights can be very cold. For this reason, cloudy days tend to have a lower range of temperatures than clear days.

There are a variety of conditions needed for clouds to form. First, clouds form when air reaches its dew point. This can happen in two ways: (1) Air temperature stays the same but humidity increases. This is common in locations that are warm and humid. (2) Humidity can remain the same, but temperature decreases. When the air cools enough to reach 100% humidity, water droplets form. Air cools when it comes into contact with a cold surface or when it rises.

Rising air creates clouds when it has been warmed at or near the ground level and then is pushed up over a mountain or mountain range or is thrust over a mass of cold, dense air. Water vapor is not visible unless it condenses to become a cloud. Water vapor condenses around a nucleus, such as dust, smoke, or a salt crystal. This forms a tiny liquid droplet. Billions of these water droplets together make a cloud.

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Clouds are classified in several ways. The most common classification used today divides clouds into four separate cloud groups, which are determined by their altitude and if precipitation is occurring or not.

High-level clouds form from ice crystals where the air is extremely cold and can hold little water vapor. **Cirrus**, **cirrostratus**, and **cirrocumulus**are all names of high clouds. Cirrocumulus clouds are small, white puffs that ripple across the sky, often in rows. Cirrus clouds may indicate that a storm is coming.

Middle-level clouds, including **altocumulus** and **altostratus** clouds, may be made of water droplets, ice crystals or both, depending on the air temperatures. Thick and broad altostratus clouds are gray or blue-gray. They often cover the entire sky and usually mean a large storm, bearing a lot of precipitation, is coming.

Low-level clouds are nearly all water droplets. **Stratus**, **stratocumulus** and **nimbostratus** clouds are common low clouds. Nimbostratus clouds are thick and dark that produce precipitation. Clouds with the prefix 'cumulo-' grow vertically instead of horizontally and have their bases at low altitude and their tops at high or middle altitude. Clouds grow vertically when strong unstable air currents are rising upward. Common clouds include **cumulus humilis**, **cumulus mediocris**, **cumulus congestus**, and **cumulonimbus**.

To learn more about the various types of cloud formations from the National Oceanic and Atmospheric Administration (NOAA), click here.

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FOG

Fog is a cloud located at or near the ground . When humid air near the ground cools below its dew point, fog is formed. The several types of fog that each form in a different way.

Radiation fog forms at night when skies are clear and the relative humidity is high. As the ground cools, the bottom layer of air cools below its dew point. Tule fog is an extreme form of radiation fog found in some regions. San Francisco, California, is famous for its summertime **advection fog**. Warm, moist Pacific Ocean air blows over the cold California current and cools below its dew point. Sea breezes bring the fog onshore. **Steam fog**appears in autumn when cool air moves over a warm lake. Water evaporates from the lake surface and condenses as it cools, appearing like steam. Warm humid air travels up a hillside and cools below its dew point to create **upslope fog**.



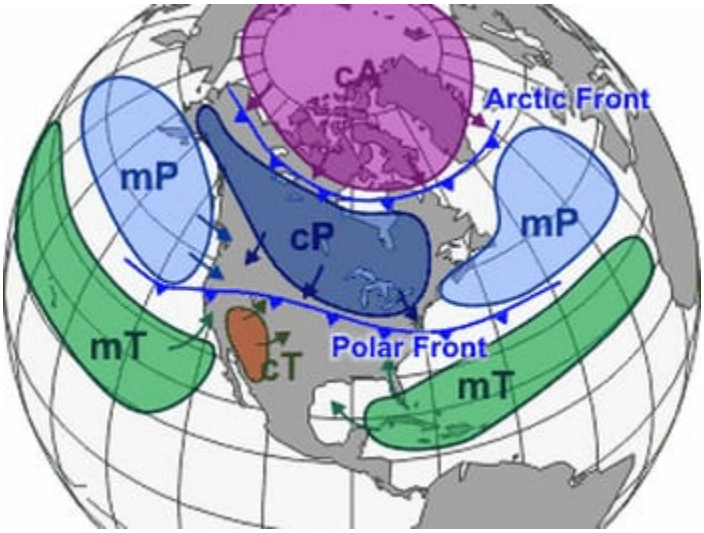
PRECIPITATION

Precipitation is an extremely important part of weather. Some precipitation forms in place. The most common precipitation comes from clouds. Rain or snow droplets grow as they ride air currents in a cloud and collect other droplets. They fall when they become heavy enough to escape from the rising air currents that hold them up in the cloud. One million cloud droplets will combine to make only one rain drop ! If temperatures are cold, the droplet will hit the ground as a snowflake.

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Air Masses

An **air mass** is a large mass of air that has similar characteristics of*temperature* and *humidity* within it. An air mass acquires these characteristics above an area of land or water known as its source region. When the air mass sits over a region for several days, or longer, it picks up the distinct temperature and humidity characteristics of that region.	An interactive or media element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/es/?p=140



AIR MASS FORMATION

Where an air mass receives it's characteristics of temperature and humidity is called the **source region**. Air masses are slowly pushed along by high-level winds, when an air mass moves over a new region, it shares its temperature and humidity with that region. So the temperature and humidity of a particular location depends partly on the characteristics of the air mass that sits over it.

Storms arise if the air mass and the region it moves over have different characteristics. For example, when a colder air mass moves over warmer ground, the bottom layer of air is heated. That air rises, forming clouds, rain, and sometimes thunderstorms. How would a moving air mass form an inversion? When a warmer air mass travels over colder ground, the bottom layer of air cools and, because of its high density, is trapped near the ground.

In general, cold air masses tend to flow toward the equator and warm air masses tend to flow toward the poles. This brings heat to cold areas and cools down areas that are warm. It is one of the many processes that act towards balancing out the planet's temperatures. Air masses are slowly pushed along by high-level winds. When an air mass moves over a new region, it shares its temperature and humidity with that region. So the temperature and humidity of a particular location depends partly on the

characteristics of the air mass that sits over it. Air masses are classified based on their temperature and humidity characteristics. Below are examples of how air masses are classified over North America.

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Weather Front

The rest of this section will be devoted to four types of fronts. Three of these fronts move and one is stationary. With cold fronts and warm fronts, the air mass at the leading edge of the front gives the front its name. In other words, a cold front is right at the leading edge of moving cold air and a warm front marks the leading edge of moving warm air.

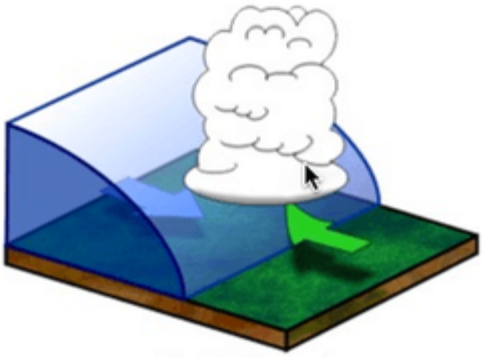
When two air masses meet together, the boundary between the two is called a **weather front**. At a front, the two air masses have different densities, based on temperature, and do not easily mix. One air mass is lifted above the other, creating a low pressure zone. If the lifted air is moist, there will be condensation and precipitation. Winds are common at a front. The greater the temperature difference between the two air masses, the stronger the winds will be. Fronts are the main cause of stormy weather.	An interactive or media element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/es/?p=140



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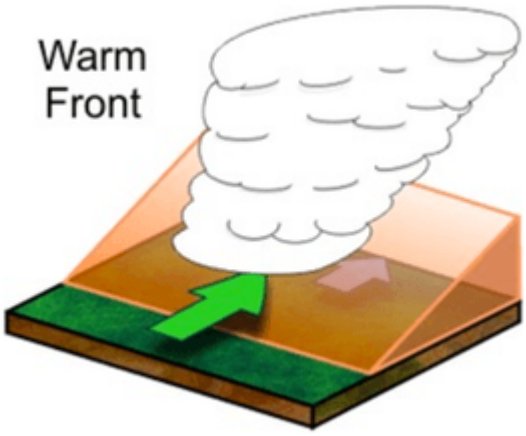
At a **stationary fron**t the air masses do not move. A front may become stationary if an air mass is stopped by a barrier, such as a mountain range.

A stationary front may bring days of rain, drizzle, and fog. Winds usually blow parallel to the front, but in opposite directions. After several days, the front will likely break apart. When a cold air mass takes the place of a warm air mass, there is a cold front.



COLD FRONTS

Imagine that you are standing in one spot as a **cold front** approaches. Along the cold front, the denser, cold air pushes up the warm air, causing the air pressure to decrease. If the humidity is high enough, some types of cumulus clouds will grow. High in the atmosphere, winds blow ice crystals from the tops of these clouds to create cirrostratus and cirrus clouds. At the front, there will be a line of rain showers, snow showers, or thunderstorms with blustery winds. A **squall line** is a line of severe thunderstorms that forms along a cold front. Behind the front is the cold air mass. This mass is drier so precipitation stops. The weather may be cold and clear or only partly cloudy. Winds may continue to blow into the low pressure zone at the front. The weather at a cold front varies with the season.



WARM FRONTS

Along a **warm front**, a warm air mass slides over a cold air mass. When warm, less dense air moves over the colder, denser air, the atmosphere is relatively stable.

Imagine that you are on the ground in the wintertime under a cold winter air mass with a warm front approaching. The transition from cold air to warm air takes place over a long distance so the first signs of changing weather appear long before the front is actually over you. Initially, the air is cold: the cold air mass is above you and the warm air mass is above it. High cirrus clouds mark the transition from one air mass to the other.

Over time, cirrus clouds become thicker and cirrostratus clouds form. As the front approaches, altocumulus and altostratus clouds appear and the sky turns gray. Since it is winter, snowflakes fall. The clouds thicken and nimbostratus clouds form. Snowfall increases. Winds grow stronger as the low pressure approaches. As the front gets closer, the cold air mass is just above you but the warm air mass is not too far above that. The weather worsens. As the warm air mass approaches, temperatures rise and snow turns to sleet and freezing rain. Warm and cold air mix at the front, leading to the formation of stratus clouds and fog.

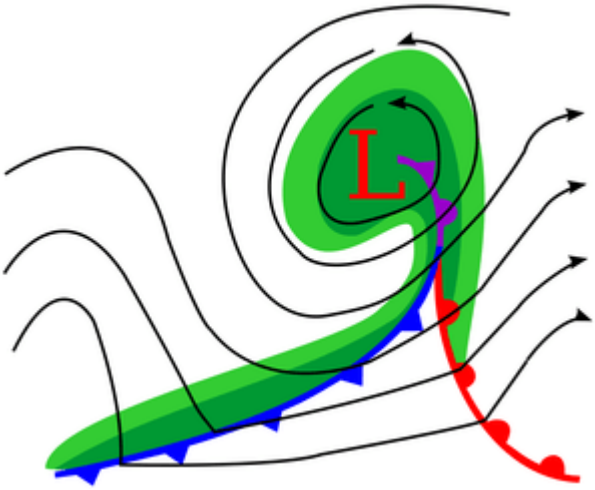


OCCLUDED FRONTS

An **occluded front** usually forms around a low pressure system. The occlusion starts when a cold front catches up to a warm front. The air masses, in order from front to back, are cold, warm, and then cold again.

Coriolis Effect curves the boundary where the two fronts meet towards the pole. If the air mass that arrives third is colder than either of the first two air masses, that air mass slip beneath them both. This is called a cold occlusion. If the air mass that arrives third is warm, that air mass rides over the other air mass. This is called a warm occlusion.

The weather at an occluded front is especially fierce right at the occlusion. Precipitation and shifting winds are typical. The Pacific Coast has frequent occluded fronts.



Remember, a weather front is basically the boundary between two air masses of different densities. At the center of each air mass is typically a high pressure. This means that weather is typically sunny within air masses, but their temperatures could vary with the season and humidity could vary based on the source region of the air mass.

Now more often than not, these weather fronts are not isolated events. Often times, they are part of a larger rotating system called a mid-latitude cyclone. This type of cyclone will be discussed later in this chapter, but as an introduction it is a low pressure system that is usually mixing warmer air from the south (in the Northern Hemisphere) and colder air from the north.

Thunderstorms



Weather happens every day, but only some days have storms. Storms vary immensely depending on whether they're warm or cold, coming off the ocean or off a continent, occurring in summer or winter, and many other factors. The effects of storms also vary depending on whether they strike a populated area or a natural landscape. Hurricane Katrina is a good example, since the flooding after the storm severely damaged New Orleans, while a similar storm in an unpopulated area would have done little damage.

Thunderstorms are extremely common: Worldwide there are 14 million per year; that's 40,000 per day! Most drop a lot of rain on a small area quickly, but some are severe and highly damaging. They form when ground temperatures are high, ordinarily in the late afternoon or early evening in spring and summer. The two figures below show two stages of thunderstorm buildup.

THUNDERSTORM GENESIS

All thunderstorms go through a three-stage life cycle. The first stage is called the **cumulus stage**, where an air parcel is forced to rise, cool, and condense, called the lower condensation level, to develop into a cumulus cloud. The process of water vapor condensing into liquid water releases large quantities of latent heat, which makes the air within the cloud warmer, and unstable causing the cloud continues to grow upward like a hot air balloon. These rising air parcels, called updrafts, prevent precipitation from falling from the cloud. But once the precipitation becomes too heavy for the updrafts to hold up, the moisture begins to fall creating downdrafts within the cloud. The downdrafts also begin to pull cold, dry air from outside the cloud toward the ground in a process called**entrainment**.

Once the precipitation begins to fall from the cloud, the storm has reached the **mature stage**. During this stage, updrafts and downdrafts exist side-by-side and the cumulonimbus is called a **cell**. If the updrafts reach the top of the troposphere, the cumulus cloud will begin to spread outward creating a defined **anvil**. At the same time, the downdrafts spread within the cloud and at first make the cloud become wider, but eventually overtaking the updrafts. Cool downdrafts form when precipitation and the cool air from entrainment are dragged down to the lower regions of a thunderstorm. It is also during the mature stage when the storm is most intense producing strong, gusting winds, heavy precipitation, lightning, and possibly small hail.

Once the downdrafts overtake the updrafts, which also prevents the release of latent heat energy, the thunderstorm will begin to weaken into the third and final stage, called the **dissipating stage**. During this stage, light precipitation and downdrafts become the dominate feature within the cloud as it weakens. In all, only twenty percent of the moisture within the cloud fell as precipitation whereas the other eighty percent evaporates back into the atmosphere.

- spring and summer: The air is unstable so thunderstorms or tornadoes may form.
- spring: If the temperature gradient is high, strong winds blow.
- autumn: Strong rains fall over a large area.

- winter: The cold air mass is likely to have formed in the frigid arctic so there are frigid temperatures and heavy snows.



- With severe thunderstorms, the downdrafts are so intense that when they hit the ground it sends warm air from the ground upward into the storm. The warm air gives the convection cells more energy. Rain and hail grow huge before gravity pulls them to Earth. Severe thunderstorms can last for hours and can cause a lot of damage because of high winds, flooding, intense hail, and tornadoes.

Thunderstorms can form individually or in squall lines along a cold front. In the United States, squall lines form in spring and early summer in the Midwest where the maritime tropical (mT) air mass from the Gulf of Mexico meets the continental polar (cP) air mass from Canada.

So much energy collects in cumulonimbus clouds that a huge release of electricity, called **lightning**, may result. The electrical discharge may be between one part of the cloud and another, two clouds, or a cloud and the ground.

Lightning heats the air so that it expands explosively. The loud clap is thunder. Light waves travel so rapidly that lightning is seen instantly. Sound waves travel much more slowly, so a thunderclap may come many seconds after the lightning is spotted. Thunderstorms kill approximately 200 people in the United States and injure about 550 Americans per year, mostly from lightning strikes. Have you heard the common misconception that lightning doesn't strike the same place twice? In fact, lightning strikes the New York City's Empire State Building about 100 times per year.	An interactive or media element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/es/?p=140

Tornadoes



Tornadoes, also called twisters, are fierce products of severe thunderstorms. As air in a thunderstorm rises, the surrounding air races in to fill the gap, forming a funnel. A tornado lasts from a few seconds to several hours. The average wind speed is about 177 kph (110 mph), but some winds are much faster. A tornado travels over the ground at about 45 km per hour (28 miles per hour) and goes about 25 km (16 miles) before losing energy and disappearing.

An individual tornado strikes a small area, but it can destroy everything in its path. Most injuries and deaths from tornadoes are caused by flying debris. In the United States an average of 90 people are killed by tornadoes each year. The most violent two percent of tornadoes account for 70% of the deaths by tornadoes.

Tornadoes form at the front of severe thunderstorms. Lines of these thunderstorms form in the spring where where maritime tropical (mT) and continental polar (cP) air masses meet. Although there is an average of 770 tornadoes annually, the number of tornadoes each year varies greatly.

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In late April 2011, the situation was ripe for the deadliest set of tornadoes in 25 years. In addition to the meeting of cP and mT mentioned above, the jet stream was blowing strongly in from the west. The result was more than 150 tornadoes reported throughout the day.

The entire region was alerted to the possibility of tornadoes in those late April days. But meteorologists can only predict tornado danger over a very wide region. No one can tell exactly where and when a tornado will touch down. Once a tornado is sighted on radar, its path is predicted and a warning is issued to people in that area. The exact path is unknown because tornado movement is not very predictable.

The intensity of tornadoes is measured on the Fujita Scale, which assigns a value based on wind speed and damage.

F-Scale	3 Second Gust (mph)	Damage
EF0 (Gale)	65-85	Light – tree branches fall and chimneys may collapse
EF1 (Weak)	86-110	Moderate – mobile homes, automobiles pushed aside
EF2 (Strong)	111-135	Considerate – roofs torn off houses, large trees uprooted
EF3 (Severe)	136-165	Severe – houses torn apart, trees uprooted, cars lifted
EF4 (Devastating)	166-200	Devastating – houses leveled, cars thrown
EF5 (Incredible)	Over 200	Incredible – structures fly, cars become missiles

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Cyclones



Cyclones can be the most intense storms on Earth. A **cyclone** is a system of winds rotating counterclockwise in the Northern Hemisphere around a low pressure center. The swirling air rises and cools, creating clouds and precipitation.

There are two types of cyclones: middle latitude (mid-latitude) cyclones and tropical cyclones. Mid-latitude cyclones are the main cause of winter storms in the middle latitudes. Tropical cyclones are also known as hurricanes.

An **anticyclone** is the opposite of a cyclone. An anticyclone's winds rotate clockwise in the Northern Hemisphere around a center of high pressure. Air comes in from above and sinks to the ground. High pressure centers generally have fair weather.



MID-LATITUDE CYCLONES

Mid-latitude cyclones, sometimes called **extratropical cyclones**, form at the polar front when the temperature difference between two air masses is large. These air masses blow past each other in opposite directions. Coriolis Effect deflects winds to the right in the Northern Hemisphere, causing the winds to strike the polar front at an angle. Warm and cold fronts form next to each other. Most winter storms in the middle latitudes, including most of the United States and Europe, are caused by mid-latitude cyclones.

The warm air at the cold front rises and creates a low pressure cell. Winds rush into the low pressure and create a rising column of air. The air twists, rotating counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Since the rising air is moist, rain or snow falls.

Mid-latitude cyclones form in winter in the mid-latitudes and move eastward with the westerly winds. These two- to five-day storms can reach 1,000 to 2,500 km (625 to 1,600 miles) in diameter and produce winds up to 125 km (75 miles) per hour. Like tropical cyclones, they can cause extensive beach erosion and flooding.

Mid-latitude cyclones are especially fierce in the mid-Atlantic and New England states where they are called **nor'easters**, because they come from the northeast. About 30 nor'easters strike the region each year.



HURRICANES

Tropical cyclones have many names. They are called hurricanes in the North Atlantic and eastern Pacific oceans, typhoons in the western Pacific Ocean, tropical cyclones in the Indian Ocean, and willi-willi's in the waters near Australia. By any name, they are the most damaging storms on Earth.

Hurricanes arise in the tropical latitudes (between 10 degrees and 25 degrees N) in summer and autumn when sea surface temperature are 28 degrees C (82 degrees F) or higher. The warm seas create a large humid air mass. The warm air rises and forms a low pressure cell, known as a tropical depression. Thunderstorms materialize around the tropical depression.

If the temperature reaches or exceeds 28 degrees C (82 degrees F) the air begins to rotate around the low pressure (counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere). As the air rises, water vapor condenses, releasing energy from latent heat. If wind shear is low, the storm builds into a hurricane within two to three days.

Hurricanes are huge with high winds. The exception is the relatively calm eye of the storm where air is rising upward. Rainfall can be as high as 2.5 cm (1″) per hour, resulting in about 20 billion metric tons of water released daily in a hurricane. The release of latent heat generates enormous amounts of energy, nearly the total annual electrical power consumption of the United States from one storm. Hurricanes can also generate tornadoes.

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Hurricanes are huge with high winds. The exception is the relatively calm eye of the storm where air is rising upward. Rainfall can be as high as 2.5 cm (1″) per hour, resulting in about 20 billion metric tons of water released daily in a hurricane. The release of latent heat generates enormous amounts of energy, nearly the total annual electrical power consumption of the United States from one storm. Hurricanes can also generate tornadoes.

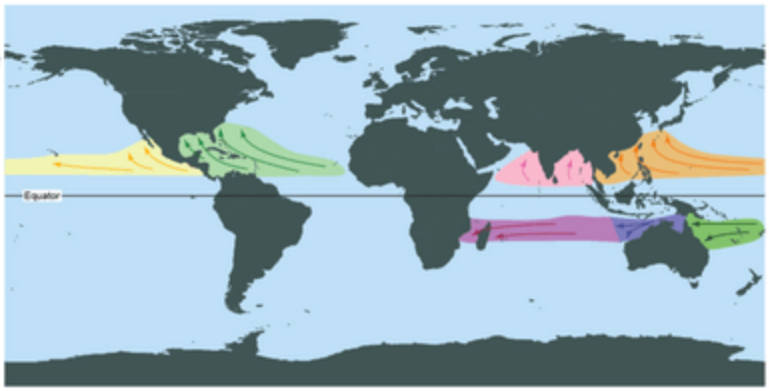
Hurricanes are strange creatures because they are deadly monsters, yet have a gentle, but cold heart. The anatomy of a hurricane is fairly simple, though the processes involved are quite complex. As a low pressure disturbance forms, the warm, moist air rushes towards the low pressure in order to rise upward to form towering thunderstorms. Around the low pressure disturbance is a wall of clouds called an **eye wall**. Within the eye wall, the wind speeds are greatest, the clouds are the tallest, atmospheric pressure is at its lowest, and precipitation is most intense.

At the center or heart of the hurricane is called the **eye**. Within the eye of a hurricane, winds are light, precipitation is minimal, and occasionally the skies above are clear. It is the calm region of the tropical storm, but that is what makes it so dangerous. Many people tend to go outside as the eye moves overhead because they believe the storm is over. But what some don't realize is that "round two" is coming from behind.

Moving away from the eye wall are organized, intense thunderstorms, called **spiral rain bands**, that rotate around and toward the storm's eye wall. These rain bands are the first

Hurricanes are assigned to categories based on their wind speed. The categories are listed on the **Saffir-Simpson Scale**.

Category	**MPH**	**Estimated Damage**
1 (Weak)	74-95	Above normal; no read damage to structures
2 (Moderate)	96-110	Some property damage; considerable damage to vegetation
3 (Strong)	111-130	Some buildings damaged; mobile homes destroyed
4 (Very strong)	131-156	Complete roof failure on small residences; major beach erosion of beach areas
5 (Devastating)	Over 156	Complete roof and some building failure on most residential and industrial buildings



Hurricanes move with the prevailing winds. In the Northern Hemisphere, theyoriginate in the trade winds and move to the west. When they reach the latitude of the westerlies, they switch direction and travel toward the north or northeast. Hurricanes may cover 800 km (500 miles) in one day.

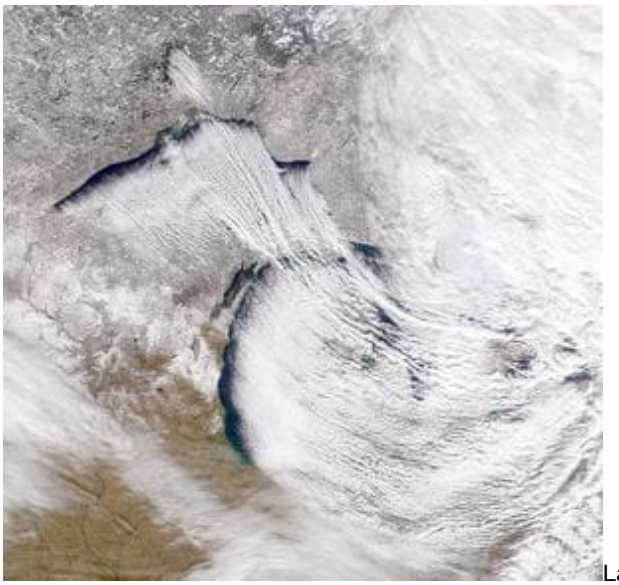
Damage from hurricanes comes from the high winds, rainfall, and storm surge.**Storm surge** occurs as the storm's low pressure center comes onto land, causing the sea level to rise unusually high. A storm surge is often made worse by the hurricane's high winds blowing seawater across the ocean onto the shoreline. Flooding can be devastating, especially along low-lying coastlines such as the Atlantic and Gulf Coasts. Hurricane Camille in 1969 had a 7.3 m (24 foot) storm surge that traveled 125 miles (200 km) inland.

Hurricanes typically last for 5 to 10 days. Over cooler water or land, the hurricane's latent heat source shut downs and the storm weakens. When a hurricane disintegrates, it is replaced with intense rains and tornadoes.

There are about 100 hurricanes around the world each year, plus many smaller tropical storms and tropical depressions. As people develop coastal regions, property damage from storms continues to rise. However, scientists are becoming better at predicting the paths of these storms and fatalities are decreasing. There is, however, one major exception to the previous statement: Hurricane Katrina.

For over a decade, the conversation in the United States over hurricanes was directed toward Hurricane Katrina. But in late October 2012, a Category 3 hurricane called Hurricane Sandy, sometimes called Superstorm Sandy, struck the eastern coast of the United States. It is estimaged that the storm system caused $68 billion in damage and killed nearly 300 people. What made Hurricane Sandy different from most tropical storms was how powerful it was so late in the hurricane season. The concern is that as the planet warms from anthropogenic (human-enhanced) climate change, the oceans will likely warm up allow hurricanes to become stronger, travel farther toward the poles, and the hurricane season last longer.	An interactive or media element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/es/?p=140

To view an interactive map on hurricanes created by the National Oceanic and Atmospheric Administration, click here.


Lake-effect Snow off the Great Lakes.

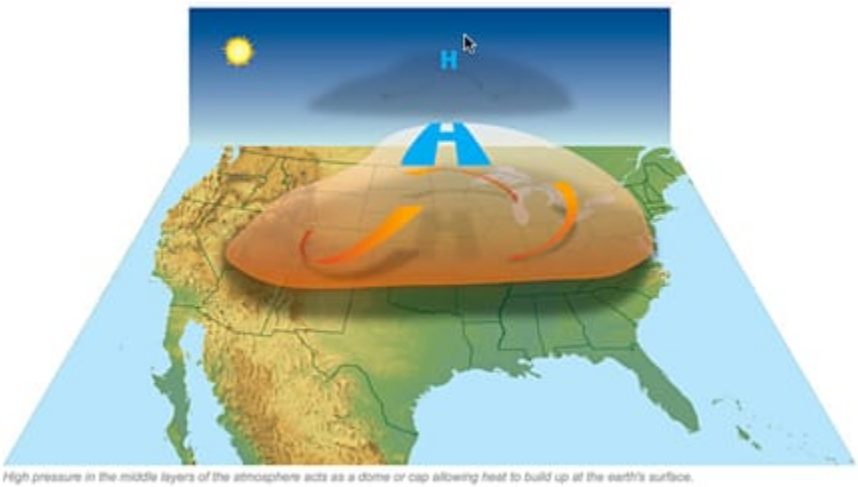
BLIZZARDS AND LAKE EFFECTS

A **blizzard** is distinguished by certain conditions:

- Temperatures below -7 degrees C (20 degrees F); -12 degrees C (10 degrees F) for a severe blizzard.
- Winds greater than 56 kmh (35 mph); 72 kmh (45 mph) for a severe blizzard.
- Snow so heavy that visibility is 2/5 km (1/4 mi) or less for at least 3 hours; near zero visibility for a severe blizzard.

Blizzards happen across the middle latitudes and toward the poles, usually as part of a mid-latitude cyclone. Blizzards are most common in winter, when the jet stream has traveled south and a cold, northern air mass comes into contact with a warmer, semitropical air mass. The very strong winds develop because of the pressure gradient between the low pressure storm and the higher pressure west of the storm. Snow produced by the storm gets caught in the winds and blows nearly horizontally. Blizzards can also produce **sleet** or **freezing rain**.

In winter, a continental polar air mass travels down from Canada. As the frigid air travels across one of the Great Lakes, it warms and absorbs moisture. When the air mass reaches the leeward side of the lake, it is very unstable and it drops tremendous amounts of snow. This **lake-effect snow** falls on the snowiest, metropolitan areas in the United States: Buffalo and Rochester, New York.



High pressure in the middle layers of the atmosphere acts as a dome or cap allowing heat to build up at the earth's surface.

HEAT WAVES

Even more insidious are the deadliest weather phenomena, a **heat wave**. A heat wave is different for different locations; it is a

long period of hot weather, at least 86 degrees F (30 degrees C) for at least three days in cooler locations but much more in hotter locations. Heat waves have increased in frequency and duration in recent years.

What do you think caused the heat wave in the image below? A high pressure zone kept the jet stream further north than normal for August.

Attributions

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5.3: Extreme Weather Events

The year 2020 was a record year for tropical storms in the Atlantic basin. There were 30 named storms, which is two higher than the previous record of 28 (in 2005), and 2005 and 2020 are the only years in which the Greek alphabet had to be used for Atlantic storm names because there aren't enough letters in the Roman alphabet. Of the 28 storms 2020, 14 were classified as hurricanes and 6 were classified as major hurricanes, both of those numbers are just 1 shy of the record. Five of the 2020 Atlantic tropical storms can be seen—active at the same time—on Figure 15.3.1.

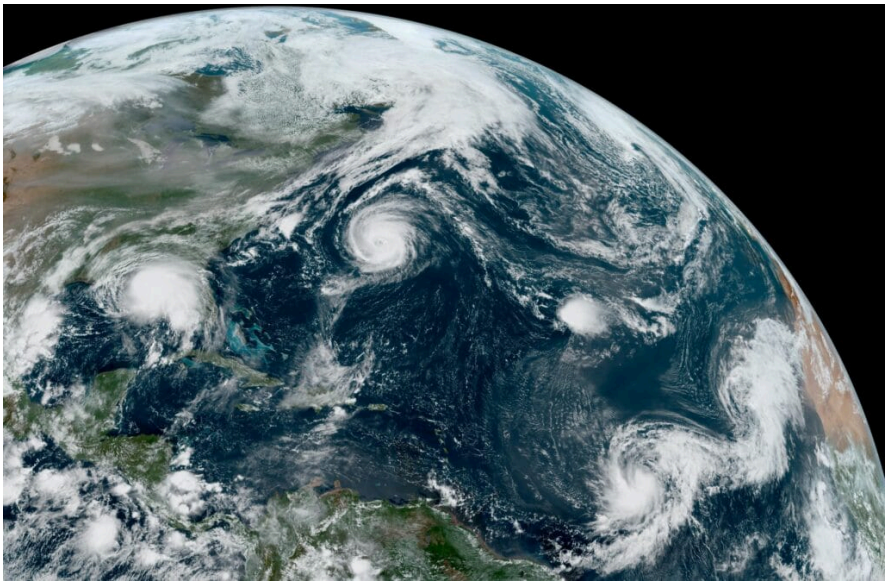


Figure 15.3.1 Tropical Storm Vicky (left, over Florida), Hurricane Paulette (centre left), the Beginning of Tropical Storm Rene (in the mid-Atlantic), Hurricane Teddy (Southeast of Rene), and Tropical Storm Vicky (Off the East Coast of Africa), September 14th, 2020

There are two main reasons that 2020 was such a remarkable year for Atlantic tropical storms. One is that it wasn't a strong El Niño year (Atlantic tropical storms are less likely to develop under strong El Niño conditions). The other is that our climate is getting hotter, there is more heat stored in the surface waters of the ocean, and that heat is what powers tropical storms. The correlation between the global temperature and the number of tropical storms per year is illustrated on Figure 15.3.2. The numbers of both tropical storms and temperatures were relatively flat from 1880 to 1930, but both values have climbed steadily and steeply since about 1960.

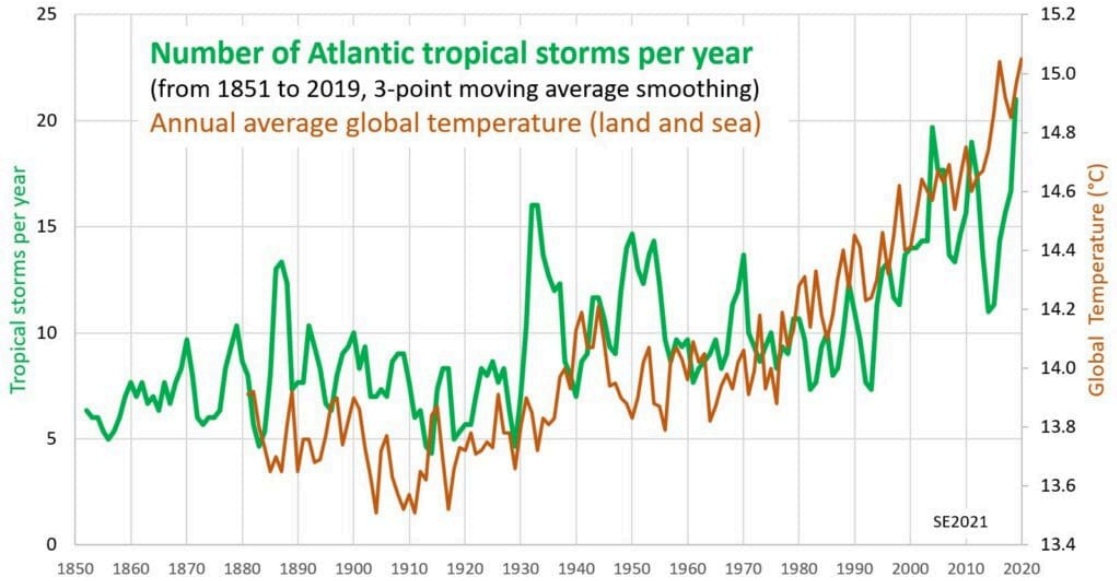


Figure 15.3.2 Number of Tropical Storms per Year Since 1851 (in green), and Average Global Temperatures Since 1880 (in orange)

Large storms—not just tropical storms—have several important implications for geological processes, including destruction in coastal areas because of the storm surge, flooding inland because of intense rainfall, and triggering of slope failures because intense rainfall has weakened material on slopes.
Storm surge—the increase in water level when a large storm approaches land—results from three main factors:

1. The strong winds push water towards the coast, forcing it to "pile up" against the shore potentially reaching several metres above normal sea level,
2. The very low barometric pressure associated with large storms creates a bulge in the water surface, and for a typical intense storm this bulge could be over 1 m above the surrounding sea surface, and
3. Large waves can add several metres more height to the surge.

Some of the largest storm surges have been over 8 metres above typical high tide levels, and those have caused extreme damage, such as that visible on Figure 15.3.3, showing coastal Texas in 2008. If you look closely at that image, you can see that only a handful of buildings remain (out of several hundred), a bridge has been damaged, a highway has been washed out in some areas, and parts of the land have been severely eroded. What was formerly a straight coast (on the right) is now significantly embayed with evidence of damage to structures designed to prevent coastal erosion.



Figure 15.3.3 Storm Surge Damage on the Bolivar Peninsula, Texas, from Hurricane Ike, September 2008

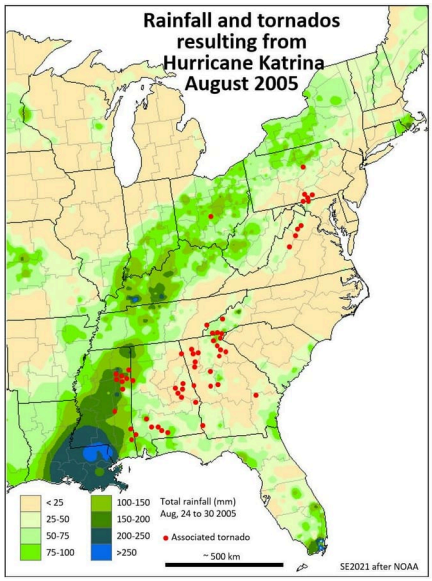


Figure 15.3.4 Rainfall and Tornadoes Along the Inland Track of Hurricane Katrina in August 2005

We typically associate tropical storm damage and casualties with heavy winds, giant waves and storm surges, but in fact most deaths associated with tropical storms (59%) result from freshwater flooding. Tropical storms carry massive amounts of water, and a lot of that falls as torrential rain after they cross over onto land. As shown on Figure 15.3.4, heavy rainfall associated with Hurricane Katrina in 2005 extended across at least 8 states and even into southern Canada. Much of the resulting flooding occurred near to the coast in Louisiana and Mississippi, but it also affected areas over a thousand kilometres inland. A total of 62 tornadoes, which led to two deaths and $23 million in damages, were spawned from Hurricane Katrina as it spun across the continent and those are also shown on Figure 15.3.4. As described in Section 13.2, Hurricane Harvey dumped record-breaking amounts of rain on parts of Texas in August 2017, leading to 100 deaths and over $125 billion in damages.

Heavy rainfall leads to flooding, of course, but one of the other consequences is slope failure. Soaking with water from a tropical storm and then seismic shaking led to the occurrence of thousands of slope failures in the Sapporo area of Hokkaido, Japan in September 2018, as shown on Figure 5.1.7 in Section 5.1. The region, which was already wet from summer rain, was further soaked with rain from Typhoon Jebi on September 4th. On September 6th it was shaken by a M6.6 earthquake which triggered over 6000 slumps, mud flows and debris flows in weathered volcanic soils on both steep and moderate slopes. There were 41 deaths related to the slope failures.

Figure 15.3.6 provides a view of a small part of the area affected by the September 2018 slope failures on Hokkaido. Several types of outcomes are evident in this small area, including runout onto farmland (A and B), runout into buildings and a road (C), blockage of a stream (D, in this case the Atsuma River), and a long runout train (about 2 km) from several separate failures along both sides of a narrow valley (E).



Figure 15.3.5 Detail of the September 6th 2018 Slope Failures in the Sapporo Area of Japan (see text for explanation of letters).

While tropical storms and other climate-change related phenomena can lead to extreme precipitation events, climate change can also contribute to intense drought conditions. One example of that is the significant drought that has affected the southwestern region of the US since about 2012, contributing the unprecedented wildfire episodes of recent years, and especially the summer of 2020 (as described in the Chapter 15 Introduction). Another example is the El Niño phenomenon (a.k.a. El Niño Southern Oscillation or ENSO). ENSO varies on a cycle of between 2 and 7 years and leads to extreme weather conditions in many parts of the world. In Australia the El Niño phase brings hot and dry weather, while the opposing La Niña phase typically brings wet conditions (and often serious flooding). Under the hot and dry El Niño conditions there is a high probability of severe wildfires, especially in the eastern part of the country. Interestingly, Australia's record-breaking fire season of late 2019 to early 2020 took place during an ENSO-neutral period (neither strong La Niña nor strong El Niño), although it was a particularly hot year globally.

In summary, while the ongoing increase in global temperatures, and the long-term changes to precipitation patterns continue to have geological impacts, shorter-term events like the ENSO cycle and tropical storms, which are becoming more severe because of climate change, will likely punctuate the climate-change narrative with extreme events that each result in billions of dollars of damage. A NOAA summary of damaging weather events in the US during 2020 is provided on Figure 15.3.6.[1] In that year there were 22 billion-dollar-plus weather disasters, with a combined economic cost of $95 billion. The severity of many of these events can be attributed to climate change, and most of these types of events have implications for environmental geology.

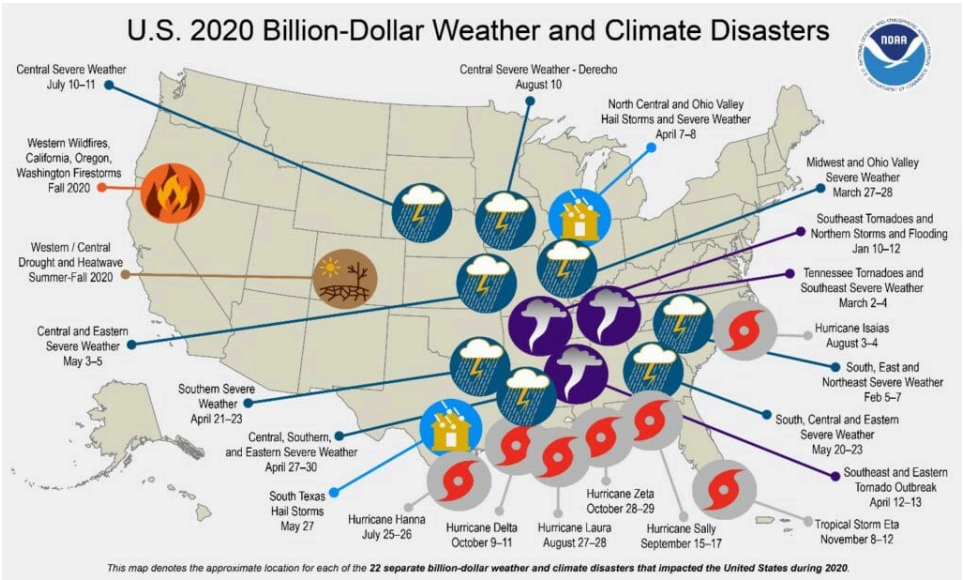


Figure 15.3.6 NOAA Summary of 22 Weather Events During 2020. Each had economic costs of over a billion dollars.

Media Attributions

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- **Figure 15.3.6** Fast Facts: Hurricane Costs by NOAA, 2021, public domain, https://coast.noaa.gov/states/fast-f...ane-costs.html

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1. US National Oceanographic and Atmospheric Administration (2021). U.S. 2020 Billion-dollar weather and climate disasters [graphic]. In *Fast facts: Hurricane costs*. https://www.noaa.gov/ ↩

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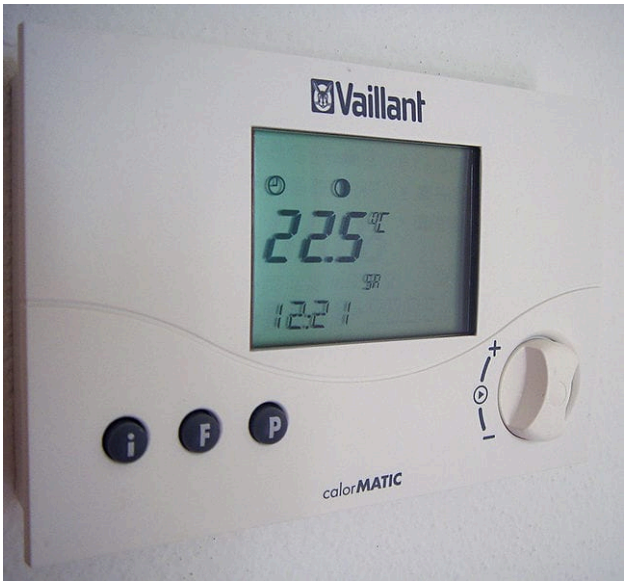
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5.4: Collecting Weather Data and Forecasting Weather

Weather forecasts are better than they ever have been. According to the World Meteorological Organization (WMO), a 5-day weather forecast today is as reliable as a 2-day forecast was 20 years ago! This is because forecasters now use advanced technologies to gather weather data, along with the world's most powerful computers. Together, the data and computers produce complex models that more accurately represent the conditions of the atmosphere. These models can be programmed to predict how the atmosphere and the weather will change. Despite these advances, weather forecasts are still often incorrect. Weather is extremely difficult to predict because it is a complex and chaotic system.

To make a weather forecast, the conditions of the atmosphere must be known for that location and for the surrounding area. Temperature, air pressure, and other characteristics of the atmosphere must be measured and the data collected.

Thermometers



Thermometers measure temperature. In an old-style mercury thermometer, mercury is placed in a long, very narrow tube with a bulb. Because mercury is temperature sensitive, it expands when temperatures are high and contracts when they are low. A scale on the outside of the thermometer matches up with the air temperature.Some modern thermometers use a coiled strip composed of two kinds of metal, each of which conducts heat differently. As the temperature rises and falls, the coil unfolds or curls up tighter. Other modern thermometers measure infrared radiation or electrical resistance. Modern thermometers usually produce digital data that can be fed directly into a computer.

Barometers

Meteorologists use **barometers** to measure air pressure. A barometer may contain water, air, or mercury, but like thermometers, barometers are now mostly digital. A change in barometric pressure indicates that a change in weather is coming. If air pressure rises, a high pressure cell is on the way and clear skies can be expected. If pressure falls, a low pressure cell is coming and will likely bring storm clouds. Barometric pressure data over a larger area can be used to identify pressure systems, fronts, and other weather systems.

Weather Stations

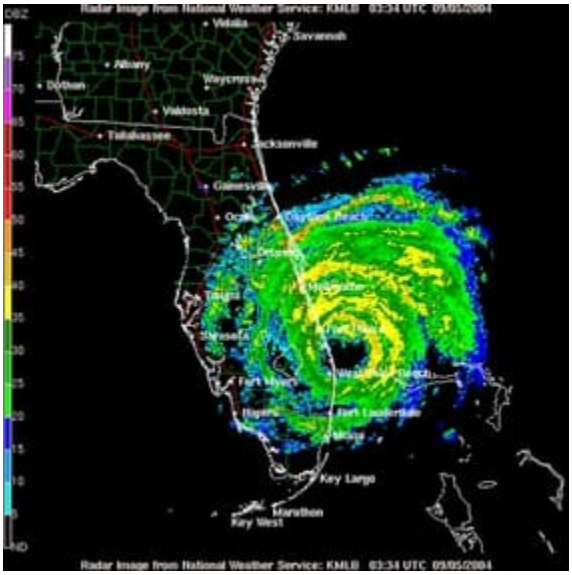
Weather stations contain some type of thermometer and barometer. Other instruments measure different characteristics of the atmosphere such as wind speed, wind direction, humidity, and amount of precipitation. These instruments are placed in various

locations so that they can check the atmospheric characteristics of that location. According to the WMO, weather information is collected from 15 satellites, 100 stationary buoys, 600 drifting buoys, 3,000 aircraft, 7,300 ships, and some 10,000 land-based stations. The official weather stations used by the National Weather Service is called the Automated Surface Observing System (ASOS).

Radiosondes

Radiosondes is a balloon that measures atmospheric characteristics, such as temperature, pressure, and humidity as they move through the air. Radiosondes in flight can be tracked to obtain wind speed and direction. Radiosondes use a radio to communicate the data they collect to a computer. Radiosondes are launched from about 800 sites around the globe twice daily to provide a profile of the atmosphere. Radiosondes can be dropped from a balloon or airplane to make measurements as they fall. This is done to monitor storms, for example, since they are dangerous places for airplanes to fly.

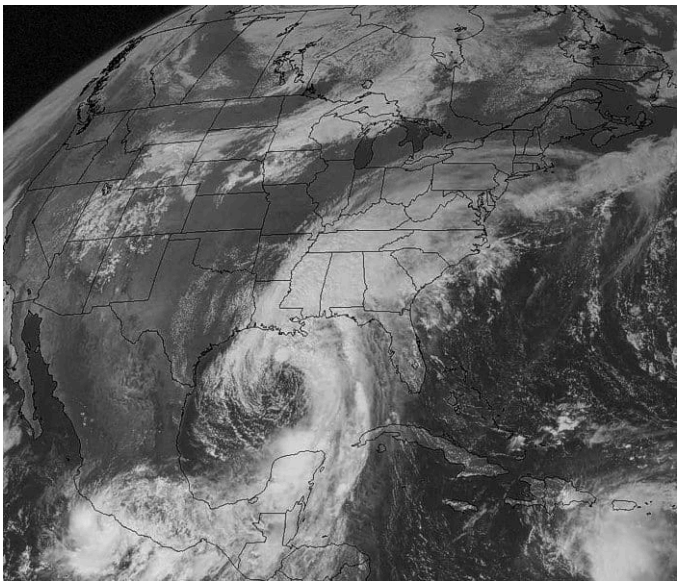
Radar



Radar stands for Radio Detection and Ranging. A transmitter sends out radio waves that bounce off the nearest object and then return to a receiver. Weather radar can sense many characteristics of precipitation: its location, motion, intensity, and the likelihood of future precipitation. Doppler radar can also track how fast the precipitation falls. Radar can outline the structure of a storm and can be used to estimate its possible effects.

Satellites

Weather satellites have been increasingly important sources of weather data since the first one was launched in 1952 and are the best way to monitor large scale systems, such as storms. Satellites are able to record long-term changes, such as the amount of ice cover over the Arctic Ocean in September each year.

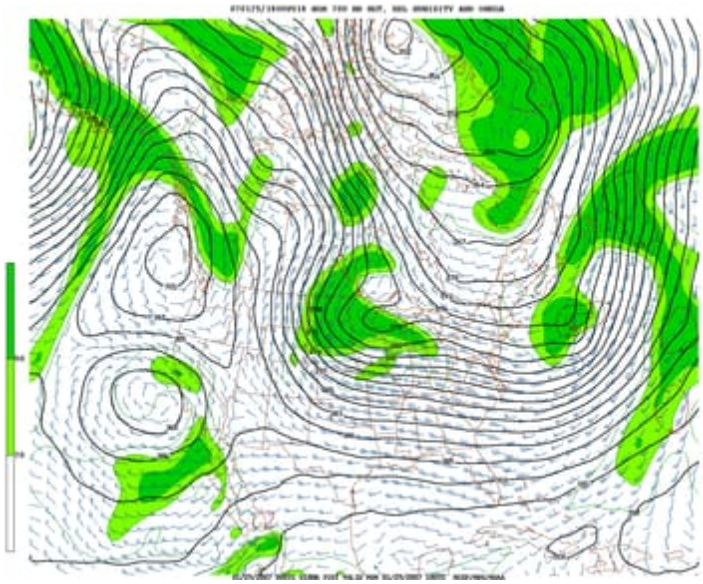


They also observe all energy from all wavelengths in the electromagnetic spectrum.The flagship of the National Weather Service is the Geostationary Operational Environmental Satellites (GOES). These satellites are the ones you see on the nightly news where it looks like the clouds are moving, but not the planet. That is because these satellites are “geo-fixed” on a particular location over Earth rotating around the planet as fast as Earth’s rotation at a distance of over 23,000 miles above the planet. There are basically three different types of GOES: visible, infrared, and water vapor. Visible light images record storms, clouds, fires, and smog. Infrared images record clouds, water and land temperatures, and features of the ocean, such as ocean currents**.** The final type of GOES imagery is water vapor. This type of imagery looks at the moisture content in the upper-half of the atmosphere. This is important for determining if clouds can grow to great heights like cumulonimbus thunderstorms.

The other type of satellite commonly used in weather forecasting is called a Polar Orbiting Environmental Satellites (POES). These types of satellites fly much lower to the earth, only about 530 miles, and orbit the planet pole-to-pole. You’ve probably seen these satellites at night when you see one crossing the sky. Look for their direction and odds are they are moving northward or southward toward each pole.

Just like the weather satellites on the news, you’ve seen these images often when you are looking at natural disasters like hurricanes or volcanic eruptions, wars like have occurred in Afghanistan, Iraq, or recently in Syria. Even the Malaysian flight that “disappeared” in the Indian Ocean for weeks was ultimately discovered using polar orbiting satellites. Common types of these satellites include: Landsat, MODIS, and the Tropical Rainfall Measuring Mission (TRMM).

Numerical Weather Prediction



The most accurate weather forecasts are made by advanced computers, with analysis and interpretation added by experienced meteorologists. These computers have up-to-date mathematical models that can use much more data and make many more calculations than would ever be possible by scientists working with just maps and calculators. Meteorologists can use these results to give much more accurate weather forecasts and climate predictions.

In Numerical Weather Prediction (NWP), atmospheric data from many sources are plugged into supercomputers running complex mathematical models. The models then calculate what will happen over time at various altitudes for a grid of evenly spaced locations. The grid points are usually between 10 and 200 kilometers apart. Using the results calculated by the model, the program projects weather further into the future. It then uses these results to project the weather still further into the future, as far as the meteorologists want to go. Once a forecast is made, it is broadcast by satellites to more than 1,000 sites around the world.

NWP produces the most accurate weather forecasts, but as anyone knows, even the best forecasts are not always right. Weather prediction is extremely valuable for reducing property damage and even fatalities. If the proposed track of a hurricane can be predicted, people can try to secure their property and then evacuate.

Weather maps

Weather maps, also called **synoptic maps**, simply and graphically depict meteorological conditions in the atmosphere from a spatial perspective. Weather maps may display only one feature of the atmosphere or multiple features. They can depict information from computer models or from human observations.

On a weather map, important meteorological conditions are plotted for each weather station. Metorologists use many different symbols as a quick and easy way to display information on the map.



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Once conditions have been plotted, points of equal value can be connected by isolines. Weather maps can have many types of connecting lines. For example:

- **Isotherms**, likes connecting points of equal temperature. They spatially show temperature gradients and can indicate the location of a front. In terms of precipitation, what does the 0 °C (32 °F) isotherm show?
- **Isobars** are lines of equal average air pressure at sea level. Closed isobars represent the locations of high and low pressure cells.
- **Isotachs** are lines of constant wind speed. Where the minimum values occur high in the atmosphere, tropical cyclones may develop. The highest wind speeds can be used to locate the jet stream.

Surface weather analysis maps are weather maps that only show conditions on the ground**.**

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6: CLIMATE AND CLIMATE CHANGE

6.1: Introduction to Climate Change and Objectives
6.2: The Sun – Earth Relationship and the Seasons
6.3: The Sun and the Earth-Moon System
6.4: Weather vs Climate
6.5: Earth's Heat Budget and the Greenhouse Effect
6.6: What Makes the Climate Change?
6.7: Prehistoric Climate Change and Proxys for Studying Past Climates
6.8: Anthropogenic Climate Change
6.9: Implications of Climate Change

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6.1: Introduction to Climate Change and Objectives

Introduction to Climate & Climate Change

This chapter focuses on understanding the causes and effects of long-term shifts in temperature and weather patterns, including those due to human activities such as burning fossil fuels and deforestation. Global climate science collects data from climate models, historical records, and current observations to predict future climate conditions and assess the impacts on natural systems and human societies. The consensus among scientists is that increasing greenhouse gas emissions are driving global warming, leading to significant environmental, economic, and health challenges worldwide.

We will explore the relationship between the Sun and Earth, examining how it influences the seasons and the interplay between the Sun, Earth, and Moon. We'll differentiate between weather and climate, diving into Earth's heat budget and the greenhouse effect. Our journey will also take us back in time to study prehistoric climate change using proxies like ice cores and tree rings, providing a context for understanding current anthropogenic climate change. Finally, we will discuss the wide-ranging implications of climate change on Earth's biomes, highlighting the urgent need for sustainable solutions. Get ready to gain a comprehensive understanding of the forces shaping our planet's climate and the critical challenges we face in mitigating their impacts.

Learning Objectives

1. Explain the causes and effects of long-term climate shifts, including natural factors and human activities such as burning fossil fuels and deforestation.
2. Analyze the relationship between the Sun and Earth, including the role of the Sun-Earth-Moon system in driving seasonal changes.
3. Differentiate between weather and climate, and understand Earth's heat budget and the greenhouse effect.
4. Evaluate historical climate change using proxies, and compare it with current anthropogenic climate change.
5. Assess the implications of climate change on natural systems, human societies, and Earth's biomes, and discuss strategies for mitigation and adaptation.



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6.2: The Sun – Earth Relationship and the Seasons

SOLAR RADIATION ON EARTH

The amount of solar radiation (insolation, aka **in**coming **sol**ar radi**ation**) received at the Earth's surface varies with location and time of day. Different parts of the Earth receive different amounts of solar radiation. Which part of the planet receives the most insolation? On average, the Sun's rays strike the surface most directly at the equator. The amount of sunlight striking the Earth's surface also varies with the season. What causes the seasons? The seasons are caused by the angle of Earth's axis relative to the Sun.

The Earth revolves around the Sun once each year and spins on its axis of rotation once each day. This axis of rotation is tilted 23.5 degrees relative to its plane of orbit around the Sun. The axis of rotation is pointed toward Polaris, the North Star. As the Earth orbits the Sun, the tilt of Earth's axis stays lined up with the North Star.



NORTHERN HEMISPHERE SUMMER
The North Pole is tilted towards the Sun and the Sun's rays strike the Northern Hemisphere more directly in summer. At the summer solstice, June 21 or 22, the Sun's rays hit the Earth most directly along the Tropic of Cancer (23.5 degrees N); that is, the angle of incidence of the sun's rays there is zero (the angle of incidence is the deviation in the angle of an incoming ray from straight on). When it is summer solstice in the Northern Hemisphere, it is winter solstice in the Southern Hemisphere.

NORTHERN HEMISPHERE WINTER
Winter solstice for the Northern Hemisphere happens on December 21 or 22. The tilt of Earth's axis points away from the Sun. Light from the Sun is spread out over a larger area, so that area isn't heated as much. With fewer daylight hours in winter, there is also less time for the Sun to warm the area. When it is winter in the Northern Hemisphere, it is summer in the Southern Hemisphere.

EQUINOX
Halfway between the two solstices, the Sun's rays shine most directly at the equator, called an "equinox." The daylight and nighttime hours are exactly equal on an equinox. The autumnal equinox happens on September 22 or 23 and the vernal or spring equinox happens March 21 or 22 in the Northern Hemisphere.

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6.3: The Sun and the Earth-Moon System

The solar system includes the Sun, the planets that orbit the Sun, their satellites, dwarf planets and many, many small objects, like asteroids and comets. All of these objects move and we can see these movements. We notice the Sun rises in the eastern sky in the morning and sets in the western sky in the evening. We observe different stars in the sky at different times of the year. When ancient people made these observations, they imagined the sky was moving while the Earth stood still. In 1543, Nicolaus Copernicus (Figure 24.21) proposed a radically different idea: the Earth and the other planets make regular revolutions around the Sun. He also suggested that the Earth rotates once a day on its axis. Copernicus' idea slowly gained acceptance and today we base our view of motions in the solar system on his work. We also now know that everything in the universe is moving.



Figure 24.21: Nicholas Copernicus.

In this lesson you will learn about how the movements of the Earth, Moon, and Sun affect different phenomena on Earth, including day and night, the seasons, tides, and phases of the Moon.

Lesson Objectives

- Describe how Earth's movements affect seasons and cause day and night.
- Explain solar and lunar eclipses.
- Describe the phases of the Moon and explain why they occur.
- Explain how the movements of the Earth and Moon affect Earth's tides.

Positions and Movements

Earlier we discussed Earth's rotation and revolution. The Earth rotates once on its axis about every 24 hours. If you were to look at Earth from the North Pole, it would be spinning counterclockwise. As the Earth rotates, observers on Earth see the Sun moving across the sky from east to west with the beginning of each new day. We often say that the Sun is "rising" or "setting", but actually it is the Earth's rotation that gives us the perception of the Sun rising up or setting over the horizon. When we look at the Moon or the stars at night, they also seem to rise in the east and set in the west. Earth's rotation is also responsible for this. As Earth turns, the Moon and stars change position in our sky.

Earth's Day and Night

Another effect of Earth's rotation is that we have a cycle of daylight and darkness approximately every 24 hours. This is called a day. As Earth rotates, the side of Earth facing the Sun experiences daylight, and the opposite side (facing away from the Sun) experiences darkness or nighttime. Since the Earth completes one rotation in about 24 hours, this is the time it takes to complete one day-night cycle. As the Earth rotates, different places on Earth experience sunset and sunrise at a different time. As you

move towards the poles, summer and winter days have different amounts of daylight hours in a day. For example, in the Northern hemisphere, we begin summer on June 21. At this point, the Earth's North Pole is pointed directly toward the Sun. Therefore, areas north of the equator experience longer days and shorter nights because the northern half of the Earth is pointed toward the Sun. Since the southern half of the Earth is pointed away from the Sun at that point, they have the opposite effect—longer nights and shorter days.

For people in the Northern hemisphere, winter begins on December 21. At this point, it is Earth's South Pole that is tilted toward the Sun, and so there are shorter days and longer nights for those who are north of the equator.

Earth's Seasons

It is a common misconception that summer is warm and winter is cold because the Sun is closer to Earth in the summer and farther away from it during the winter. Remember that seasons are caused by the 23.5 degree tilt of Earth's axis of rotation and Earth's yearly revolution around the Sun (Figure 24.22). This results in one part of the Earth being more directly exposed to rays from the Sun than the other part. The part tilted away from the Sun experiences a cool season, while the part tilted toward the Sun experiences a warm season. Seasons change as the Earth continues its revolution, causing the hemisphere tilted away from or towards the Sun to change accordingly. When it is winter in the Northern hemisphere, it is summer in the Southern hemisphere, and vice versa.

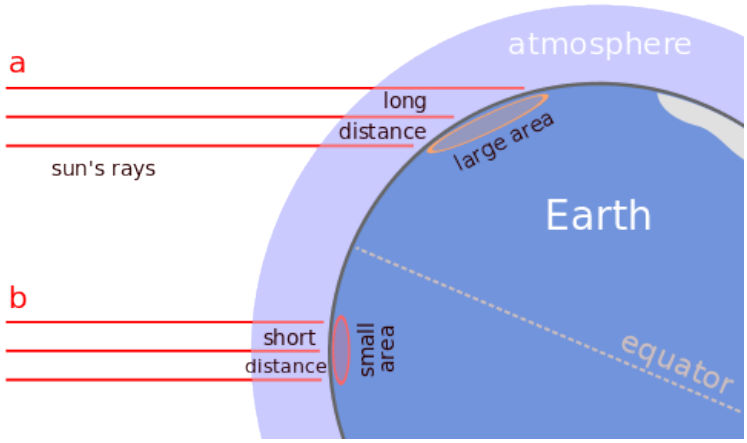


Figure 24.22: The Earth's tilt on its axis leads to one hemisphere facing the Sun more than the other hemisphere and gives rise to seasons.

NORTHERN HEMISPHERE SUMMER
The North Pole is tilted towards the Sun and the Sun's rays strike the Northern Hemisphere more directly in summer. At the **summer solstice**, June 21 or 22, the Sun's rays hit the Earth most directly along the Tropic of Cancer (23.5 degrees N); that is, the angle of incidence of the sun's rays there is zero (the angle of incidence is the deviation in the angle of an incoming ray from straight on). When it is summer solstice in the Northern Hemisphere, it is winter solstice in the Southern Hemisphere.

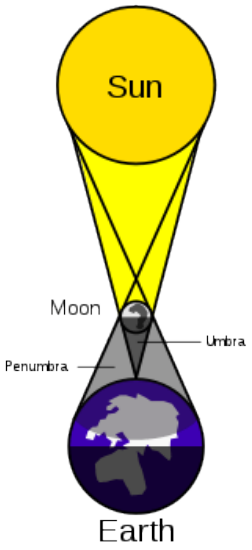
NORTHERN HEMISPHERE WINTER
Winter solstice for the Northern Hemisphere happens on December 21 or 22. The tilt of Earth's axis points away from the Sun. Light from the Sun is spread out over a larger area, so that area isn't heated as much. With fewer daylight hours in winter, there is also less time for the Sun to warm the area. When it is winter in the Northern Hemisphere, it is summer in the Southern Hemisphere.



EQUINOX

Halfway between the two solstices, the Sun's rays shine most directly at the equator, called an "**equinox**." The daylight and nighttime hours are exactly equal on an equinox. The autumnal equinox happens on September 22 or 23 and the vernal or spring equinox happens March 21 or 22 in the Northern Hemisphere.

Solar Eclipses



A **solar eclipse** occurs when the new moon passes directly between the Earth and the Sun (Figure 24.23). This casts a shadow on the Earth and blocks our view of the Sun. A total solar eclipse occurs when the Moon's shadow completely blocks the Sun (Figure 24.24). When only a portion of the Sun is out of view, it is called a partial solar eclipse. Solar eclipses are rare events that usually only last a few minutes. That is because the Moon's shadow only covers a very small area on Earth and Earth is turning very rapidly. As the Sun is covered by the moon's shadow, it will actually get cooler outside. Birds may begin to sing, and stars will become visible in the sky. During a solar eclipse, the corona and solar prominences can be seen.

Figure 24.23: A solar eclipse.

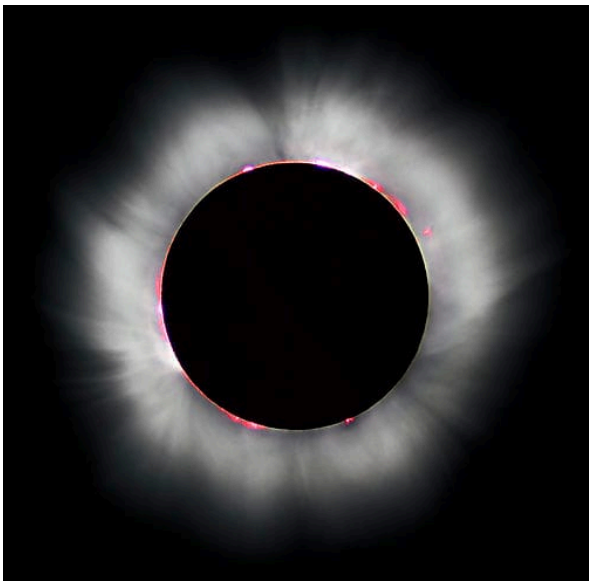


Figure 24.24: Photo of a total solar eclipse. The corona is the white region surrounding the Sun.

A Lunar Eclipse

A **lunar eclipse** occurs when the full moon moves through the shadow of the Earth (Figure 24.25). This can only happen when the Earth is between the Moon and the Sun and all three are lined up in the same plane, called the ecliptic. The ecliptic is the plane of Earth's orbit around the Sun. The Earth's shadow has two distinct parts: the umbra and the penumbra. The **umbra** is the inner, cone shaped part of the shadow, in which all of the light has been blocked. The outer part of Earth's shadow is the **penumbra** where only part of the light is blocked. In the penumbra, the light is dimmed but not totally absent. A total lunar eclipse occurs when the Moon travels completely in Earth's umbra. During a partial lunar eclipse, only a portion of the Moon enters Earth's umbra. A penumbral eclipse happens when the Moon passes through Earth's penumbra. The Earth's shadow is quite large, so a lunar eclipse lasts for hours and can be seen by anyone with a view of the Moon at the time of the eclipse.

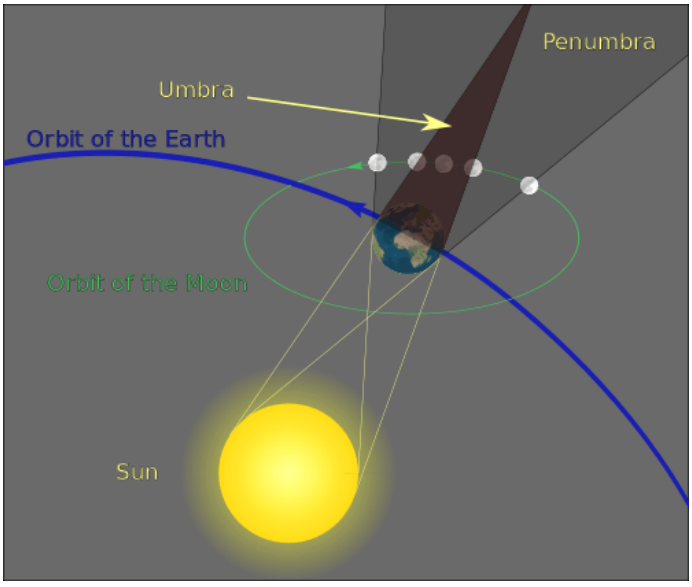


Figure 24.25: The formation of a lunar eclipse.

Partial lunar eclipses occur at least twice a year, but total lunar eclipses are less common. The next total lunar eclipse will occur December 21, 2010. The moon glows with a dull red coloring during a total lunar eclipse.

The Phases of the Moon

The Moon does not produce any light of its own—it only reflects light from the Sun. As the Moon moves around the Earth, we see different parts of the near side of the Moon illuminated by the Sun. This causes the changes in the shape of the Moon that we notice on a regular basis, called the phases of the Moon. As the Moon revolves around Earth, the illuminated portion of the near side of the Moon will change from fully lit to completely dark and back again.

A full moon is the lunar phase seen when the whole of the Moon's lit side is facing Earth. This phase happens when Earth is between the Moon and the Sun. About one week later, the Moon enters the quarter-moon phase. At this point, the Moon appears as a half-circle, since only half of the Moon's lit surface is visible from Earth. When the Moon moves between Earth and the Sun, the side facing Earth is completely dark. This is called the new moon phase, and we do not usually see the Moon at this point. Sometimes you can just barely make out the outline of the new moon in the sky. This is because some sunlight reflects off the Earth and hits the moon. Before and after the quarter-moon phases are the **gibbous** and **crescent** phases. During the gibbous moon phase, the moon is more than half lit but not full. During the crescent moon phase, the moon is less than half lit and is seen as only a sliver or crescent shape. It takes about 29.5 days for the Moon to revolve around Earth and go through all the phases (Figure 24.26).

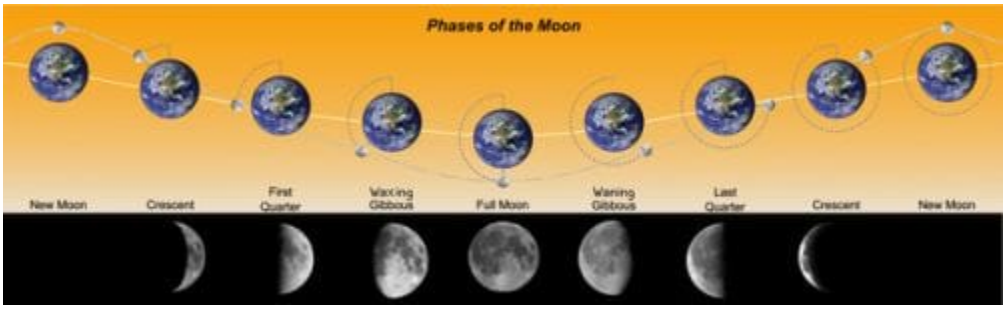


Figure 24.26: The phases of the Moon. Note that the Sun would be above the top of this picture, and thus, the Sun's rays would be directed downward.

The Tides

Tides are the regular rising and falling of Earth's surface water in response to gravitational attraction from the Moon and Sun. The Moon's gravity causes the oceans to bulge out in the direction of the Moon. In other words, the Moon's gravity is pulling upwards on Earth's water, producing a high tide. On the other side of the Earth, there is another high tide area, produced where the Moon's pull is weakest. As the Earth rotates on its axis, the areas directly in line with the Moon will experience high tides. Each place on Earth experiences changes in the height of the water throughout the day as it changes from high tide to low tide. There are two high tides and two low tides each tidal day. Figure 24.27 and Figure 24.28 will help you better understand how tides work.

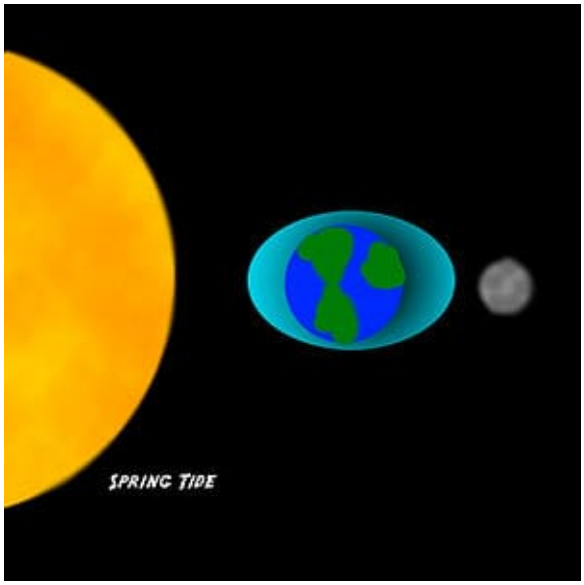


Figure 24.27: A spring tide.

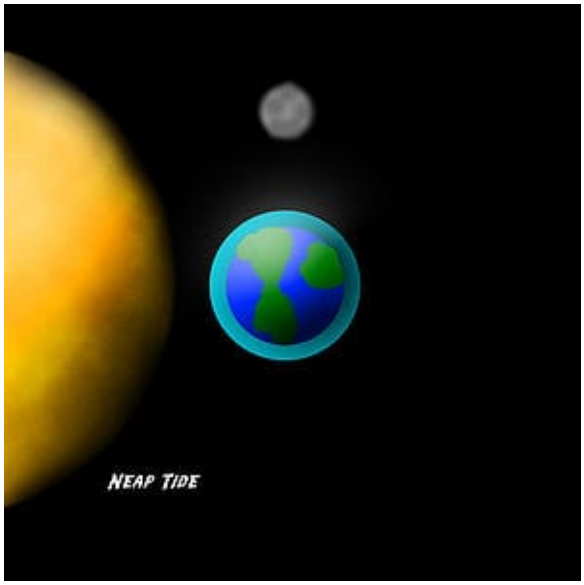


Figure 24.28: A neap tide.

The first picture shows what is called a **spring tide**. Confusingly, this tide has nothing to do with the season “Spring”, but means that the tide waters seem to spring forth. During a spring tide, the Sun and Moon are in line. This happens at both the new moon and the full moon. The Sun’s gravity pulls on Earth’s water, while the Moon’s gravity pulls on the water in the same places. The high tide produced by Sun adds to the high tide produced by the Moon. So spring tides have higher than normal high tides. This water is shown on the picture as the gray bulges on opposite sides of the Earth. Notice that perpendicular to the gray areas, the water is at a relatively low level. The places where the water is being pulled out experience high tides, while the areas perpendicular to them experience low tides. Since the Earth is rotating on its axis, the high-low tide cycle moves around the globe in a 24-hour period.

The second picture shows a **neap tide**. A neap tide occurs when the Earth and Sun are in line but the Moon is perpendicular to the Earth. This happens when the moon is at first or last quarter moon phase. In this case, the pull of gravity from the Sun partially cancels out the pull of gravity from the Moon, and the tides are less pronounced. Neap tides produce less extreme tides than the normal tides. This is because the high tide produced by the Sun adds to the low tide area of the Moon and vice versa. So high tide is not as high and low tide is not as low as it usually might be.

Lesson Summary

- As the Earth rotates on its axis and revolves around the Sun, several different effects are produced.
- When the new moon comes between the Earth and the Sun along the ecliptic, a solar eclipse is produced.
- When the Earth comes between the full moon and the Sun along the ecliptic, a lunar eclipse occurs.
- Observing the Moon from Earth, we see a sequence of phases as the side facing us goes from completely darkened to completely illuminated and back again once every 29.5 days.
- Also as the Moon orbits Earth, it produces tides aligned with the gravitational pull of the Moon.
- The Sun also produces a smaller solar tide. When the solar and lunar tide align, at new and full moons, we experience higher than normal tidal ranges, called spring tides.
- At first and last quarter moons, the solar tide and lunar tide interfere with each other, producing lower than normal tidal ranges called neap tides.

Review Questions

1. The globe is divided into time zones, so that any given hour of the day in one time zone occurs at a different time in other time zones. For example, New York City is in one time zone and Los Angeles is in another time zone. When it is 8 am in New

York City, it is only 5 am in Los Angeles. Explain how Earth's motions cause this difference in times.
2. Explain how Earth's tilt on its axis accounts for seasons on Earth.
3. Explain how the positions of the Earth, Moon, and Sun vary during a solar eclipse and a lunar eclipse.
4. Draw a picture that shows how the Earth, Moon, and Sun are lined up during the new moon phase.
5. Why are neap tides less extreme than spring tides?

Vocabulary

crescent
: Phase of the moon when it is less than half full but still slightly lit.

gibbous
: Phase of the moon when it is more than half lit but not completely full.

lunar eclipse
: An eclipse that occurs when the Moon moves through the shadow of the Earth and is blocked from view.

neap tide
: Type of tide event when the Sun and Earth are in line and the Moon is perpendicular to the Earth.

penumbra
: Outer part of shadow that remains partially lit during an eclipse.

solar eclipse
: Occurs when moon passes directly between the Earth and Sun; the Moon's shadow blocks the Sun from view.

spring tide
: An extreme tide event that happens when the Earth, Moon, and the Sun are aligned; happens at full and new moon phases.

tide
: The regular rising and falling of Earth's surface waters twice a tidal day as a result of the Moon's and Sun's gravitational attraction.

umbra
: Inner cone shaped part of a shadow when all light is blocked during an eclipse.

Points to Consider

- Why don't eclipses occur every single month at the full and new moons?
- The planet Mars has a tilt that is very similar to Earth's. What does this produce on Mars?
- Venus comes between the Earth and the Sun. Why don't we see an eclipse when this happens?

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6.4: Weather vs Climate

a) Weather and Climate

Weather and climate are related but they differ in the time scales of changes and their predictability. They can be defined as follows.

Weather is the instantaneous state of the atmosphere around us. It consists of **short-term variations** over minutes to days of variables such as temperature, precipitation, humidity, air pressure, cloudiness, radiation, wind, and visibility. Due to the non-linear, chaotic nature of its governing equations, weather **predictability is limited** to days.

Climate is the statistics of weather over a longer period. It can be thought of as the **average** weather that varies slowly over periods of months, or longer. It does, however, also include other statistics such as probabilities or frequencies of *extreme events*. Climate is **potentially predictable** if the *forcing* is known because Earth's average temperature is controlled by energy conservation. For climate, not only the state of the atmosphere is important but also that of the ocean, ice, land surface, and biosphere.

In short: 'Climate is what you expect. Weather is what you get.'

b) The Climate System

Earth's climate system consists of interacting **components** (Fig. 6.4.1). The **atmosphere**, which is the air and clouds above the surface, is about 10 km thick (more than two thirds of its mass is contained below that height). The **ocean** covers more than two thirds of Earth's surface and has an average depth of roughly 4 km. Contrast those numbers with Earth's radius which is approximately 6,400 km and you'll find that Earth's atmosphere and ocean are very thin layers compared to the size of the planet itself. In fact, they are about 1,000 times thinner. They are comparable perhaps to the outer layer of an onion or the water on a wet soccer ball. Yet all life is constrained to these thin layers. The major ocean basins are the Pacific, the Atlantic, the Indian, and the Southern Ocean. Ice and snow comprises the **cryosphere**, which includes sea ice, mountain glaciers and ice sheets on land. Sea ice is frozen sea water, up to several meters thick, floating on the ocean. Ice sheets on land, made out of compressed snow, can be several kilometers thick. The **biosphere** includes all living things on land and in the sea from the smallest microbes to trees and whales. The **lithosphere**, which is the solid Earth (upper crust and mantle), could also be considered an active part of Earth's climate sytem because it responds to ice load[1] and impacts atmospheric carbon dioxide (CO_2) concentrations and climate on long timescales through the movements of the continents.



Figure 6.4.1: The blue marble. A composite image of Earth from space. It shows all four components of Earth's climate system. The atmosphere with its complex cloud patterns. The ocean, which covers about 70% of Earth's surface. The cryosphere is visible as the white areas on the top: sea ice covering the Arctic Ocean and the Greenland ice sheet. Green colors on land and turquoise shades along the ocean's margin indicate the biosphere as forests and phytoplankton blooms. Notice in the lower left the thin layer of the atmosphere surrounding Earth. From nasa.gov.

The components **interact** with each other by exchanging energy, water, momentum, and carbon thus creating a deliciously complex coupled system. Imagine water evaporating from the tropical ocean heated by the sun (Fig. 6.4.1). The air containing that water rises and cools. The water *condenses* into a cloud. The cloud is carried by winds over land where it rains. The rain sustains a forest. Trees are dark, having a low albedo. This influences the amount of sunlight absorbed by the Earth. Dark surfaces absorb more sunlight and get warmer compared to bright surfaces such as desert sand or snow. Air warmed by the surface rises and affects the wind.

c) Processes

Figure 6.4.2 illustrates some of the important processes that contribute to the complex interactions within the climate system. Earth's energy source is the sun. Both solar and terrestrial *radiation* are affected by gases, *aerosols*, and clouds in the atmosphere. Thus, the atmospheric composition affects the heating and cooling of the earth. Heating and cooling affect the temperature and circulation of the atmosphere and oceans. Circulations of the air and sea affect temperatures and precipitation over both ocean and land, which impact the biosphere and cryosphere. Atmosphere and oceans exchange heat, water (evaporation and precipitation), and momentum. Wind blowing over the ocean pushes the surface water ahead. Air temperatures and snow fall affect the growth and melting of glaciers and ice sheets. Water from melting ice flows through rivers into the ocean affecting its salinity, its density and movement. Variations in solar irradiance can cause global climate to change. Volcanoes can eject large amounts of aerosol into the atmosphere with climatic implications. Humans are influencing the climate system through emissions of *greenhouse gases*, *aerosols*, and *land use changes*.

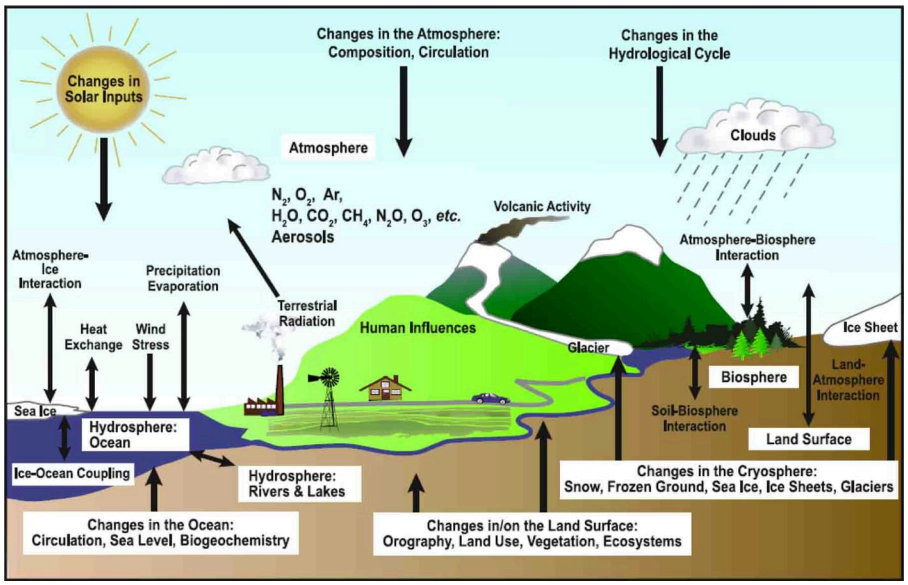


Figure 6.4.2: Schematic view of components of the climate system and processes involved in their interactions. From Le Treut et al. (2007).

The complexity makes studying the climate system challenging. Scientists from many disciplines contribute such as physicists, chemists, biologists, geologists, oceanographers, atmospheric scientists, paleoclimatologists, mathematicians, statisticians, and computer scientists. To me, the challenges and interdisciplinary nature of climate science are fascinating and fun. I learn something new about it every day.

Recorded Lectures

Weather and Climate

References

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical Overview of Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Questions

- What are the two main differences between weather and climate?
- How big is Earth? How thick is the atmosphere, how deep the ocean?
- What are the components of Earth's climate system?
- List processes that cause interactions between the components: atmosphere-ocean, atmosphere-biosphere, atmosphere-cryosphere, ocean-biosphere, ocean-cryosphere.
- Name three processes (*forcings*) that can cause global climate to change.

Explore

Go to one of the following websites and explore **temporal variations** of surface temperature observations in a location of your interest. Plot today's data, yesterday's, last week's, last month's, last year's, the last decade's, as far back as you can and make some notes on what you observe. Note regular, predictable cycles such as the diurnal and annual cycle in contrast with irregular, unpredictable variations such as day-to-day and year-to-year fluctuations. What causes the regular cycles? Try to order the variations with respect to their amplitude (strength). Discuss with fellow students and instructor.

Hourly and daily data are available at: https://www.wunderground.com/history/. Enter a location of your interest. Click on the "Weekly", "Monthly", or "Custom" tabs to select different time periods. Unfortunately, when I tried it Jan. 30th, 2017 the "Custom" option didn't allow one to plot more than one year of data. However, you may be able to identify diurnal (daily) cycles in temperature. Fig. 6.4.3 shows an example. Although some nights can be warmer than some days and sometimes days and nights have the same temperature, on average days are warmer than nights. Thus the average diurnal cycle is part of climate. It is forced by the diurnal cycle of solar irradiance. Does pressure have a diurnal cycle? Answer: no. What is the typical timescale of pressure variations? Often it is about a week or so. This timescale is associated with the transition of weather systems (high and low pressure systems) passing by.

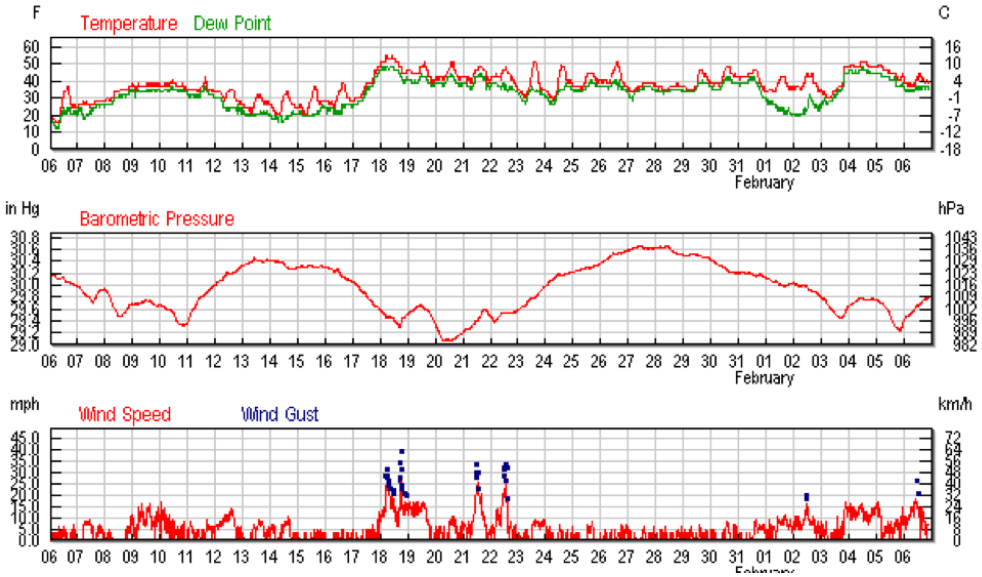


Figure 6.4.3: Weather data from Corvallis, Oregon from January 2017. In the upper panel we can see diurnal cycles in temperature. Pressure varies on longer timescales. Low pressure is associated with storms (high winds and wind gusts).

Help on finding past weather data is available at https://www.weather.gov/help-past-weather. Following the instructions and clicking on Oregon brings up http://www.wrh.noaa.gov/pqr/.

Clicking on "local", choosing the "Local Data/Records" tab, and clicking on "Daily Records for cities in Oregon" brings me to the website of the Western Regional Climate Center http://www.wrcc.dri.edu/summary/climsmor.html where I can choose a city. Now I choose "Corvallis Oregon State University" and scroll down on the left side menu to "Graph and Lister" under "Daily Data". Now select the time period (I choose 20120101 to 20160101) and click on the "Daily Precipitation" button and then "Create Graph".

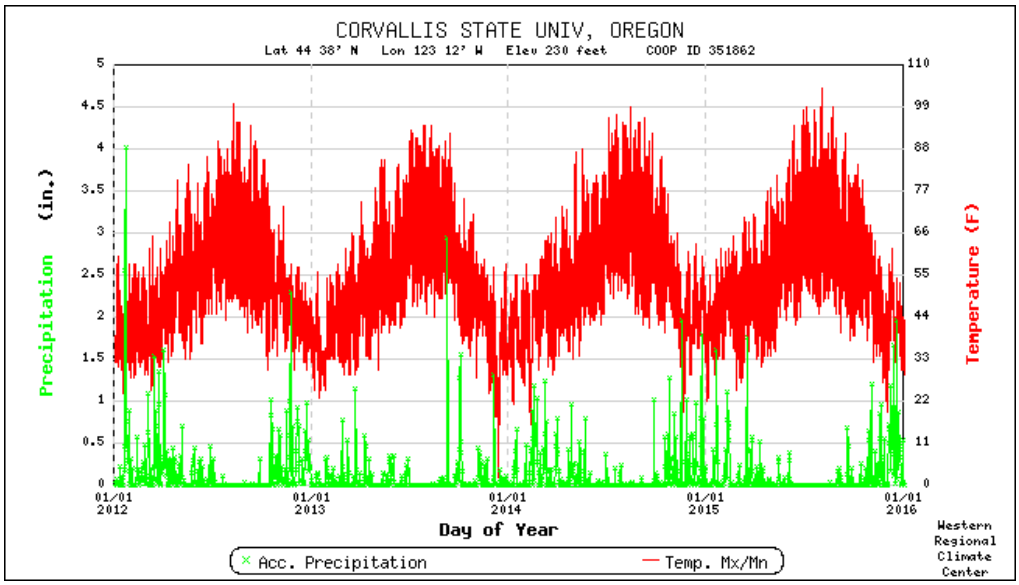


Figure 6.4.4: Local weather data (daily minimum and maximum temperature and daily precipitation) from Corvallis, Oregon, from 2012 to 2016. Large variations in temperatures from ~40°F in winter to ~65°F in summer indicate the seasonal (or annual) cycle. Precipitation, which is very episodic, also shows a large annual cycle with lots of rain in winter and less rain in summer. The mean seasonal cycle is shown in Figure 6.4.5. From wrcc.dri.edu

Averaging many years of these weather data yields a climatology. At the WRCC website you can see plots of climatologies over 30 years by scrolling back up the left side menu and clicking on one of the "Daily Temp. & Precip." links. For Corvallis it shows average temperatures around 40°F (4°C) in winter and 65°F (18°C) in summer. It also shows a larger diurnal cycle in summer than in winter. What could be the reason for that? Answer: less cloud cover in summer. Clouds lead to cooler days and warmer nights, thus decreasing the diurnal cycle. As expected, precipitation is low in summer and high in winter. Curves are smooth in the climatology. In contrast to Figure 6.4.4 the weather variations have been averaged out.

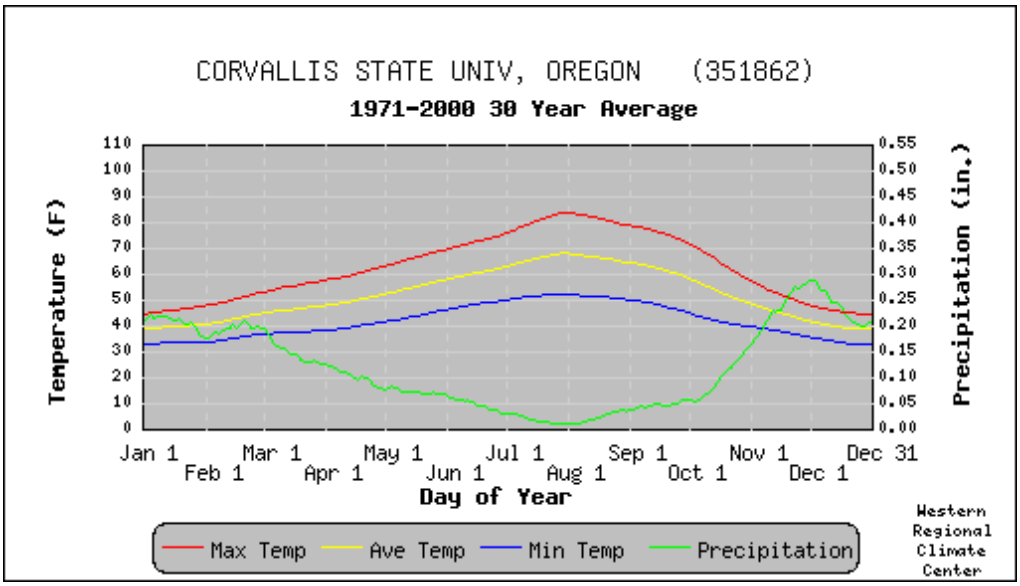


Figure 6.4.5: Climatology of temperature and precipitation in Corvallis, Oregon. The difference between the red and blue curve denotes the average diurnal cycle.

Now try a forecast of temperature for next August and next January. What is your guess? Answer: a good guess would be the climatology, i.e. 65°F for August and 40°F for January. Thus the average seasonal cycle is climate and it is predictable because it is forced by the seasonal cycle of solar irradiance. However, deviations from the climatology for a certain day next year are unpredictable weather.

Statistical properties of climate can be summarized in a frequency histogram. Let's explore those with an example. Download

from the WRCC website daily average temperature data from a certain day of year, e.g. May 1st. You can do this by clicking on the “Lister” link in the left menu. Next choose start and end days (e.g. 19851001 and 20161101) to create a list of 30 years of data. Enter “wrcc35” as the password. Let’s choose “Average Temperature” as the element to list. Now select a day of the year (e.g. May 1st) for both “Starting Date” and “Ending Date”, and click the “Get Listing” button. This gives the following list (or vector mathematically speaking) of N=30 temperatures $\boldsymbol{T}$ = ($T1$, $T2$, … , TN) = (52, 52, 44, 52, 52, 54, 48, 52, 50, 56, 59, 46, 64, 58, 55, 48, 54, 54, 63, 54, 51, 54, 42, 52, 52, 48, 48, 48, 66, 56). Here N = 1 corresponds to 1985, N = 2 to 1986 and so on. In order to construct the frequency histogram we first need to choose bin sizes. I propose to choose 6 bins: 40-44, 45-49, 50-54, 55-59, 60-64, and 65-70. Now simply count how many years fall into each bin. I get 2, 6, 14, 6, 2, 1. Using python I produced the following graph (Fig. 6.4.6).

Climate change can be expressed as a change in the mean, which would correspond simply to a shift of the whole histogram to warmer or colder temperatures. However, it can also change the shape of the histogram. For example by making the distribution wider or narrower. This would increase or decrease the occurrences of extreme events. And, of course, it can both change the mean and the width. Most of the time, including in this text, discussions of climate change consider only changes in the mean. But we should keep in mind that changes to the tails of the distribution may be equally important because it is those tails that can have large impacts (heat waves, cold spells, droughts, floods, etc).

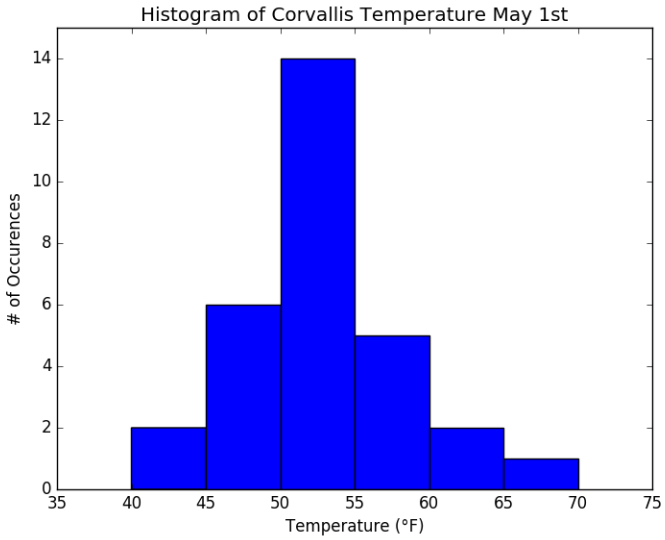


Figure 6.4.6: Histogram of 30 year (1985-2016) temperatures in Corvallis on May 1st. Most years (14 out of the 30) the temperature is between 50 and 55°F. The mean of the distribution is 52.8°F, its standard deviation of σ =5.4°F represents its width (about 2/3 of all years have temperatures within ±1 σ of the mean). The histogram, although it approximates well a Gaussian (normal) distribution, is slightly asymmetric such that very warm years (65-70) occur slightly more often than very cold extremes (35-40). The tails of the distribution are the upper and lower bins. They represent rare or extreme events. Only one year was warmer than 65°F. This year (2014) can be regarded as an extreme event. It was a record warm year in Oregon.

Now let’s explore effects of **spatial scales** on climate variations. Go to https://www.ncdc.noaa.gov/cag and start with the U.S. tab selection. We want to compare the annual average temperature change in a city of your choice (e.g. Salem in Oregon), averaged over the larger region of a state, for the U.S. as a whole, and the globe (use “Globe” tab and plot “Land and Ocean”, “Land”, and “Ocean” separately). For “Timescale” select “Annual”. Check the “Display Trend” box. This will include a trend line on the graph. Compare the trends and year-to-year variations. Are the trends larger for the global ocean or for the global land?

Compare the year-to-year variations and trends in regionally and globally averaged temperatures (Figs. 6.4.7 - 6.4.12) to the local diurnal cycle, day-to-day weather fluctuations (Figure 6.4.3), and to the seasonal cycle (Figs. 6.4.4 - 6.4.5). Even though the global temperature trends (~0.1°C/decade) are much smaller than diurnal, day-to-day or seasonal fluctuations, which can be 10°C or more, we will see in the remainder of this course that global temperature changes of a few degrees C will have important impacts on natural systems and human societies.

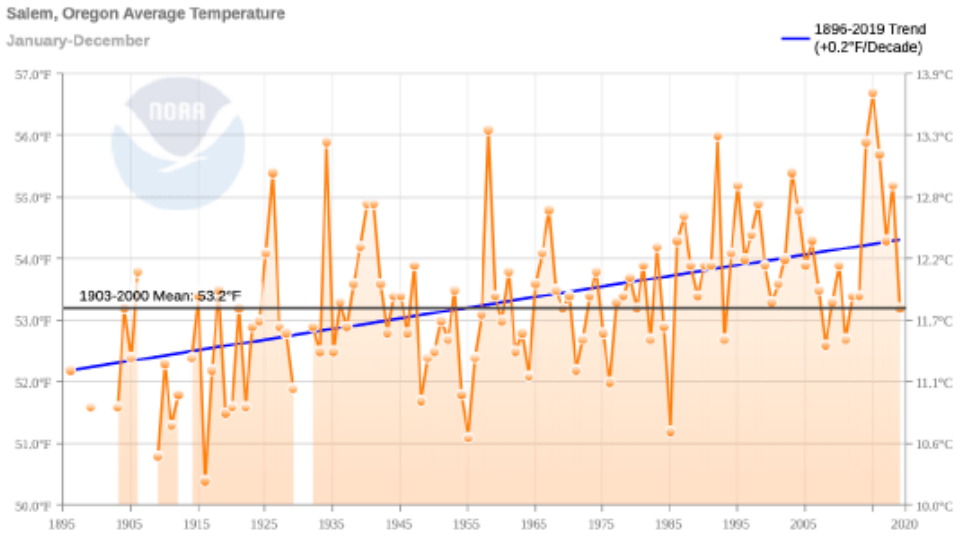


Figure 6.4.7: Annual average temperature changes in Salem, Oregon. Note the large year-to-year variations of 2-3°C and the small overall trend (blue line).

Figure 6.4.7: Annual average temperature changes in Salem, Oregon. Note the large year-to-year variations of 2-3°C and the small overall trend (blue line).

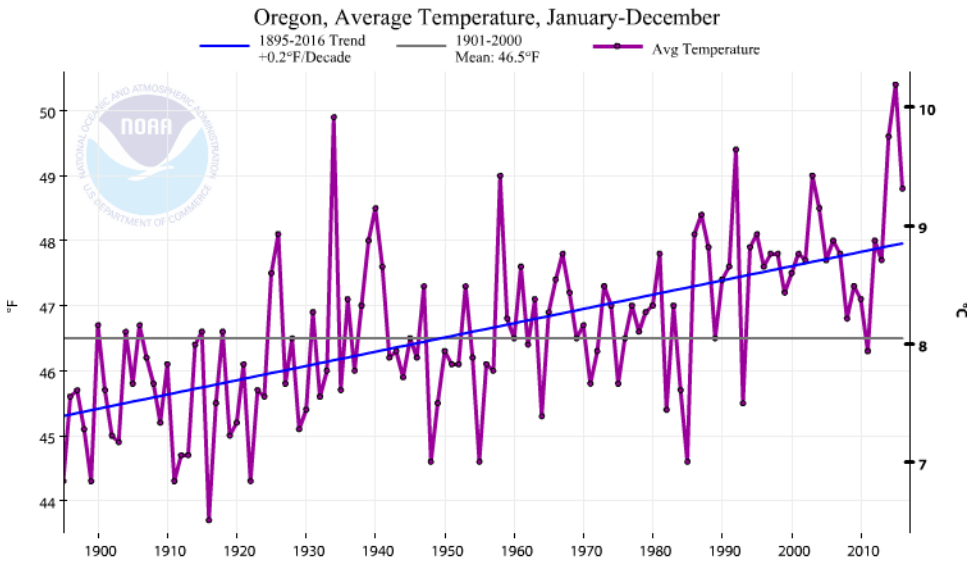


Figure 6.4.8: Averaged over the state of Oregon temperature fluctuations from year-to-year are reduced (1-2°C) compared with the figure from Salem and there is a strong (0.1°C/decade) warming trend.

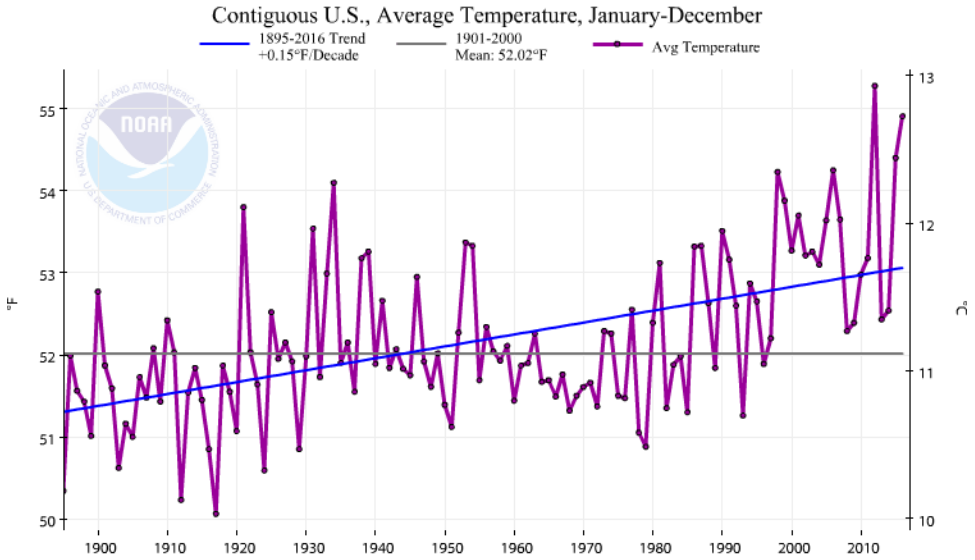


Figure 6.4.9: Averaged over the contiguous U.S. the year-to-year variability has slightly decreased compared to Oregon. The warming trend is similar but slightly lower.

9

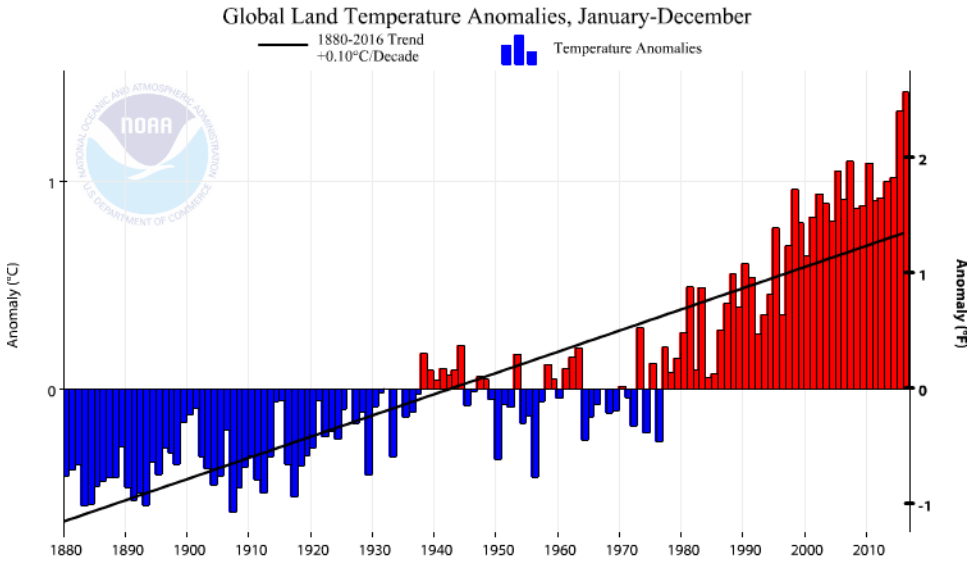


Figure 6.4.10: This figure shows anomalies (differences) with respect to the 1901-2000 average of global averaged land temperatures. Averaged over all of Earth's land areas the year-to-year variations are further reduced (~1°C) and the trend is with 0.1°C/decade slightly larger than that in the U.S.

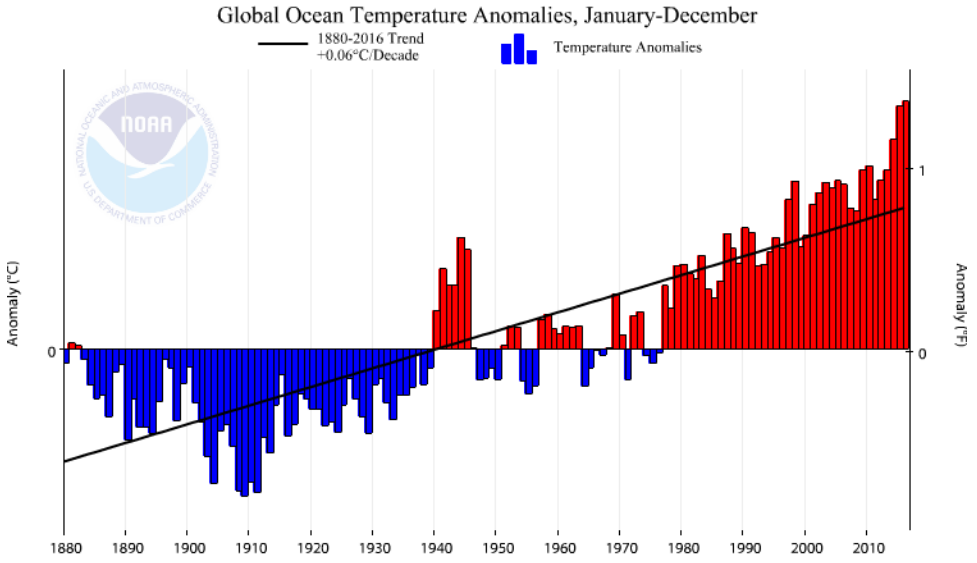


Figure 6.4.11: Averaged over the global ocean the year-to-year variations are still smaller (~0.5°C) than over land and the trend is also smaller (0.06°C/decade).

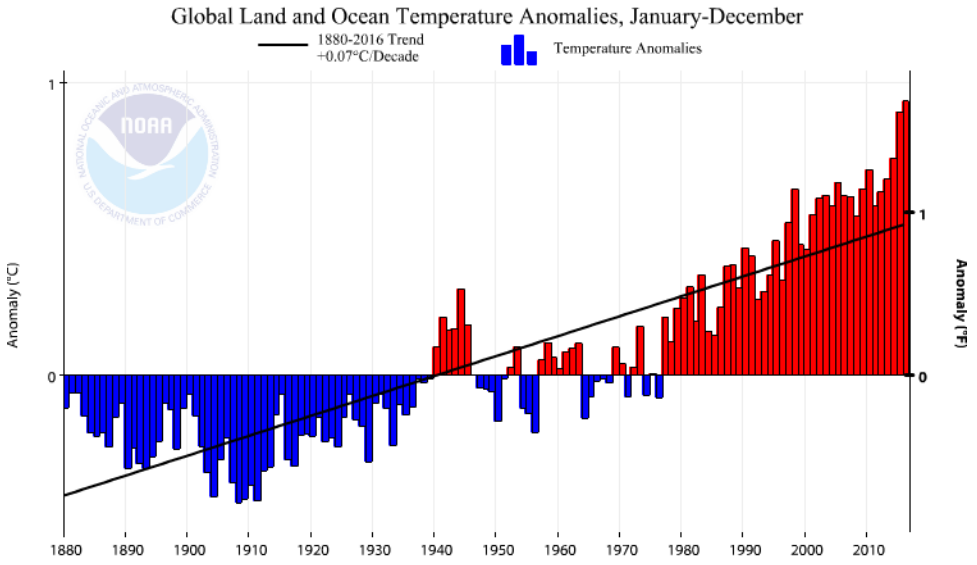


Figure 6.4.2: Averaged over land and ocean the increase in Earth's temperature over the past 100 years has been approximately 0.7°C (0.07°C/decade). This result is very robust. Several groups around the world have analyzed the available data in different ways and came to the same conclusion. This is a key figure.

1. The weight of the ice depresses the lithosphere, which provides a feedback to the ice by lowering its surface elevation. Traditionally it has been thought that this feedback acts on long (millennial and longer) timescales, but recent research indicates that in certain regions such as West Antarctica, where the lithosphere is thin and the mantle viscosity is low the lithosphere can respond on much shorter (decadal to centennial) timescales. ↵

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6.5: Earth's Heat Budget and the Greenhouse Effect

We have seen how global climate has changed and we've learned that some of these changes have been related to *forcings* and *feedbacks* such as atmospheric CO_2 concentrations and the seasonal distribution of solar irradiance. Now we want to proceed to understand quantitatively why climate is changing. To do this we will consider Earth's energy budget, review what electromagnetic radiation is, how it interacts with matter, how it passes through the atmosphere, and how this creates the greenhouse effect. But first, we will briefly discuss the general budget equation because it is widely used by scientists and it will be used at different occasions throughout this book.

Box 1: Budget Equation

Scientists like to keep track of things: energy, water, carbon, anything really, because it allows them to exploit conservation laws. In physics, for example, we have the law of energy conservation. It is the first law of thermodynamics and states that energy cannot be destroyed or created; it can only change between different forms or flow from one object to another. Similarly, the total amounts of water and carbon on earth are conserved although they may change forms or flow from one component to another one (e.g., from the ocean to the atmosphere, from terrestrial biomass to soil organic matter, etc.). To start, we need a well-defined quantity of interest. Let's call that quantity *X*. It could be energy, water, carbon, or something else that obeys a conservation law. It can be restricted to a specific part or component of the climate system, e.g. water in the cryosphere. Mathematically a budget equation can be written as

$$\frac{\partial X}{\partial t} = I - O \tag{6.5.1}$$

where the differentials ∂ denote an infinitesimal small change, *t* is time, *I* is the input, and *O* is the output. The left-hand-side of this equation is the time rate-of-change of *X*. In practice the differentials can be replaced by finite differences (Δ) such that we get

$$\frac{\Delta X}{\Delta t} = I - O \tag{6.5.2}$$

Finite differences can be easily calculated: $\Delta X = X_2 - X_1$ and $\Delta t = t_2 - t_1$. Here X_1 corresponds to the quantity *X* at time t_1 and X_2 corresponds to the quantity *X* at time t_2. Note that the inputs and outputs have units of the quantity *X* divided by time. They are often called *fluxes*.

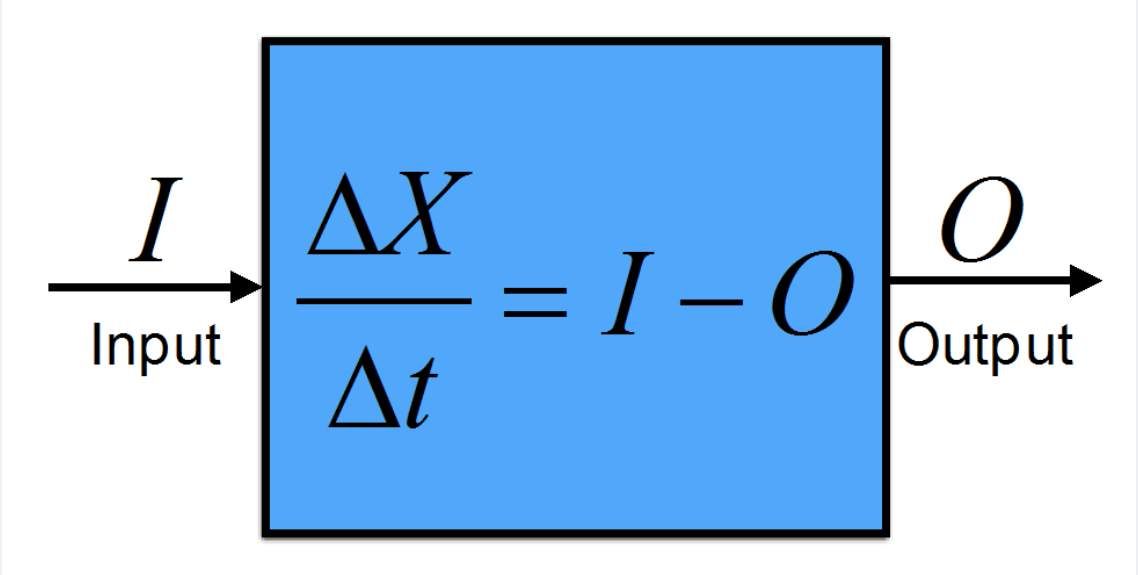


Figure B6.5.1.1: Illustration of the budget equation. A box containing a conserved quantity X that does not include internal sources or sinks will change in time according to the external inputs minus the outputs.

Different boxes can be connected such that the output of one box becomes the input of another box.

A budget is in **balance** if the quantity X does not change in time. In this case $\Delta X = 0$ and the input equals the output:

$$I = O \tag{6.5.3}$$

Let's do a little example. Assume a student gets a monthly stipend of \$1,000 and \$400 from his/her parents. Those are the inputs to the student's bank account in units of dollars per month I = \$1,000/month + \$400/month = \$1,400/month. The outputs would be the student's monthly expenses. Let's say he/she pays \$400 for tuition, \$420 for rent, \$390 for food, and \$100 for books (not for this one though) such that O = \$400/month + \$420/month + \$390/month + \$100/month = \$1,310/month. The rate-of-change of his/her bank account is $\Delta X/\Delta t = I - O$ = \$1,400/month – \$1,310/month = \$90/month. The student saves \$90 per month.

Equation 6.5.2 can be used to predict the quantity X at time t_2

$$X_2 = X_1 + (I - O)\,\Delta t \tag{6.5.4}$$

from its value X_1 at time t_1 if the inputs and outputs are known. In climate modeling this method, called forward modeling, is used to predict quantities into the future one time step Δt at a time.

In our example, if the student starts at time t_1, let's say in January, with X_1= \$330 in his/her bank account then we can predict that in February he/she will have X_2 = \$330 + (\$1,400/month – \$1,310/month)×(1 month) = \$330 + \$90 = \$420. Note that in this case the time step Δt = 1 month.

a) Electromagnetic Radiation

Earth's energy budget is determined by energy input from the sun (solar radiation) and energy loss to space by thermal or terrestrial *radiation*, which is emitted from Earth itself. Solar radiation has shorter wavelengths than terrestrial radiation because the sun is hotter than Earth. To understand this let's consider the electromagnetic radiation spectrum (Figure 6.5.1). Electromagnetic radiation are waves of electric and magnetic fields that can travel through vacuum and matter (e.g. air) at the speed of light (c). It is one way that energy can be transferred from one place to another. The wavelength of electromagnetic radiation (λ), which is the distance from one peak to the next, varies by more than 16 orders of magnitude. Visible light, which has wavelengths from about 400 nm (nanometers, 1 nm = 10^{-9} m = one millionth of a millimeter) to about 700 nm, occupies only a small part of the entire spectrum of electromagnetic radiation. The frequency (ν) times the wavelength equals the speed of light $c = \nu\lambda$.

Albert Einstein showed in 1905 that electromagnetic radiation has particle properties. In modern quantum physics the light particle is called a photon. Each photon has a discrete amount of energy $E = h\nu = hc/\lambda$ that corresponds to its wavelength, where h = 6.63×10^{-34} Js is Planck's constant. The shorter the wavelength the higher the energy. High energy photons at ultraviolet, X-ray, and gamma ray wavelengths can be harmful to biological organisms because they can destroy organic molecules such as DNA.

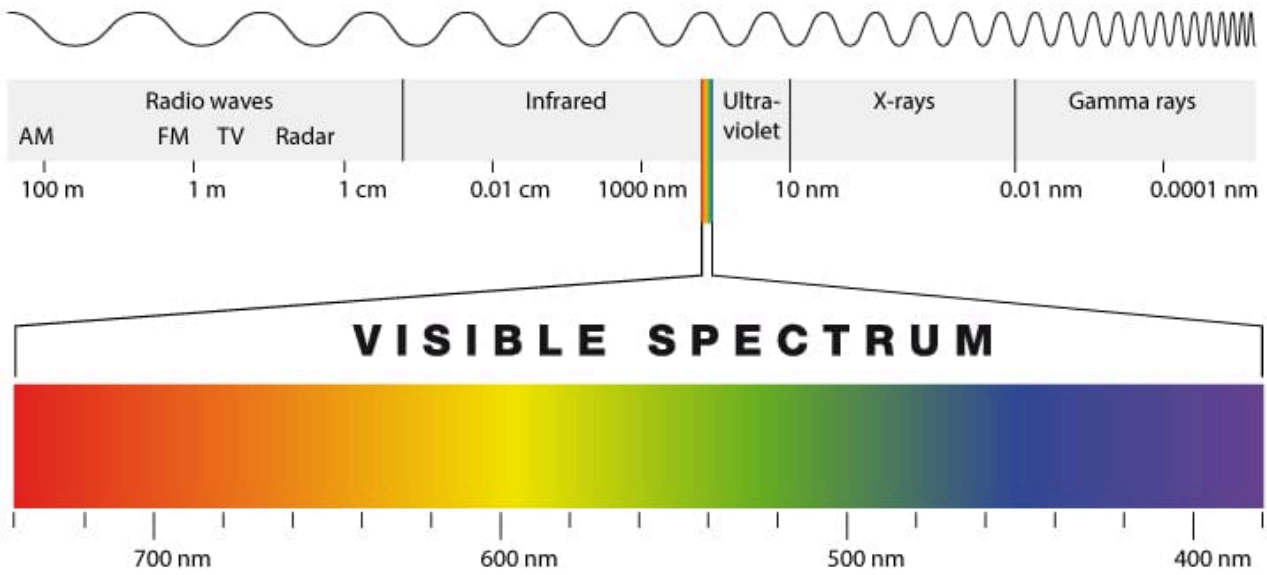
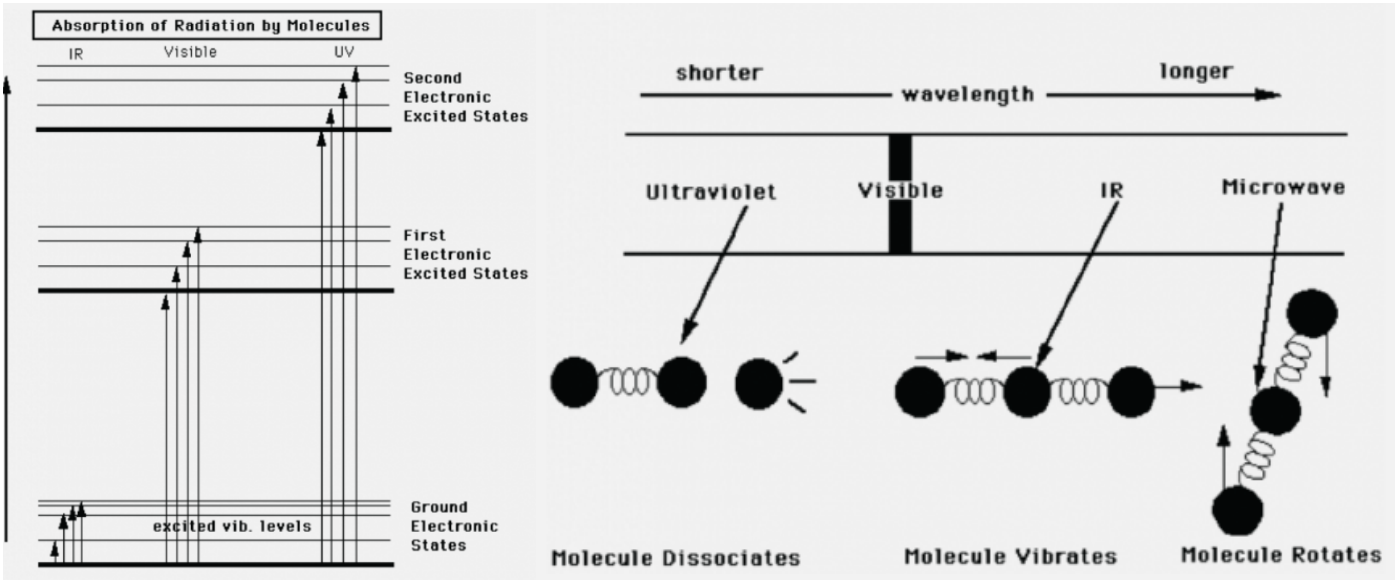


Figure 6.5.1: The Spectrum of Electromagnetic Radiation. Electromagnetic radiation ranges from radio-waves with wavelengths of hundreds of meters and more, to gamma rays, with wavelengths of 10^{-12} m, which is as small as the size of an atomic nucleus. From chromacademy.com.

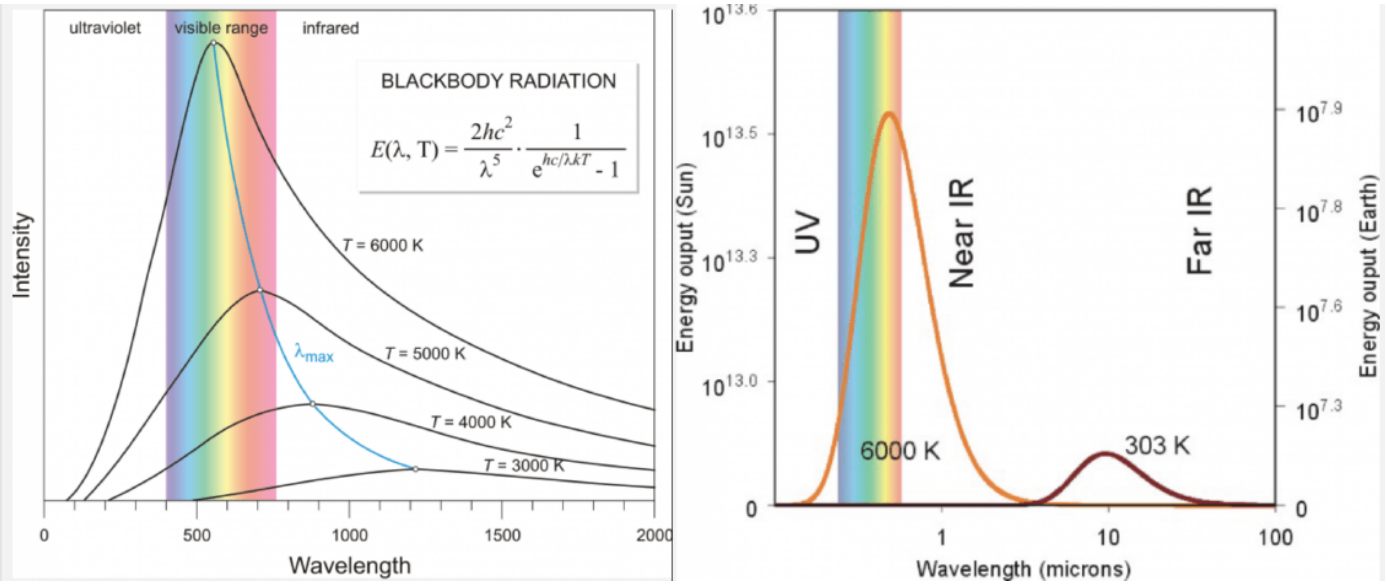
Interaction of electromagnetic radiation with matter depends on the wavelength of the radiation. Molecules have different discrete energy states and they can transition from one state to another one by absorbing or emitting a photon at a wavelength that corresponds to that energy difference (Figure 6.5.2). Absorption (capture) of a photon leads to a transition from a lower to a higher energy state. Note that once absorbed the photon is gone and its energy has been added to the molecule. Emission (release) of a photon leads to a transition from a higher to a lower state (reversing the direction of the arrows in Figure 6.5.2)A. Note that the emitted photon can have a different wavelength that the absorbed photon. If, e.g., a UV photon was absorbed and has caused the energy of the molecule to increase from the ground electronic state to the second excited state, the molecule can emit two visible photons, first one that leads to a transition from the second to the first excited electronic state, and then another that leads to a transition to the ground state.



A B

Figure 6.5.2: Interactions of electromagnetic radiation with molecules. A: Absorption of a high-energy photon with an ultraviolet or visible wavelength can lead to excited electronic states. Each excited electronic energy state has sub-states with different vibrational levels. Absorption of a lower energy, infrared photon can excite a vibrational level without changing the electronic state. B\: Absorption of low-energy photons at microwave or infrared wavelengths can lead to rotation or vibration of molecules, whereas high-energy photons at ultraviolet wavelengths can break apart molecules. From wag.caltech.edu.

In physics a ***blackbody*** is an idealized object that can absorb and emit radiation at all frequencies. A blackbody emits radiation according to Planck's law (Figure 6.5.3). In classical physics experiments a closed box covered on the inside with graphite is used to study its properties. It has only a small hole as an opening to measure the radiation that comes out of the box. Although a blackbody is an idealization many objects behave like a blackbody. Even fresh snow. Or the sun.



A B

Figure 6.5.3: The intensity of blackbody radiation (arbitrary units) according to Planck's law as a function of its wavelength (in nm in Figure 6.5.3 A and μm (micrometers, 1 μm = 10^{-6} m = 1,000 nm) in Figure 6.5.3B). The sun's temperature is about 6,000 K, with a peak in the visible part of the spectrum. The blue curve in the top panel shows Wien's law, which describes how the maximum moves towards larger wavelengths at colder temperatures. The bottom panel shows curves representative of the Sun's (6,000 K) and Earth's (303 K) temperatures. Note that the bottom panel uses a logarithmic x-axis and that the values for the sun (left scale) are about 6 orders of magnitude larger than those for Earth (right scale). Top image from periodni.com, bottom image from learningweather.psu.edu.

Integration of the Planck curve over all frequencies results in the **Stefan-Boltzmann law**

$$F = \varepsilon \sigma T^4 \tag{6.5.5}$$

which states that the total energy flux F in units of watts per square meter of surface area (Wm^{-2}) emitted from an object is proportional to the absolute temperature of the object T in units of Kelvin (K) to the power four. The Stefan Boltzmann constant is $\sigma = 5.67 \times 10^{-8}$ $Wm^{-2}K^{-4}$ and ε is the emissivity ($0 < \varepsilon < 1$), a material-specific constant that allows for deviations from the ideal blackbody behavior (for which $\varepsilon = 1$). For $\varepsilon = 1$, F represents the area under the Planck curve. The emissivity for ice is 0.97, that for water is 0.96, and that for snow it is between 0.8 and 0.9. Thus, water and ice are almost perfect blackbodies, whereas for snow the approximation is less perfect but still good. Highly reflective materials such as polished silver ($\varepsilon = 0.02$) and aluminum foil ($\varepsilon = 0.03$) have low emissivities.

Equation 6.5.5 states that any object at a temperature larger than absolute zero emits energy. The energy emitted increases rapidly with temperature. E.g. a doubling of temperature will cause its radiative energy output to increase by a factor of $2^4 = 16$.

Box 2: Earth's Energy Balance Model (Bare Rock)

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this Interactive Content online

Figure B6.5.2.1: Illustration of the 'Bare Rock' Energy Balance Model. Yellow arrows indicate solar radiation. The red arrow represents terrestrial radiation. https://open.oregonstate.education/climatechange/?p=104

We can now attempt to construct a simple model of the Earth's energy budget in balance. The energy input is the absorbed solar radiation (*ASR*). The energy output is the emitted terrestrial radiation (*ETR*). Thus, equation **B**6.5.2.1 becomes

$$ASR = ETR \tag{6.5.6}$$

The absorbed solar radiation can be calculated from the total solar irradiance (*TSI* = 1,370 Wm^{-2}), which is the average flux of solar radiation through a plane perpendicular to the sun's rays at the top of Earth's atmosphere. (*TSI* is also sometimes called the solar constant although it is not constant but varies slightly due to solar flares, sunspots, etc.). Since Earth is a rotating sphere the amount of radiation received per area is S = *TSI*/4 = 342 Wm^{-2} because the area of a sphere is 4 times the area of a disc with the same radius.

Part of the incident solar radiation is reflected to space by bright surfaces such as clouds or snow. This part is called *albedo* (*a*) or reflectivity. Earth's average albedo is about *a* = 0.3. This means that one third of the incident solar radiation is reflected to space and does not contribute to heating the climate system. Therefore *ASR* = (1 – *a*) S = 240 Wm^{-2}. Assuming Earth is a perfect blackbody *ETR* = σT^4. With this equation B2.1 becomes

$$(1-a)\,S = \varepsilon\sigma T^4 \tag{6.5.7}$$

and we can solve for $T = ((1 - a)\ S\ /\ \sigma)^{1/4}$. Inserting the above values for a, S, and σ gives T = 255 K or T = -18°C, suggesting Earth would completely freeze over as illustrated by ice sheets moving from the pole to the equator in the above animation. This is of course not what is going on in the real world and Earth's actual average surface temperature, which is about 15°C, is much warmer. What's wrong with this model? It is bare rock without an atmosphere! The model works well for planets without or with a very thin atmosphere like Mars, but it fails for planets that have thick atmospheres with gases that absorb infrared radiation such as Venus or Earth.

Temperature is the macroscopic expression of the molecular motions in a substance. In any substance such as the ideal gas depicted in Figure 6.5.6 molecules are constantly in motion. They bump into each other and thus exchange energy. A single molecule is sometimes slow and at other times fast, but it is their average velocity that determines the temperature of a gas. More precisely, the temperature of an ideal gas $T \sim E$ is proportional to the average kinetic energy $E = \frac{1}{2}mv^2$ of its molecules. The faster they move the higher the temperature. At absolute zero temperature T = 0 K all motions would cease.

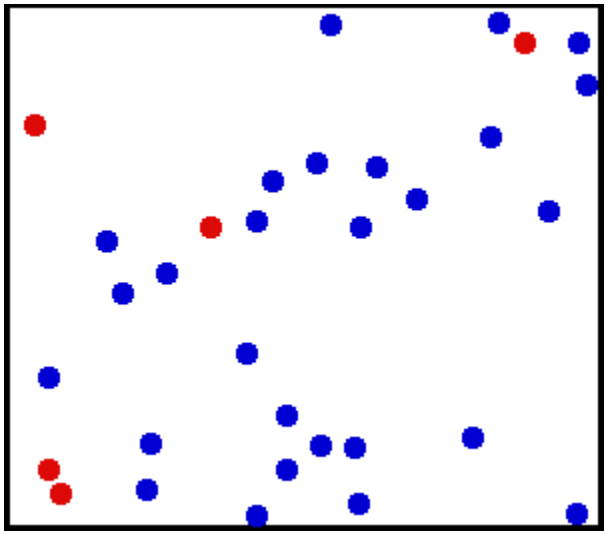


Figure 6.5.4: Animation of molecular motions in an ideal gas. From en.Wikipedia.org.

The Figure 6.5.3 shows blackbody curves for temperatures representative of the sun and Earth. Due to Earth's lower temperature the peak in the radiation occurs at longer wavelengths around 10 μm in the infrared part of the spectrum. The sun's radiation peaks around 0.5 μm in the visible part of the spectrum, but it also emits radiation at ultra-violet and near infrared wavelengths. Sunlight at the top-of-the-atmosphere is almost perfectly described by a blackbody curve (Figure Figure 6.5.5). Some solar radiation is absorbed by gases in the atmosphere but most is transmitted.

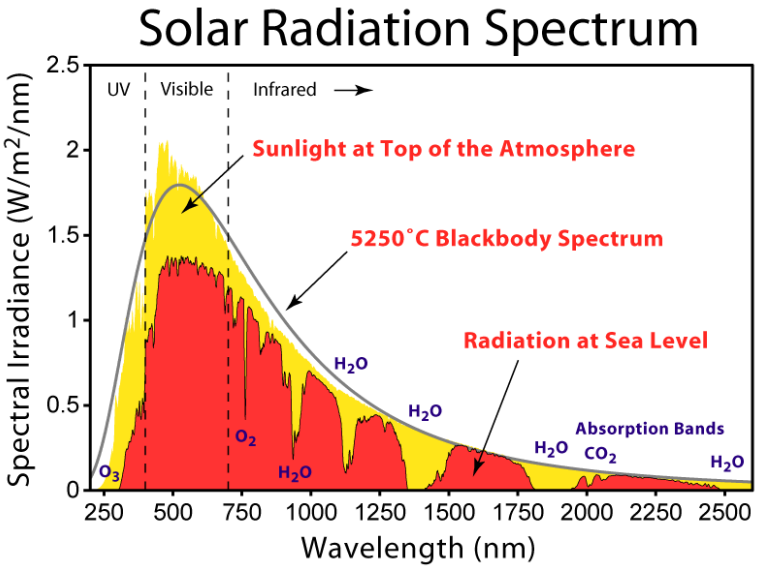


Figure 6.5.5: Solar radiation spectra for the incident sunlight at the top-of-the-atmosphere (yellow), at sea level (red), and a blackbody curve (grey). From en.Wikipedia.org.

b) The Greenhouse Effect

Absorption by water vapor in the infrared and by ozone (O_3) in the ultraviolet and scattering of light remove 25-30% of solar radiation before it hits the surface (Figure 6.5.5). For Earth's radiation, on the other hand, total absorption is with 70-85% much larger. The most important absorbers in the infrared are water vapor and CO_2 whereas oxygen/ozone, methane, and nitrous oxide absorb smaller amounts. Gases that absorb infrared radiation are called *greenhouse gases*. There is only a relatively narrow window around 10 μm through which Earth's atmosphere allows radiation to pass without much absorption. Thus, Earth's atmosphere is mostly *transparent* to solar radiation, whereas it is mostly *opaque* to terrestrial radiation.

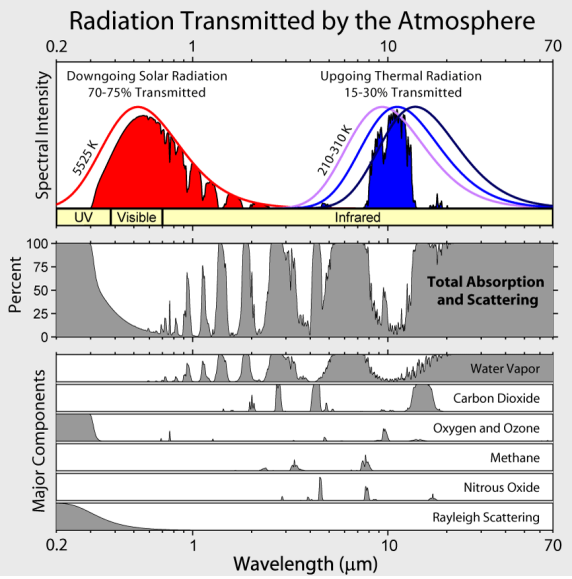


Figure 6.5.6: Radiation transmitted and absorbed by the cloud-free atmosphere. The left part of the figure shows the solar radiation and the right part shows Earth's radiation. The blackbody curve at 5525 K (red curve in the top panel) represents the incident (downgoing) solar radiation at the top-of-the-atmosphere. The red filled area is the radiation transmitted through the atmosphere. The difference between the two (the white area between the red curve and the red area) is the amount absorbed by the atmosphere. For Earth's radiation blackbody curves are shown for three temperatures (210, 260, and 310 K) and represent upgoing radiation from the surface. This is a key figure. From commons.wikimedia.org

Why is it that only certain gases in the atmosphere absorb infrared radiation? After all there is much more nitrogen (N_2)

and oxygen (O_2) gas in the atmosphere than water vapor and CO_2 (Figure \({6{.}5{.}\eatSpaces{7\)). However, nitrogen and oxygen gas both consist of two atoms of the same element. Therefore, they do not have an electric dipole moment, which is critical for the interaction with electromagnetic radiation. Gas molecules that consist of different elements like water or CO_2, on the other hand, do have dipole moments and can interact with electromagnetic radiation. Since CO_2 is a linear and symmetric molecule it does not have a permanent dipole moment. However, during certain vibrational modes (Figure Extra close brace or missing open brace) it attains a dipole moment and can absorb and emit infrared radiation. Detailed spectroscopic measurements of absorption coefficients show thousands of individual peaks in the spectra for water vapor and CO_2 caused by the interaction of vibrational with rotational modes and broadening of lines by collisions (e.g. Pierrehumbert, 2011). These data are used by detailed, line-by-line radiative transfer models to simulate atmospheric transmission, absorption, and emission of radiation at individual wavelengths.

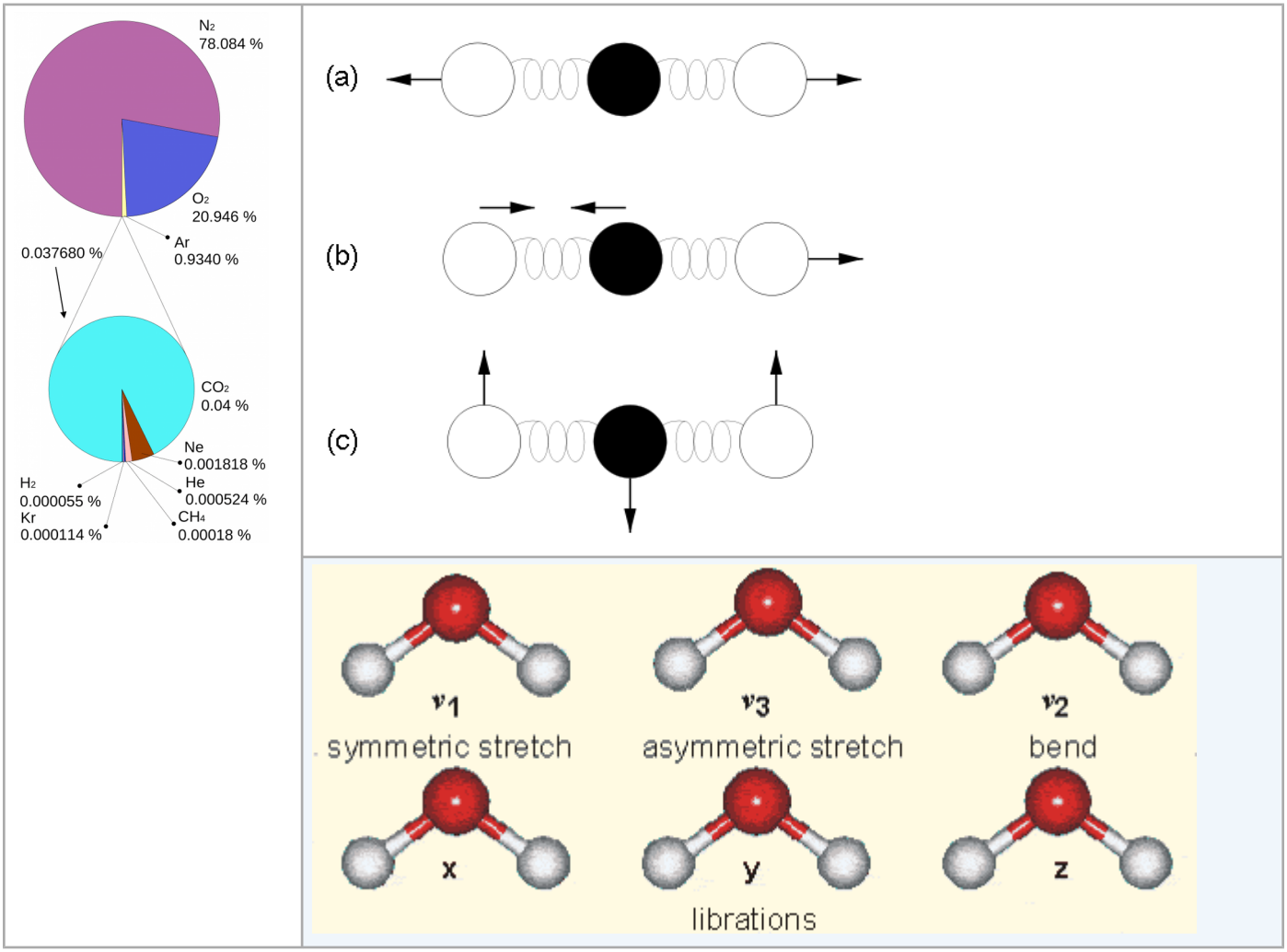


Figure 6.5.7: Left: Composition of the dry atmosphere. Water vapor, which is not included in the image, varies widely but on average makes up about 1 % of the troposphere.

Top right: Vibrational modes of CO_2. The black circles in the center represent the carbon atom, which carries a positive charge, whereas the oxygen atoms (white) carry negative charges. The asymmetric stretch mode (b) and the bend mode (c) lead to an electrical dipole moment, whereas the symmetrical stretch (a) does not. Modes (b) and (c) correspond to the absorption peaks around 4 and 15 μm, respectively (Figure 6.5.7).

Bottom right: Vibrational modes of H_2O. The red balls in the center represent the negatively charged oxygen atom, whereas the white balls represent the positively charged hydrogen atoms. Due to its angle, it has a permanent dipole moment and various modes of vibration and rotation.

Absorption (emission) of radiation by the atmosphere tends to increase (decrease) its temperature. At equilibrium the atmosphere will emit just as much energy as it absorbs, but it will emit radiation in all directions, half of which goes downward and increases the heat flux to the surface. This additional heat flux from the atmosphere warms the surface. This is the greenhouse effect.

An atmosphere in which only radiative heat fluxes are considered and that was perfectly transparent in the visible and perfectly absorbing in the infrared would result in a much warmer surface temperature than our current Earth (see Perfect Greenhouse Model box below). It can also be easily shown that adding more absorbing layers would further increase surface temperatures to $T_s = (n + 1)^{1/4} T_1$, where $T_1 = 255$ K is the temperature of the top-most of n layers. For two layers $T_s = 335$ K and the intermediate atmospheric layer's temperature is $T_2 = 303$ K. This could be called the 'Super Greenhouse Model'. Thus, even though no infrared radiation from the surface can escape to space already with one perfectly absorbing layer, adding more absorbing layers further increases surface temperatures because it insulates the surface further from the top, which will always be at 255 K. In atmospheric sciences, this process is called increasing the optical thickness of the atmosphere.

Box 3: Earth's Energy Balance Model 2 (Perfect Greenhouse)

Since Earth's atmosphere absorbs most terrestrial radiation emitted from the surface, we may want to modify our 'Bare Rock' Energy Balance Model by adding a perfectly absorbing atmosphere. As in the 'Bare Rock' model the energy balance at the top-of-the-atmosphere gives us the emission temperature of the planet, which we now interpret as the atmospheric temperature $T_a = 255$ K. We now have an additional equation for the atmospheric energy balance. At equilibrium, the total emitted terrestrial radiation from the atmosphere (two times $ETR_a = \sigma T_a^4$ since one ETR_a goes downward and one goes upward) must equal the absorbed radiation coming from the surface ($ETR_s = \sigma T_s^4$). This gives us a surface temperature of $T_s = 2^{1/4} T_a = 303$ K, which is too warm compared with the real world.

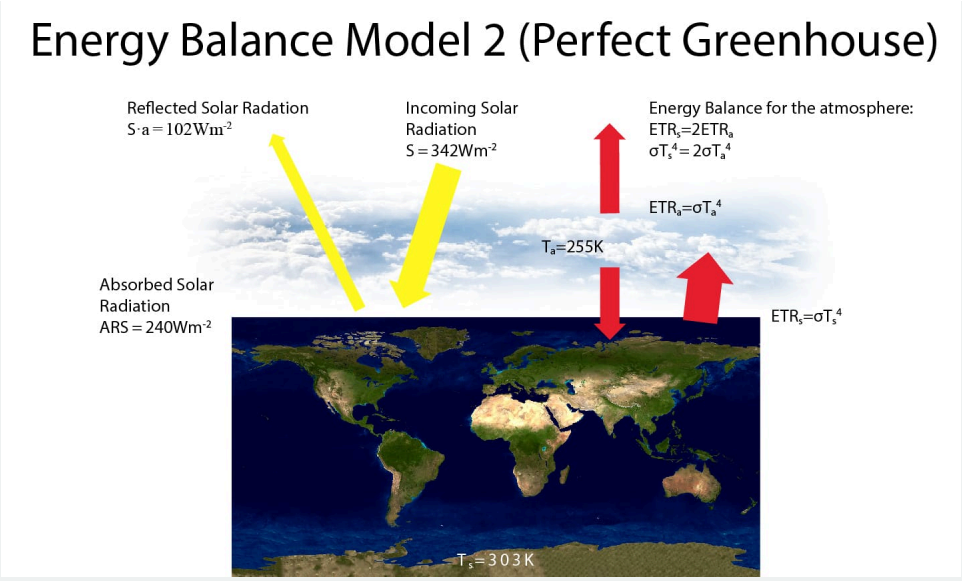


Figure B6.5.3.1: As Figure 6.5.5 but for the 'Perfect Greenhouse' model.

c) Earth's Energy Budget

In contrast to the 'Perfect Greenhouse' model, Earth's atmosphere does absorb some solar radiation, it does transmit some infrared radiation, and, importantly, it is heated by non-radiative fluxes from the surface (Figure 6.5.8. In fact, if only radiative fluxes (solar and terrestrial) are considered, surface temperatures turn out to be much warmer than they currently are and upper tropospheric temperatures are too cold (Manabe and Strickler, 1964). However, warming of the surface by absorbed solar and terrestrial radiation causes the air near the surface to warm and rise, causing *convection*. Convective motions cause both *sensible* and *latent heat* transfer from the surface to higher levels in the atmosphere. Most of this non-radiative heat transfer is in the form of latent heat. As water evaporates, it absorbs heat energy from the surrounding environment. Likewise, when it condenses, it releases heat energy to the environment. Thus, evaporation cools the surface, whereas condensation warms the atmosphere aloft. Thus, the energy and water cycles on Earth are coupled.

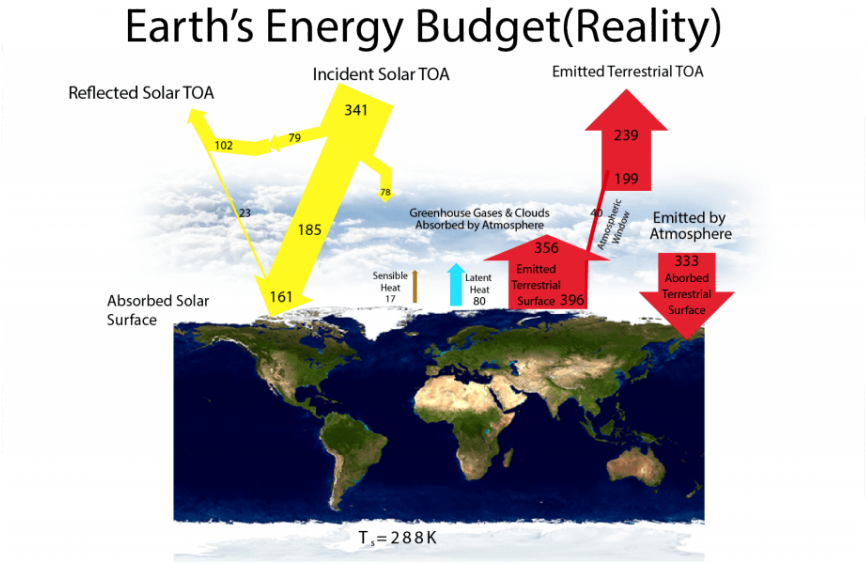


Figure 6.5.8: Earth's energy budget estimated from modern observations and models. Adapted from Trenberth et al. (2009).

The downward terrestrial radiation from the atmosphere is the largest input of heat to the surface. In fact, it is more than twice as large as the absorbed solar radiation. This illustrates the important effect of greenhouse gases and clouds on the surface energy budget. The greenhouse effect is like a blanket that keeps us warm at night by reducing the heat loss. Similarly, the glass of a

greenhouse keeps temperatures from dropping at night.

Clouds are almost perfect absorbers and emitters of infrared radiation. Therefore, cloudy nights are usually warmer than clear-sky nights. The important effect of water vapor on the greenhouse effect can be experienced by camping in the desert. Night-time temperatures there often get very cold due to the reduced greenhouse effect in the dry, clear desert air.

d) Radiative Forcings, Feedback Processes, and Climate Sensitivity

We've seen how adding greenhouse gases to the atmosphere increases its optical thickness and further insulates the surface from the top, which will lead to warming of the surface. But how much will it warm for a given increase in CO_2 or another greenhouse gas? To answer this question and because we also want to consider other drivers of climate change we introduce the concepts of radiative forcing and feedbacks. These concepts are a way to separate different mechanisms that result in climate change. **Radiative forcing** is the initial response of radiative fluxes at the top-of-the-atmosphere. It can be defined as the change in the radiative balance at the top-of-the-atmosphere (the tropopause) for a given change in one specific process that affects those fluxes with everything else held constant. Examples for such a process are changes in greenhouse gas concentrations, aerosols, or solar irradiance.

A change in the radiative balance at the top-of-the-atmosphere will cause warming if the forcing is positive (more absorbed solar radiation or less emitted terrestrial radiation), and it will cause cooling if the forcing is negative (less absorbed solar or more emitted terrestrial to space). The amount of the resulting warming or cooling will not only depend on the strength of the forcing but also on feedback processes within the climate system. A climate **feedback** is a process that amplifies (positive feedback) or dampens (negative) the initial temperature response to a given forcing. E.g. as a response to increasing CO_2 concentrations surface temperatures will warm, which will cause more evaporation and increased water vapor in the atmosphere. Since water vapor is also a greenhouse gas, this will lead to additional warming. Thus, the water vapor feedback is positive. The warming or cooling resulting from one specific forcing and all feedback processes is called **climate sensitivity**. Let's discuss some of the known radiative forcings and feedback processes in more detail.

Radiative Forcings

Detailed radiative transfer models can be used to calculate the radiative forcing for changes in atmospheric **greenhouse gas concentrations**. As shown in Figure $6.5.6$: for **CO_2**, the forcing turns out to depend logarithmically on its concentration (Ramaswamy et al., 2001)

$$\Delta F = 5.35[Wm^{-2}]ln\,(C/C_o) \tag{6.5.8}$$

where C is the CO_2 concentration and C_0 is the CO_2 concentration of a reference state (e.g. the pre-industrial).

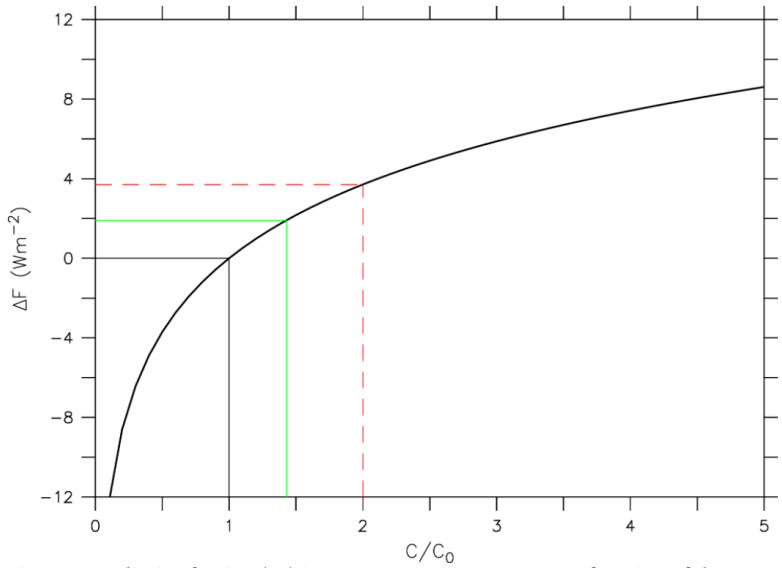
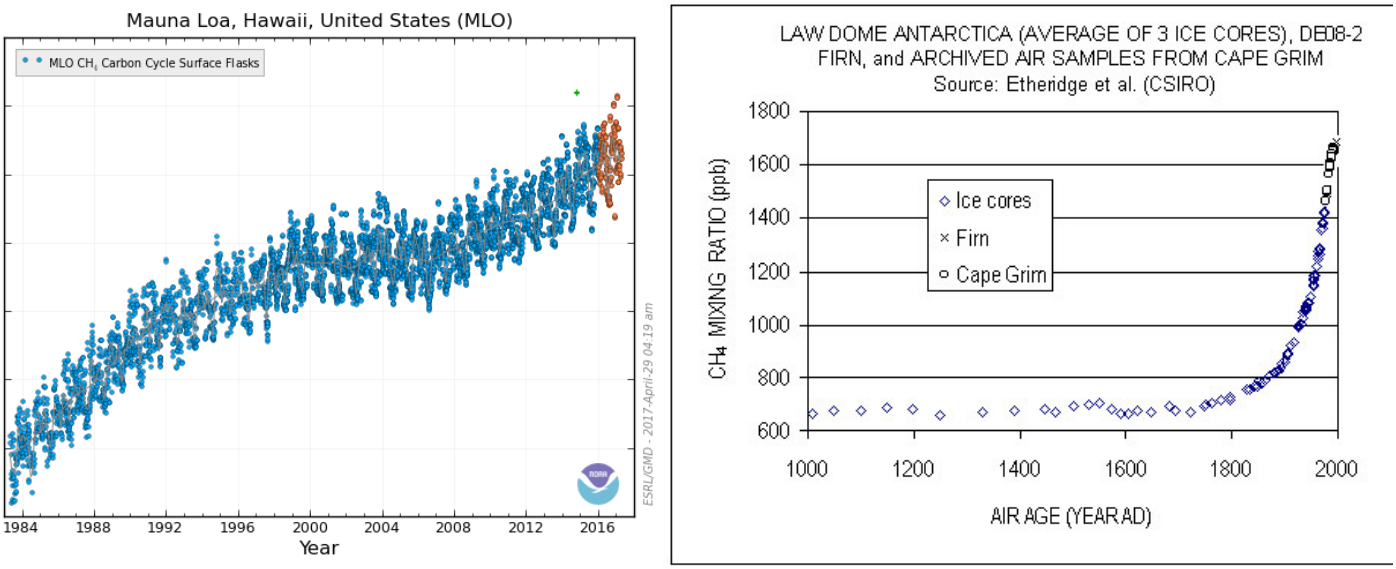


Figure 6.5.9: Radiative forcing (ΔF) in watts per square meter as a function of the atmospheric CO_2 concentration (C) relative to a reference value (C_0) according to eq. (2; black thick line). The black straight lines indicate the reference state $C = C_0$ ($\Delta F = 0$). The green and red dashed lines indicate the current (2016) state relative to the pre-industrial C/C_0 = 400 ppm / 280 ppm = 1.4 (ΔF = 1.9 Wm^{-2}) and that for a doubling of CO_2 (ΔF_{2x} = 3.7 Wm^{-2}) respectively.

This means that the radiative effect of adding a certain amount of CO_2 to the atmosphere will be smaller the more CO_2 is already in the atmosphere. The reason for this is the saturation of peaks in the absorption spectrum (Figure 6.5.6). E.g. in the center of the peak at 15 mm all radiation from the surface is already fully absorbed. Increasing CO_2 further only broadens the width of the peak.



A B

Figure 6.5.10: Atmospheric methane concentrations as a function of time A: recent air measurements at Mauna Loa. B: Ice core, firn, and air measurements from Antarctica. Note that most methane sources are in the northern hemisphere, which leads to higher concentrations there compared with the Southern Hemisphere.

Methane (CH_4) is produced naturally in wetlands and by various human activities such as in the energy industry, in rice paddies, and by agriculture (e.g. cows). It is removed by chemical reaction with OH radicals and has a lifetime of about 10 years. Anthropogenic activities have increased atmospheric methane concentrations since the industrial revolution by more than a factor of two, from around 700 ppb to more than 1600 ppb currently (Figure 6.5.10). On a per-molecule basis methane is a much

more potent greenhouse gas than CO_2, perhaps in part because its main absorption peak around 8 mm is less saturated than the one for CO_2 (Figure 6.5.6). However, since methane concentrations are more than two orders of magnitude smaller than CO_2 concentrations, its radiative forcing since the industrial revolution is 0.5 Wm^{-2}, which is less than that for CO_2. As we will see below CO_2 also has a much longer lifetime than methane and therefore it can accumulate over long timescales. Indeed, while recent measurements indicate a slowdown of methane growth rates in the atmosphere, CO_2 increases at ever higher rates (Figure 10 in Chapter 2).

Aerosols are small particles suspended in the air. Natural processes that deliver aerosols into the atmosphere are dust storms and volcanic eruptions. Burning of oil and coal by humans also releases aerosols into the atmosphere. Aerosols have two main effects on Earth's radiative balance. They directly reflect sunlight back to space (direct effect). They also act as cloud condensation nuclei such that they can cause more or brighter clouds, which also reflect more solar radiation back to space. Thus, both the direct and indirect effects of increased aerosols lead to cooling of the surface. Therefore, aerosol forcing is negative.

Large explosive volcanic eruptions can lead to ash particles and gas such as sulfur dioxide (SO_2) ejected into the stratosphere, where they can be rapidly distributed over large areas (Figure 6.5.11). In the stratosphere SO_2 is oxidized to form sulfuric acid aerosols. However, stratospheric aerosols eventually get mixed back into the troposphere and removed through precipitation or dry deposition. The lifetime of volcanic aerosols in the stratosphere is in the order of months to a few years. Estimates of the radiative forcing from volcanic eruptions depend on the eruption but varies from a few negative tenths of a watt per square meter to -3 or -4 Wm^{-2} for the largest eruptions during the last 100 years (Figure 6.5.12).

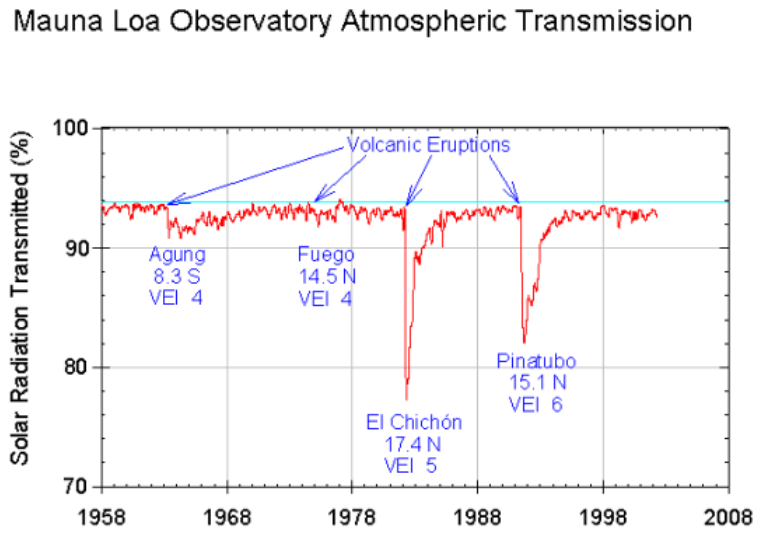


Figure 6.5.11: Effects of volcanic eruptions.
Top: Measurements of solar radiation transmitted at Hawaii's Mauna Loa Observatory.



Center: Photograph of a rising Pinatubo ash plume



Bottom: Photograph from Space Shuttle over South America taken on Aug. 8, 1991 showing the dispersion of the aerosols from the Pinatubo eruption in two layers in the stratosphere above the top of cumulonimbus clouds.

Anthropogenic aerosols are released from burning tropical forests and fossil fuels. The latter is the major component producing more sulfate aerosols currently than those naturally produced. Aerosol concentrations are higher in the northern hemisphere, where industrial activity is located. Radiative forcing estimates are uncertain but vary between about -0.5 to -1.5 Wm^{-2} for both direct and indirect effects (Figs. 6.5.12, 6.5.13). Generally, estimates of aerosol forcings are more uncertain than those for greenhouse gases.

Solar irradiance varies with the 11-year sunspot cycle. Direct, satellite-based observations of total solar irradiance show variations of about 1 Wm^{-2} between sunspot maxima and minima (Figure 6.5.12). To estimate radiative forcing TSI needs to be divided by four, which results in about 0.25 Wm^{-2}. Longer-term estimates of TSI variations based on sunspot cycles indicate an increase from the Maunder Minimum (1645-1715) to the present by about 1 Wm^{-2}. The resulting forcing is again about 0.25 Wm^{-2}.

Comparisons of the different forcings indicate that long-term trends of the last 100 years or so are dominated by anthropogenic forcings. The negative forcings from increases in aerosols compensate somewhat the positive forcings from the increase in greenhouse gases. However, the net effect is still a positive forcing of about 2 Wm^{-2}. Volcanic forcings are episodic and the estimates of solar forcing are much smaller than those of anthropogenic forcings.

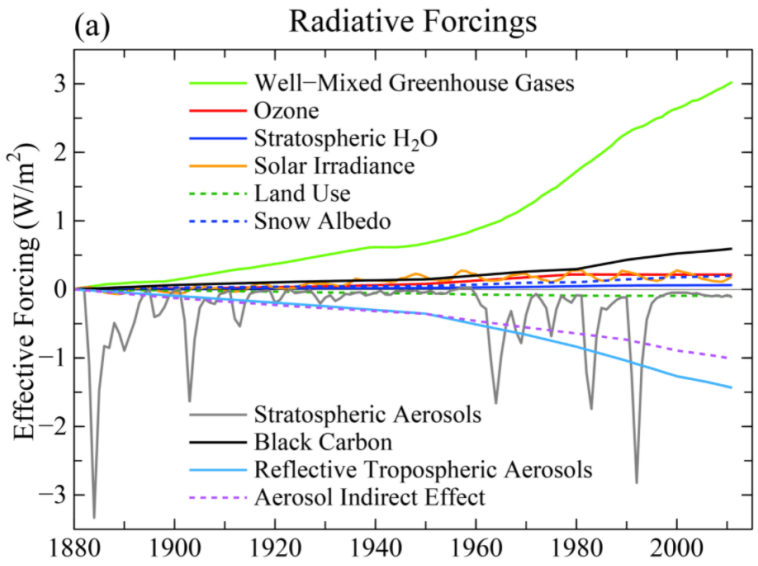


Figure 6.5.12: Radiative forcings as a function of time. From data.giss.nasa.gov.

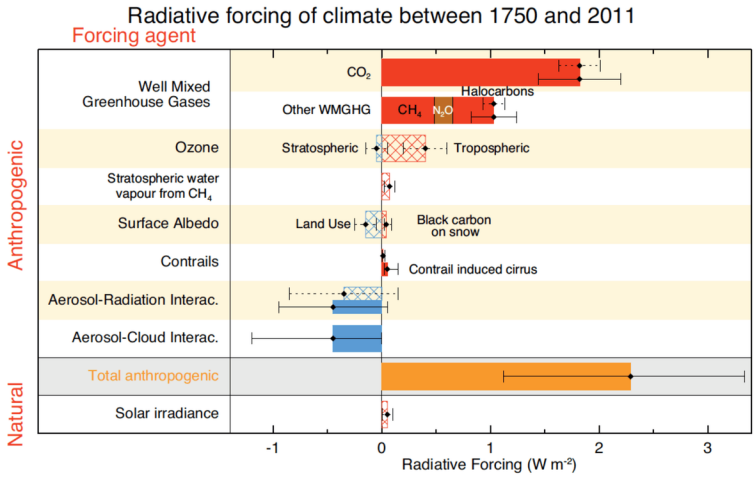


Figure 6.5.13: Summary of radiative forcings. From IPCC (2013). Hatched bars denote low confidence and scientific understanding.

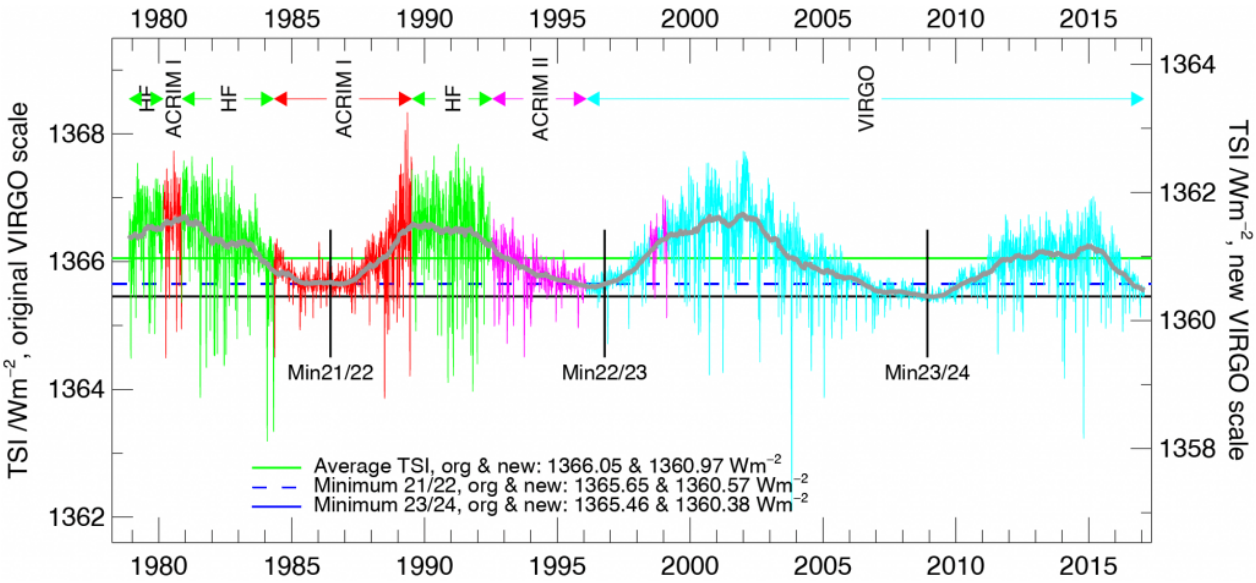
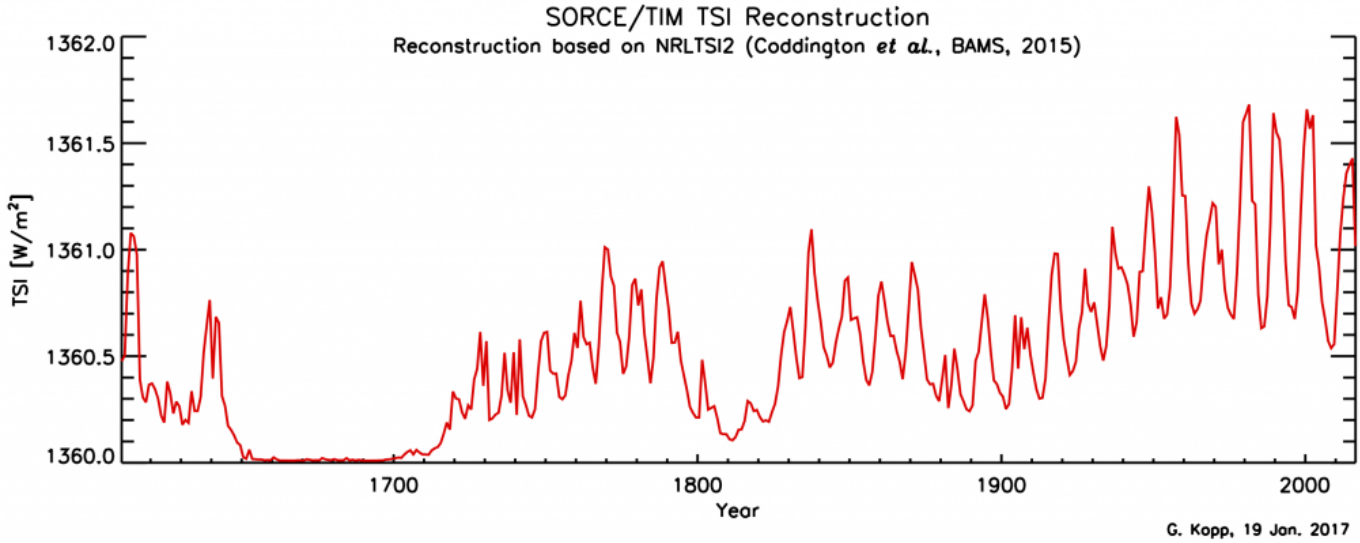


Figure 6.5.14: Total solar irradiance variations. Top: measurements based on various satellites as a function of time.



Bottom: longer term reconstructions.

Feedback Processes

A feedback process is a modifier of climate change. It can be defined as a process that can amplify or dampen the response to the initial radiative forcing through a feedback loop. In a feedback loop the output of a process is used to modify the input (Figure 6.5.15). By definition, a positive feedback amplifies and a negative feedback dampens the response. In our case, the input is the radiative forcing (ΔF) and the output is the global average temperature change (ΔT).

Interactive Content

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this Interactive Content online

Figure 6.5.15: Schematic illustration of fast climate feedback loops (left) and their effects on the vertical temperature distribution in the troposphere (right).
https://open.oregonstate.education/climatechange/?p=104

Imagine talking into a microphone. A positive feedback process works like the amplifier that makes your voice louder. It can lead to a runaway effect if no or only weak negative feedback processes are present. If you hold the microphone too close to the speaker, the runaway effect can result in a loud noise. Early in Earth's history, between about 500 million and 1 billion years ago, Earth may have experienced a runaway effect into a completely ice and snow covered planet called 'Snowball Earth' caused by the ice-albedo feedback (see below). An example of a negative feedback process would be talking into a pillow. This makes your voice quieter. A negative feedback is stabilizing. It prevents a runaway effect. Both positive and negative feedback processes operate in the climate system. (Try to imagine talking into multiple pillows and microphones.) In the following we will discuss the most important ones.

Let's assume we have an initial positive forcing ($\Delta F > 0$) as illustrated in Figure 6.5.15 As a response, temperatures in the troposphere will warm. Since the troposphere is well mixed, we can assume that the warming is uniform ($\Delta T_s = \Delta T_a > 0$). Thus,

the upper troposphere will warm, which will lead to increased emitted terrestrial radiation ($\Delta ETR_a > 0$) to space. Increased heat loss opposes the forcing and leads to cooling. This is the **Planck feedback,** and it is negative. Equilibrium will be achieved if $\Delta ETR_a = \Delta F$. Since $\Delta ETR_a = ETR_{a,f} - ETR_{a,i}$ is the difference between the final $ETR_{a,f} = \sigma(T_a + \Delta T_a)^4$ and the initial $ETR_{a,i} = 240$ Wm^{-2} as calculated above (e.g. Figure B2.1), we can calculate the surface temperature change due to the forcing and the Planck feedback $\Delta T_{pl} = \Delta T_a = [(ETR_{a,i} + \Delta F)/\sigma]^{1/4} - T_a$. For a doubling of atmospheric CO_2 $\Delta F = 3.7$ Wm^{-2} this results in $\Delta T_{pl} = 1$ K.

Thus, if only the Planck feedback was operating and everything else would be fixed, a doubling of CO_2 would result in a warming of about 1 K. However, warmer air and surface ocean temperatures will also lead to more evaporation. The amount of water vapor an air parcel can hold depends exponentially on its temperature. This relationship, which can be derived from classical thermodynamics, is called the Clausius-Clapeyron relation (Figure 6.5.19). Since most of Earth is covered in oceans there is no lack of water available for evaporation. Therefore, it is likely that warmer air temperatures will lead to more water vapor in the atmosphere. Because water vapor is a strong greenhouse gas this will lead to an additional reduction in the amount of outgoing longwave radiation and therefore to more warming. Thus, the **water vapor feedback** is positive. If we assume again that the temperature change is uniform with height the troposphere will warm by an additional amount ΔT_{wv} due to the water vapor feedback (red line in Figure 6.5.15).

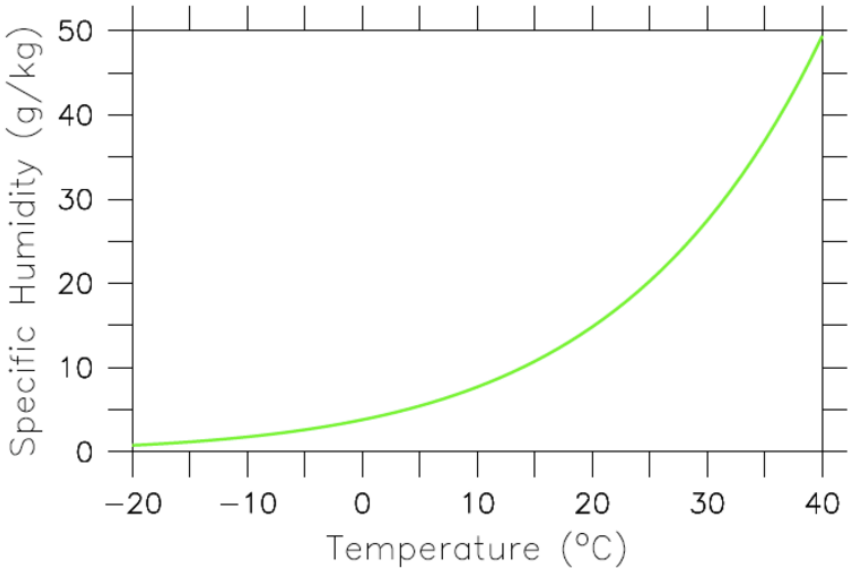


Figure 6.5.16: The Clausius-Clapeyron relation describes the amount of water vapor (in g water per kg of moist air) that air at saturation can hold as a function of temperature. All points long the green line represent 100% relative humidity. The lower a point is below the green line the lower its relative humidity will be. E.g. a point half way between the green line and the zero line would have 50% relative humidity.

Increased amounts of water vapor in the atmosphere also imply increased vertical transport of water vapor and thus more latent heat release at higher altitudes where condensation occurs. This warms the air aloft $\Delta T_{lr} > 0$. In contrast, at the surface increased evaporation leads to cooling $\Delta T_{lr} < 0$. Thus, the lapse-rate, $\Gamma = \Delta T/\Delta z$, which is the change in temperature with height in the atmosphere, is expected to decrease. Warming of the upper atmosphere will increase outgoing longwave radiation. Therefore, similarly to the Planck feedback, the **lapse rate feedback** is negative.

Since both the water vapor and the lapse rate feedback are caused by changes in the hydrologic cycle, they are coupled. This results in reduced uncertainties in climate models if the combined water vapor plus lapse rate feedback is considered rather than each feedback individually (Soden and Held, 2006).

Warming surface temperatures will also cause melting of snow and ice. This decreases the albedo and thus it increases the amount of absorbed solar radiation, which will lead to more warming. Thus, the **ice-albedo feedback** is positive. Our simple energy balance model 2 from above can be modified to include a temperature dependency of the albedo, which can exhibit a runaway transition to a snowball Earth and interesting hysteresis behavior. Hysteresis means that the state of a system does not only depend on its parameters but also on its history. Transitions between states can be rapid even if the forcing changes slowly.

Warming will also likely change clouds. However, no clearly understood mechanism has been identified so far that would make an unambiguous prediction how clouds would change in a warmer climate. Comprehensive climate models predict a large range of **cloud feedbacks**. Most of them are positive, but a negative feedback cannot be excluded at this point. The cloud feedback is the

least well understood and the most uncertain element in climate models. It is also the source of the largest uncertainty for future climate projections.

Climate models can be used to quantify individual feedback parameters y_i. They are calculated as the change in the radiative flux at the top-of-the-atmosphere ΔR_i divided by the change of the controlling variable Δx_i: $y_i = \Delta R_i / \Delta x_i$. E.g. to quantify the Planck feedback the controlling variable $\Delta x_i = \Delta T$ is atmospheric temperature. The atmospheric temperature is increased everywhere by ΔT = 1 K and then the radiative transfer model calculates ΔR at every grid point of the model, that is at all latitudes and longitudes, and then averages over the whole globe. This results in ΔR_{pl} and $y_{pl} = \Delta R_{pl} / \Delta T$. All individual feedback parameters can be added to yield the total feedback $y = y_{pl} + y_{wv} + y_{lr} + y_{ia} + y_{cl}$. The total feedback has to be negative to avoid a runaway effect. The strongest, most precisely known feedback is the Planck feedback, which is about $y_{pl} = -3.2$ $Wm^{-2}K^{-1}$. Estimates for the other feedbacks are about $y_{wv} + y_{lr} \cong +1$ $Wm^{-2}K^{-1}$ for the combined water vapor / lapse rate feedbacks, $y_{ia} = +0.3$ $Wm^{-2}K^{-1}$ for ice-albedo feedback, and $y_{cl} = +0.8$ $Wm^{-2}K^{-1}$ for the cloud feedback. This gives for the total feedback y values from about −0.8 to about −1.6 Wm^{-2}. The total feedback parameter can be used to calculate the climate sensitivity.

Climate Sensitivity

The climate sensitivity $\Delta T_{2\times}$ is usually defined as the global surface temperature change for a doubling of atmospheric CO_2 at equilibrium and it includes all fast feedbacks discussed above. Current best estimates are $\Delta T_{2\times} \cong 3$ K, however it ranges from about 1.5 to about 4.5 K. This large uncertainty is mostly due to the large uncertainty of the cloud feedback. Sometimes the climate sensitivity $S_C = -1/y$ is reported in units of $K/(Wm^{-2})$. Since we know the forcing for a doubling of CO_2 $\Delta F_{2\times} = 3.7$ Wm^{-2} quite well, one can be calculated from the other using $S_C = \Delta T_{2\times} / \Delta F_{2\times}$. *For $\Delta T_{2\times} \cong 3$ K, $S_C \cong 0.8$ $K/(Wm^{-2})$, and $y \cong 1.2$ $Wm^{-2}K^{-1}$.* Note that slow feedbacks associated with the growth and melting of ice sheets or changes in the carbon cycle are not included in these numbers. Since we would expect those feedbacks to be also positive we can expect an even higher climate sensitivity for longer timescales (hundredths to thousandths of years).

Our definitions of radiative forcings and feedbacks above are not clear cut. They are based on existing climate models and the processes included in them. For example changes in atmospheric CO_2 concentrations over long paleoclimate timescales can be thought of as a feedback rather than a forcing since the ultimate forcing of the ice age cycles are changes in the Earth's orbital parameters and hence the seasonal distribution of solar radiation.

Questions

- What is a budget equation? Describe it using your own words.
- When is a budget in balance?
- What is electromagnetic radiation?
- What is a photon?
- Which has shorter and which longer wavelengths: ultraviolet, visible, or infrared radiation?
- Which of the previous three wavelengths photons is highest/lowest in energy?
- How does electromagnetic radiation interact with matter?
- What is a blackbody?
- What are the differences between the blackbody radiation curves for the sun and Earth?
- What is the Stefan-Boltzmann law? Write down the formula and explain the variables.
- What is the 'bare rock' model of the Earth's energy balance and why did it fail to correctly predict Earth's surface temperature?
- What is temperature? Describe it using your own words.
- What is the greenhouse effect?
- What are greenhouse gases?
- What are Earth's two most important greenhouse gases?
- What is the total solar irradiance (TSI) at the top of the atmosphere on a surface perpendicular to the sun's rays (in W/m^2)?
- What is the incoming solar irradiance (S) at the top of the atmosphere averaged over the whole Earth and over one year (in W/m^2)?
- What percentage of the incident solar radiation at the top-of-the-atmosphere is absorbed by the atmosphere?

- What percentage of the upward terrestrial radiation emitted from the surface is absorbed by the atmosphere?

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6.6: What Makes the Climate Change?

There are two parts to climate change, the first one is known as **climate forcing**, which is when conditions change to give the climate a little nudge in one direction or the other. The second part of climate change, and the one that typically does most of the work, is what we call a **feedback**. When a climate forcing changes the climate a little, a whole series of environmental changes take place, many of which either exaggerate the initial change (**positive feedbacks**), or suppress the change (**negative feedbacks**). In this section we will be discussing primarily natural climate forcing. Natural climate forcing has been going on throughout geological time. A wide range of processes has been operating at widely different time scales, from a few years to billions of years.

An example of a climate-forcing mechanism is the increase in the amount of carbon dioxide (CO_2) in the atmosphere that results from our use of fossil fuels. CO_2 traps heat in the atmosphere and leads to climate warming. Warming changes vegetation patterns; contributes to the melting of snow, ice, and permafrost; causes sea level to rise; reduces the solubility of CO_2 in sea water; and has a number of other minor effects. Most of these changes contribute to more warming. Melting of permafrost, for example, is a strong positive feedback because frozen soil contains trapped organic matter that is converted to CO_2 and methane (CH_4) when the soil thaws. Both these gases accumulate in the atmosphere and add to the warming effect. On the other hand, if warming causes more vegetation growth, that vegetation should absorb CO_2, thus reducing the warming effect, which would be a negative feedback. Under our current conditions—a planet that still has lots of glacial ice and permafrost—most of the feedbacks that result from a warming climate are positive feedbacks and so the climate changes that we cause get naturally amplified by natural processes.

Natural Climate Forcing

Life Cycle of the Sun

The longest-term natural forcing variation is related to the evolution of the Sun. Like most other stars of a similar mass, our Sun is evolving. For the past 4.57 billion years, its rate of nuclear fusion has been increasing, and it is now emitting about 40% more energy (as light) than it did at the beginning of geological time (Figure 6.6.1). A difference of 40% is big, so it's a little surprising that the temperature on Earth has remained at a reasonable and habitable temperature for all of this time. The mechanism for that relative climate stability has been the evolution of our atmosphere from one that was dominated by CO_2, and also had significant levels of CH_4—both GHGs—to one with only a few hundred parts per million of CO_2 and just under 1 part per million of CH_4 because, over geological time, life and its metabolic processes have evolved and changed the atmosphere.

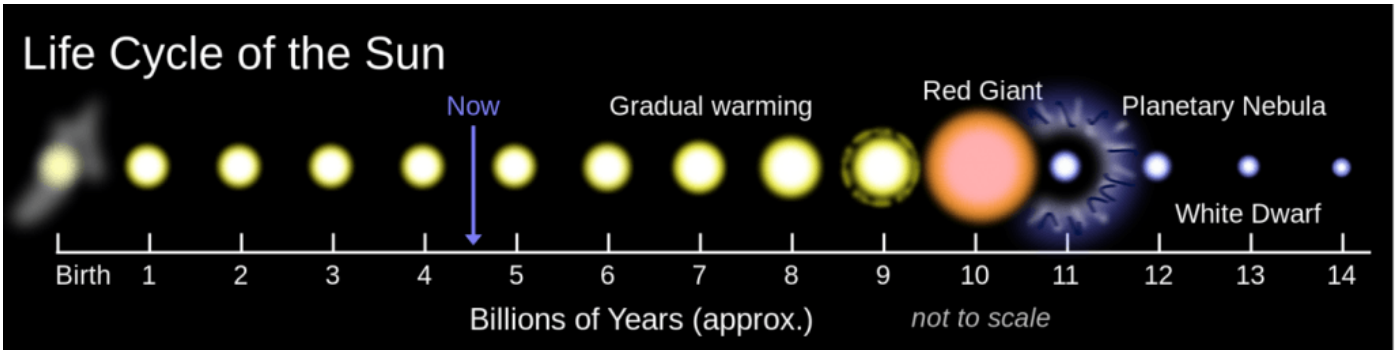


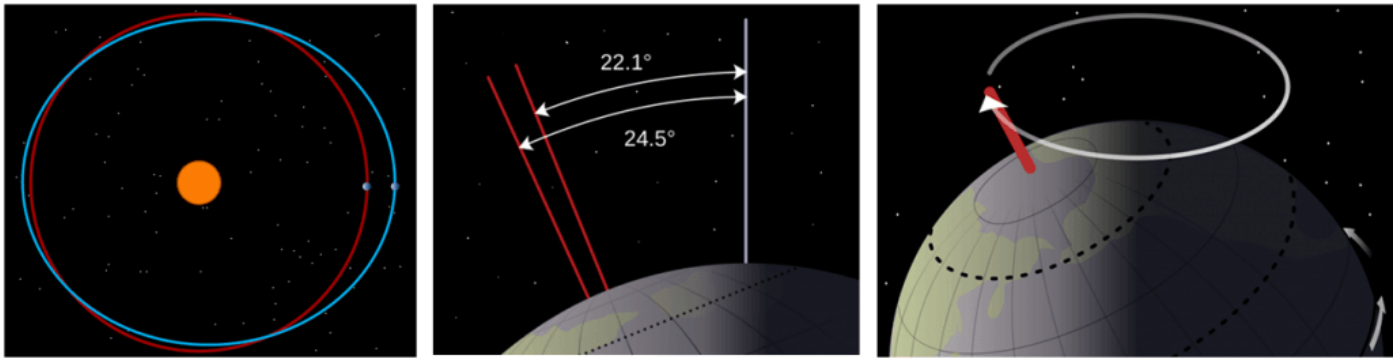
Figure 6.6.1: The life cycle of our Sun and of other similar stars.
[from https://upload.wikimedia.org/wikiped..._Cycle.svg.png
"Solar Life Cycle" by Oliver Beatson. Public domain.]

Changes occurring in the sun itself can affect the intensity of the sunlight that reaches Earth's surface. The intensity of the sunlight can cause either warming (during periods of stronger solar intensity) or cooling (during periods of weaker solar intensity). The sun follows a natural 11-year cycle of small ups and downs in intensity, but the effect of these 11-year cycles on Earth's climate is small.

Milankovitch Cycles

Earth's orbit around the Sun is nearly circular, but like all physical systems, it has natural oscillations (Figure 6.6.2). The importance of changes in the **eccentricity** (shape) of the Earth's orbit, **tilt** of the Earth, and **precession** (where the Earth's axis points) to Earth's climate cycles (now known as **Milankovitch Cycles**) was first pointed out by Yugoslavian engineer and mathematician Milutin Milankovitch in the early 1900s. Milankovitch recognized that although the variations in the orbital cycles did not affect the total amount of **insolation** (light energy from the Sun) that Earth received, *it did affect where on Earth that energy was strongest*. Glaciations are most sensitive to the insolation received at latitudes of around 65°, and with the current configuration of continents, it would have to be 65° north (because there is almost no land at 65° south).

First, the shape of the orbit changes on a regular time scale — close to 100,000 years — from being close to circular to being very slightly elliptical. But the circularity of the orbit is not what matters; it is the fact that as the orbit becomes more elliptical, the position of the Sun within that ellipse becomes less central or more eccentric (Figure 6.6.2a). **Eccentricity** is important because when it is high, the Earth-Sun distance varies more from season to season than it does when eccentricity is low.



(a) The 100,000 year cycle of eccentricity of the Sun within the Earth's orbit. The blue orbit is more elliptical than the red one, and the Sun is offset from the centre of the ellipse

(b) The 41,000 year cycle of the angle of tilt (obliquity) of the Earth's axis (red lines) compared to a line perpendicular to the plane of the Earth's orbit (light blue line).

(c) the 20,000 year cycle of precession of the Earth's rotational axis

Figure 6.6.2: The cycles of Earth's orbit and rotation. These are also called the Milankovitch Cycles.
[© Steven Earle. CC BY. after a: https://upload.wikimedia.org/wikiped..._zero.svg.png], b: https://upload.wikimedia.org/wikiped...range.svg.png] c: https://upload.wikimedia.org/wikiped...ns/thumb/4/43/ Earth_precession.svg/2000px-Earth_precession.svg.png]

Second, Earth rotates around an axis through the North and South Poles, and that axis is at an angle to the plane of Earth's orbit around the Sun (Figure 6.6.2b). The angle of tilt (also known as **obliquity**) varies on a time scale of 41,000 years. When the angle is at its maximum (24.5°), Earth's seasonal differences are accentuated. When the angle is at its minimum (22.1°), seasonal differences are minimized. The current hypothesis is that glaciation is favored at low seasonal differences as summers would be cooler and snow would be less likely to melt and more likely to accumulate from year to year.

Third, the direction in which Earth's rotational axis points also varies, on a time scale of about 20,000 years (Figure 6.6.2c). This variation, known as **precession**, means that although the North Pole is presently pointing to the star Polaris (the pole star), in 10,000 years it will point to the star Vega.

The most important aspects are whether the northern hemisphere is pointing toward the Sun at its closest or farthest approach, and how eccentric the Sun's position is in Earth's orbit. Two opposing situations are illustrated in Figure 6.6.3. In the upper panel, the northern hemisphere is at it farthest distance from the Sun during summer, which means cooler summers. In the lower panel, the northern hemisphere is at its closest distance to the Sun during summer, which means hotter summers. Cool summers—as opposed to cold winters—are the key factor in the accumulation of glacial ice, so the upper scenario in Figure 6.6.3 is the one that promotes glaciation. This factor is greatest when eccentricity is high.

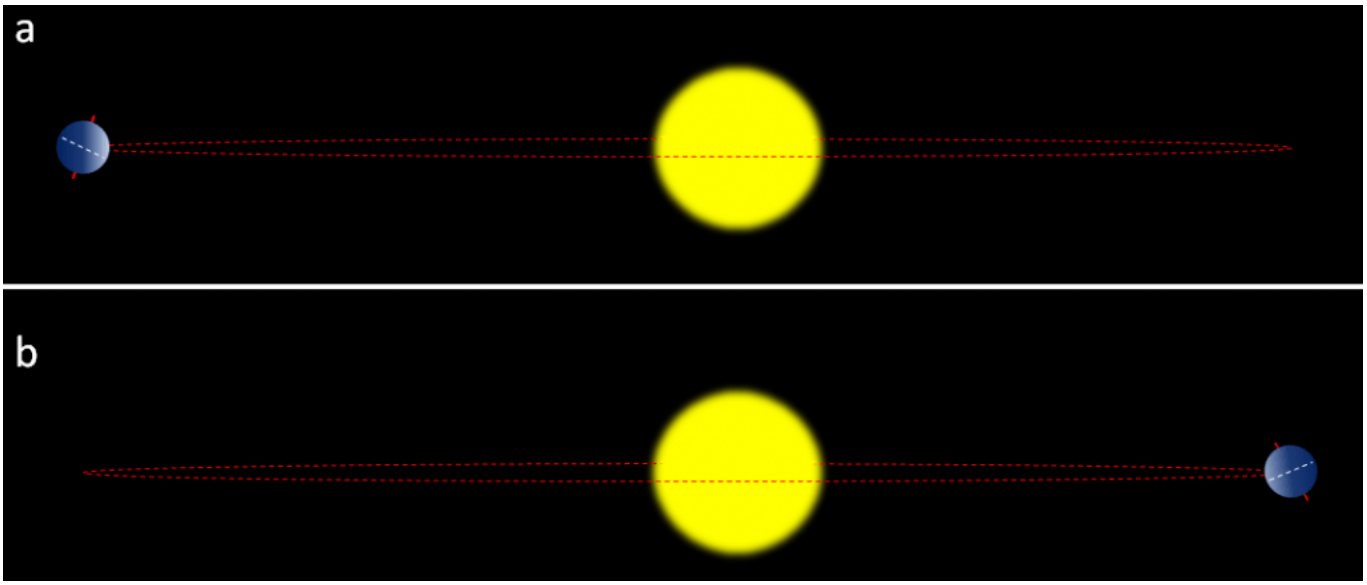


Figure 6.6.3: The effect of precession on insolation in the northern hemisphere summers. In (a) the northern hemisphere summer takes place at greatest Earth-Sun distance, so summers are cooler. In (b) (10,000 years or one-half precession cycle later) the opposite is the case, so summers are hotter. The red dashed line represents Earth's path around the Sun. © Steven Earle. CC BY.

As already stated, **climate feedbacks** are critically important in amplifying weak climate forcings into full-blown climate changes. When Milankovitch published his theory in 1924, it was widely ignored, partly because it was evident to climate scientists that the forcing produced by the orbital variations was not strong enough to drive the significant climate changes of the glacial cycles. Those scientists did not recognize the power of positive feedbacks. It wasn't until 1973, 15 years after Milankovitch's death, that sufficiently high-resolution data were available to show that the Pleistocene glaciations were indeed driven by the orbital cycles, and it became evident that the orbital cycles were just the forcing that initiated a range of feedback mechanisms that made the climate change.

Data for tilt, eccentricity, and precession over the past 400,000 years have been used to determine the insolation levels at 65° north, as shown in Figure 6.6.4. Also shown in Figure 6.6.4 are Antarctic ice-core temperatures from the same time period. The correlation between the two is clear, and it shows up in the Antarctic record because when insolation changes lead to growth of glaciers in the northern hemisphere, southern-hemisphere temperatures are also affected.

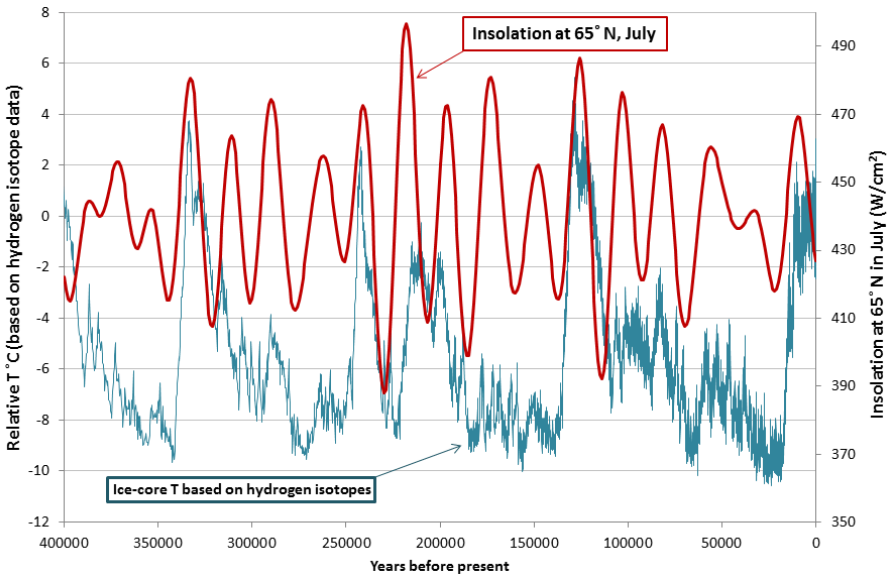


Figure 6.6.4: Insolation at 65° N in July compared with Antarctic ice-core temperatures.
[© Steven Earle. CC BY. Based on data from Valerie Masson-Delmotte, "EPICA Dome C Ice Core 800KYr Deuterium Data and Temperature Estimates," WDCA Contribution Series Number : 2007 -091, NOAA/NCDC Paleoclimatology Program, Boulder CO, USA. Retrieved from: ftp://ftp.ncdc.noaa.gov/pub/data/pal...uttemp2007.txt and from Berger, A. and Loutre, M.F. (1991). Insolation values for the climate of the last 10 million years. Quaternary Science Reviews, 10, 297-317.]

Plate Tectonic Processes

Plate tectonic processes contribute to climate forcing in several different ways, and on time scales ranging from tens of millions to hundreds of millions of years. One mechanism is related to continental position. For example, we know that Gondwana (South America + Africa + Antarctica + Australia) was positioned over the South Pole between about 450 and 250 Ma, during which time there were two major glaciations (Andean-Saharan and Karoo) affecting the South polar regions and cooling the rest of the planet at the same time. Another mechanism is related to continental collisions. For example, the collision between India and Asia, which started at around 50 Ma, resulted in massive tectonic uplift. The consequent accelerated weathering of this rugged terrain consumed CO_2 from the atmosphere and contributed to gradual cooling over the remainder of the Cenozoic. Changes in continental position can also lead to changes in ocean circulation, and therefore the distribution of energy from equator to the poles. For example, the opening of the Drake Passage — due to plate-tectonic separation of South America from Antarctica — led to the development of the Antarctic Circumpolar Current, which isolated Antarctica from the warmer water in the rest of the ocean and thus contributed to Antarctic glaciation starting at around 35 Ma.

Volcanic eruptions don't just involve lava flows and exploding rock fragments; various particulates and gases are also released, including carbon dioxide, water vapor, sulfur dioxide, hydrogen sulfide, hydrogen, and carbon monoxide. Volcanic eruptions can last a few days, but the solids and gases released during an eruption can influence the climate over a period of a few years, causing short-term climate changes. Generally, volcanic eruptions cool the climate. Sulphur dioxide is an aerosol that reflects incoming solar radiation and has a net cooling effect that is short lived (a few years in most cases, as the particulates settle out of the atmosphere within a couple of years), and doesn't typically contribute to longer-term climate change. This occurred in 1783 when volcanoes in Iceland erupted and caused the release of large volumes of sulfuric oxide. This led to haze-effect cooling, a global phenomenon that occurs when dust, ash, or other suspended particles block out sunlight and trigger lower global temperatures as a result; haze-effect cooling usually extends for one or more years. In Europe and North America, haze-effect cooling produced some of the lowest average winter temperatures on record in 1783 and 1784. Volcanic CO_2 emissions can contribute to climate warming but only if a greater-than-average level of volcanism is sustained over a long time (at least tens of thousands of years). It is widely believed that the catastrophic end-Permian extinction (at 250 Ma) resulted from warming initiated by the eruption of the massive Siberian Traps over a period of at least a million years.

Greenhouse Gas Concentrations

Since scientists cannot go back in time to directly measure climatic variables, such as average temperature and precipitation, they must instead indirectly measure temperature. Antarctic ice cores are a key example of such evidence. These ice cores are

samples of polar ice obtained by means of drills that reach thousands of meters into ice sheets or high mountain glaciers. Viewing the ice cores is like traveling backwards through time; the deeper the sample, the earlier the time period. Trapped within the ice are bubbles of air and other biological evidence that can reveal temperature and carbon dioxide data. Antarctic ice cores have been collected and analyzed to indirectly estimate the temperature of the Earth over the past 400,000 years (Figure 6.6.5a). The 0 °C on this graph refers to the long-term average. Temperatures that are greater than 0 °C exceed Earth's long-term average temperature. Conversely, temperatures that are less than 0 °C are less than Earth's average temperature. This figure shows that there have been periodic cycles of increasing and decreasing temperature.

Before the late 1800s, the Earth has been as much as 9 °C cooler and about 3 °C warmer. Note that the graph in Figure 6.6.5 b shows that the atmospheric concentration of carbon dioxide has also risen and fallen in periodic cycles; note the relationship between carbon dioxide concentration and temperature. Figure 6.6.5b shows that carbon dioxide levels in the atmosphere have historically cycled between 180 and 300 parts per million (ppm) by volume.

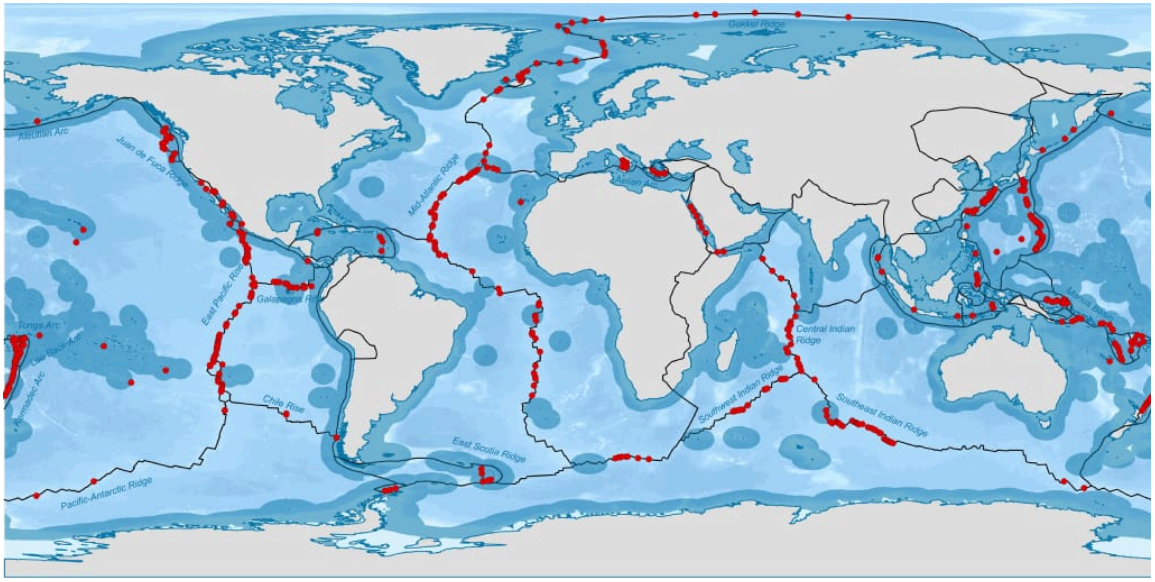


Figure 6.6.5: Ice at the Russian Vostok station in East Antarctica was laid down over the course 420,000 years and reached a depth of over 3,000 m. By measuring the amount of CO_2 trapped in the ice, scientists have determined past atmospheric CO_2 concentrations. Temperatures relative to modern day were determined from the amount of deuterium (an isotope of hydrogen) present.

Changes in Ocean Currents

Ocean currents are important to climate, and currents also have a tendency to oscillate. Glacial ice cores show clear evidence of changes in the Gulf Stream (and other parts of the thermohaline circulation system) that affected global climate on a time scale of about 1,500 years during the last glaciation.

The east-west changes in sea-surface temperature and surface pressure in the equatorial Pacific Ocean—known as the El Niño Southern Oscillation or ENSO—varies on a much shorter time scale of between two and seven years. These variations tend to garner the attention of the public because they have significant climate implications in many parts of the world. The past 65 years of ENSO index values are shown in Figure 6.6.6. The strongest **El Niños** in recent decades were in 1983 and 1998, and those were both very warm years from a global perspective. During a strong El Niño, the equatorial Pacific sea-surface temperatures are warmer than normal and heat the atmosphere above the ocean, which leads to warmer-than-average global temperatures.

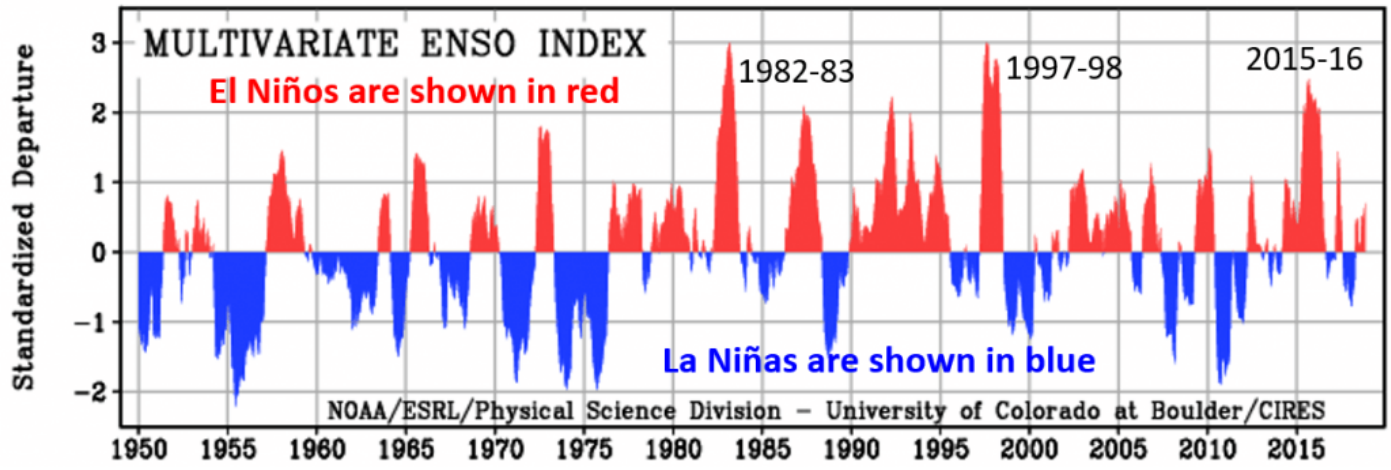


Figure 6.6.6: Variations in the ENSO index from 1950 to early-2019.
[© Steven Earle. CC BY. after NOAA at: http://www.esrl.noaa.gov/psd/enso/mei/ "Multivariate ENSO Index (MEI)" by NOAA.]

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6.7: Prehistoric Climate Change and Proxys for Studying Past Climates

Over Earth history, the climate has changed a lot. For example, during the Mesozoic Era, the Age of Dinosaurs, the climate was much warmer and carbon dioxide was abundant in the atmosphere. However, throughout the Cenozoic Era (65 Million years ago to today), the climate has been gradually cooling. This section summarizes some of these major past climate changes.

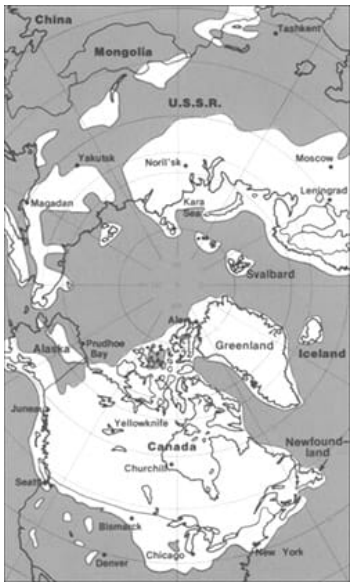


Figure 6.7.1: Maximum extent of Laurentide Ice Sheet

Past Glaciations

Through geologic history, the climate has changed slowly over millions of years. Before the most recent Pliocene-Quaternary glaciation, there were three other major glaciations [20]. The oldest, known as the Huronian, occurred toward the end of the Archean-early Proterozoic (~2.5 billion years ago). The major event of that time, the great oxygenation event, is most commonly associated with the cause of that glaciation. The increased oxygen is thought to have reacted with the potent greenhouse gas methane, causing cooling [21].

The end of the Proterozoic (about 700 million years ago) had another glaciation, known as the **Snowball Earth hypothesis** [22]. Glacial evidence has been interpreted in widespread rock sequences globally and even has been linked to low-latitude glaciation [23]. Limestone rock (usually formed in tropical marine environments) and glacial deposits (usually formed in cold climates) are often found together from this time in regions all around the world. In Utah, Antelope Island in the Great Salt Lake has interbedded limestone and glacial deposits (diamictites) interpreted to be formed by continental glaciation [24]. The idea of the controversial Snowball Earth hypothesis is that a runaway albedo effect (ice and snow reflecting solar radiation) might cause the complete freezing of land and ocean surfaces and a collapse of biological activity. The ice-covered earth would only melt when carbon dioxide from volcanoes reached high concentrations, due to the inability for carbon dioxide to enter the then-frozen ocean. Some studies estimated carbon dioxide was 350 times higher than today's concentrations [22]. The complete freezing [25] and the extent of the freezing [26] has come into question.

Glaciation also occurred in the Paleozoic, most notably with the Karoo Glaciation of the Pennsylvanian (323 to 300 million years ago). This also was caused by an increase of oxygen and a subsequent drop in carbon dioxide, most likely produced by the evolution and rise of land plants [27].

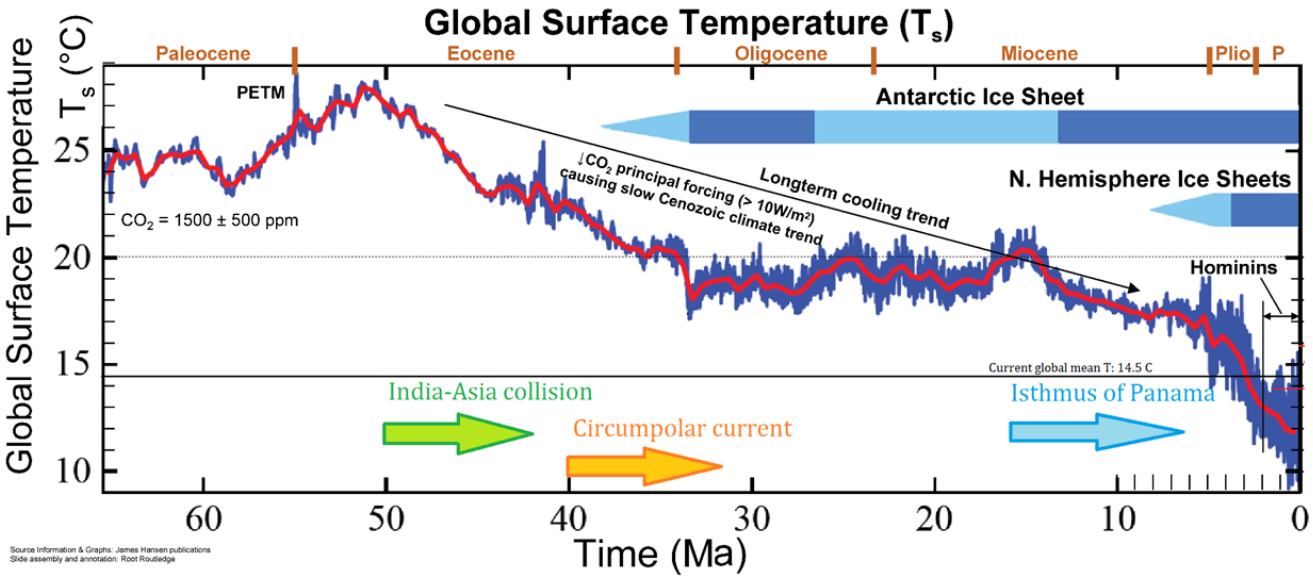


Figure 6.7.2: Global average surface temperature over the past 70 million years.

During the Cenozoic Era (the last 65 million years), the climate started out warm and gradually cooled to today. This warm time is called the **Paleocene-Eocene Thermal Maximum** and Antarctica and Greenland were ice-free during this time (Figure 6.7.2). Since the Eocene, tectonic events during the Cenozoic caused persistent and significant planetary cooling. For example, the collision of the Indian Plate with the Asian Plate created the Himalaya Mountains increasing weathering and erosion rates. An increased rate of weathering of silicate minerals, especially feldspar, consumes carbon dioxide from the atmosphere and therefore reduces the greenhouse effect, resulting in long-term cooling [28].

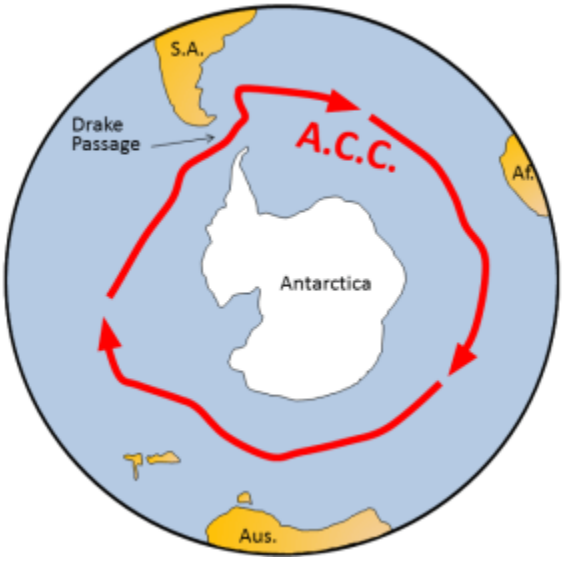


Figure 6.7.3: The Antarctic Circumpolar Current

At about 40 Ma, the narrow gap between the South American Plate and the Antarctica Plate widened, resulting in the opening of the Drake Passage. This allowed for the unrestricted west-to-east flow of water around Antarctica, the Antarctic Circumpolar Current, which effectively isolated the southern ocean from the warmer waters of the Pacific, Atlantic, and Indian Oceans (Figure 6.7.3). The region cooled significantly, and by 35-million-year ago (Oligocene) glaciers had started to form on Antarctica [29].

At around 15 Ma, subduction-related volcanism between Central and South America created the Isthmus of Panama that connected North and South America. This prevented water from flowing between the Pacific and Atlantic Oceans and reduced heat transfer from the tropics to the poles. This created a cooler Antarctica and larger Antarctic glaciers. The expansion of that ice sheet (on land and water) increased Earth's reflectivity (albedo), a positive feedback loop of further cooling: more reflective glacial ice, more cooling, more ice, and so on [30; 31].

By 5 million years ago (Pliocene Epoch), ice sheets had started to grow in North America and northern Europe. The most intense part of the current glaciation is the last 1 million years of the Pleistocene Epoch. The Pleistocene has significant temperature variations (through a range of almost 10°C) on time scales of 40,000 to 100,000 years, and corresponding expansion and contraction of ice sheets. These variations are attributed to subtle changes in Earth's orbital parameters called **Milankovitch cycles** [32; 33], which are explained in more detail in the section on natural climate forcings. Over the past million years, the glaciation cycles have been approximately every 100,000 years [34] with many glacial advances in the last 2 million years (Figure 6.7.4) (Lisiecki and Raymo, 2005) [35].

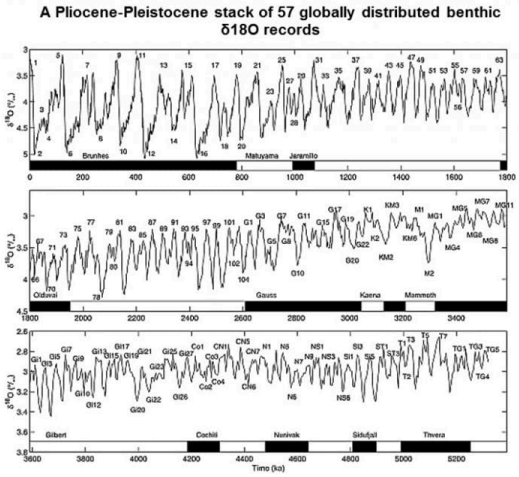


Figure 6.7.4: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. X-axis is time in thousands of years (ka) so 200 is actually 200,000. (Source: Lisiecki and Raymo, 2005)

Warmer portions of climate within an ice age are called **interglacials**, with brief versions called **interstadials**. These warming upticks are related to variations in Earth's climate like Milankovitch cycles. In the last 500,000 years, there have been 5 or 6 interglacials, with the most recent belonging to our current time, the Holocene (Figure 6.7.4).

Two of the more recent climate swings demonstrate the complexity of the changes: the Younger Dryas and the Holocene Climatic Optimum. These events are more recent and yet have conflicting information. The Younger Dryas cooling is widely recognized in the Northern Hemisphere [36], though the timing of the event (about 12,000 years ago) does not appear to be equal everywhere [37]. It also is difficult to find in the Southern Hemisphere [38]. The Holocene Climatic Optimum is the warming around 6,000 years ago [39], though it was not universally warmer, and probably not as warm as current warming [40], and not at the same time everywhere [41].

Two significant temperature anomalies, or irregularities, have occurred in the last 2000 years. These are the Medieval Climate Anomaly (or the Medieval Warm Period) and the Little Ice Age. A third temperature anomaly aligns with the Industrial Era. The Medieval Climate Anomaly occurred between 900 and 1300 AD. During this time period, many climate scientists think that slightly warmer weather conditions prevailed in many parts of the world; the higher-than-average temperature changes varied between 0.10 °C and 0.20 °C above the norm. Although 0.10 °C does not seem large enough to produce any noticeable change, it did free seas of ice. Because of this warming, the Vikings were able to colonize Greenland. The Little Ice Age was a cold period that occurred between 1550 AD and 1850 AD. During this time, a slight cooling of a little less than 1 °C was observed in North America, Europe, and possibly other areas of the Earth. This 1 °C change in global temperature is a seemingly small deviation in temperature (as was observed during the Medieval Climate Anomaly); however, it also resulted in noticeable changes. Historical accounts reveal a time of exceptionally harsh winters with much snow and frost.

Proxy Indicators of Past Climates

How do we know about past climates? Scientists use proxy indicators to understand past climate. A **proxy indicator** is a biological, chemical, or physical signature preserved in the rock, sediment, or ice record that acts like a "fingerprint" of something in the past [42]. Thus they are an indirect indicator of something like climate. For ancient glaciations from the Proterozoic and Paleozoic, there are rock formations of glacial sediments such as the diamictite (or tillite) of the Mineral Fork Formation in Utah.

This dark rock has many fine-grained components plus some large out-sized clasts like a modern glacial till [43; 44].

For climate changes during the Cenozoic Era (the last 65 Ma), there is a detailed chemical record from the coring of deep-sea sediments as part of the Ocean Drilling Program (Figure 6.7.5). Studies of deep-sea sediment use stable carbon and oxygen isotopes obtained from the shells of deep-sea benthic foraminifera that have settled on the ocean floor over millions of years. Oxygen isotopes are a proxy indicator of deep-sea temperatures and continental ice volume [45].

Sediment Cores – Stable Oxygen Isotope



Figure 6.7.5: Sediment core from the Greenland continental slope (Source: Hannes Grobe)

Oxygen isotopes are an indicator of past climate. The two main stable oxygen isotopes are ^{16}O and ^{18}O. They both occur in water (H_2O) and in the calcium carbonate ($CaCO_3$) shells of foraminifera as the oxygen component of both of those molecules. The most abundant and lighter isotope is ^{16}O. Since it is lighter, it evaporates more easily from the ocean's surface as water vapor, which later turns to clouds and precipitation on the ocean and land.

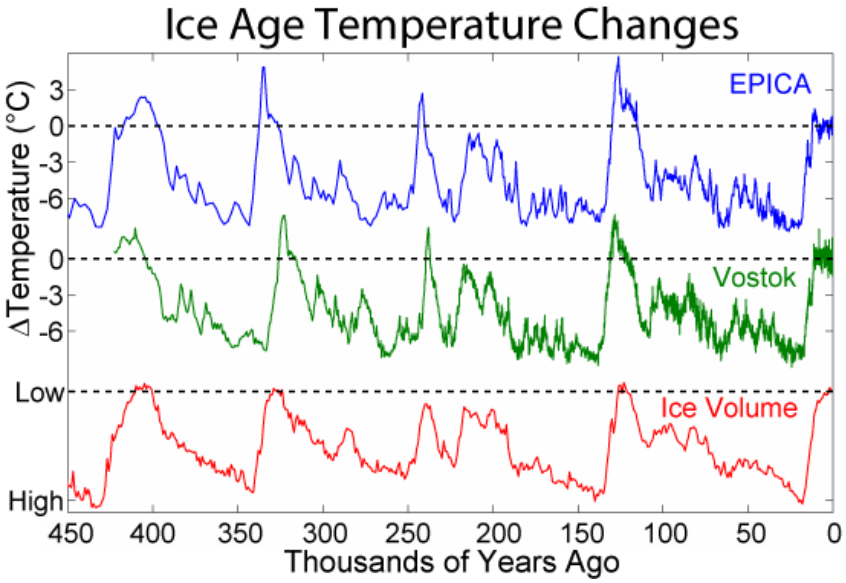


Figure 6.7.6: Antarctic temperature changes during the last few glaciations compared to global ice volume. The first two curves are based on the deuterium (heavy hydrogen) record from ice cores (EPICA Community Members 2004, Petit et al. 1999). The bottom line is ice volume based on oxygen isotopes from a composite of deep-sea sediment cores (Lisiecki and Raymo 2005).

During geologic times when the climate is cooler, more of this precipitation is locked onto land in the form of glacial ice. Consider the giant ice sheets, more than a mile thick, that covered a large part of North America during the last ice age only 14,000 years ago. During glaciation, the glaciers effectively lock away more ^{16}O, thus the ocean water and foraminifera shells become enriched in ^{18}O. Therefore, a ratio of ^{18}O to ^{16}O in calcium carbonate shells of foraminifera is an indicator of past climate. The sediment cores from the Ocean Drilling Program record a continuous accumulation of sediment (Figure 6.7.6).

Sediment Cores – Boron Isotopes and Acidity

Boron-isotope ratios in ancient planktonic foraminifera shells in deep-sea sediment cores have been used to estimate the pH (acidity) of the ocean over the past 60 million years. Ocean acidity is a proxy for past atmospheric CO^2 concentrations. In the early Cenozoic, around 60 million years ago, CO^2 concentrations were over 2,000 ppm and started falling around 55 to 40 million years ago possibly due to reduced CO^2 outgassing from ocean ridges, volcanoes, and metamorphic belts and increased carbon burial due to uplift of the Himalaya Mountains. By the Miocene (about 24 million years ago), CO^2 levels were below 500 ppm [46] and by 800,000 years ago CO^2 levels didn't exceed 300 ppm [47].

Carbon Dioxide Concentrations in Ice Cores

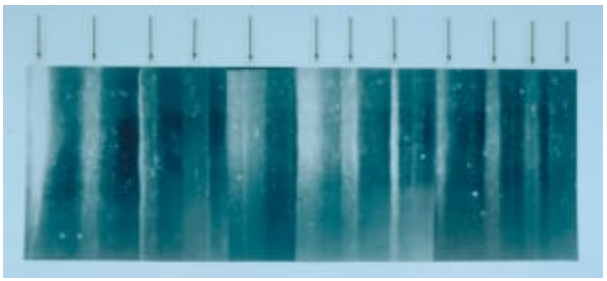


Figure 6.7.7: 19 cm long section of ice core showing 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers. (Source: US Army Corps of Engineers)

For the more recent Pleistocene climate, there is a more detailed and direct chemical record from coring into the Antarctic and Greenland ice sheets (Figure 6.7.7). Snow accumulates on these ice sheets and creates yearly layers. Ice cores have been extracted from ice sheets covering the last 800,000 years. Oxygen isotopes are collected from these annual layers and the ratio of ^{18}O to ^{16}O is used to determine temperature as discussed above. In addition, the ice traps small atmospheric gas bubbles as the snow turns to ice.

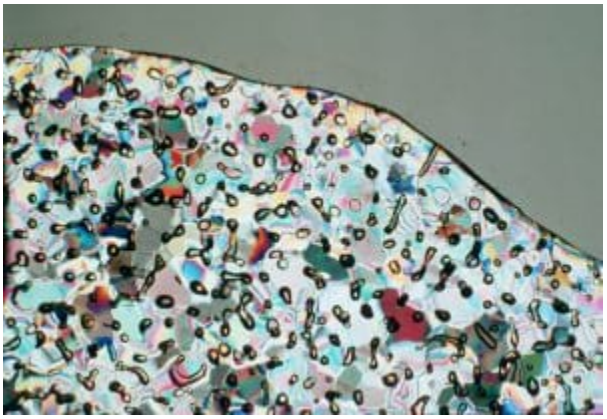


Figure 6.7.8: Antarctic ice showing hundreds of tiny trapped air bubbles from the atmosphere thousands of years ago. (Source: CSIRO)

Small pieces of this ice are crushed and the ancient air extracted into a mass spectrometer that can detect the chemistry of the ancient atmosphere. Carbon dioxide levels are recreated from these measurements. Over the last 800,000 years, the maximum carbon dioxide concentration during warm times was about 300 ppm and the minimum during cold stretches was about 170 ppm [46; 47; 48] (Figure 6.7.9). The carbon dioxide content of earth's atmosphere is currently over 400 ppm.

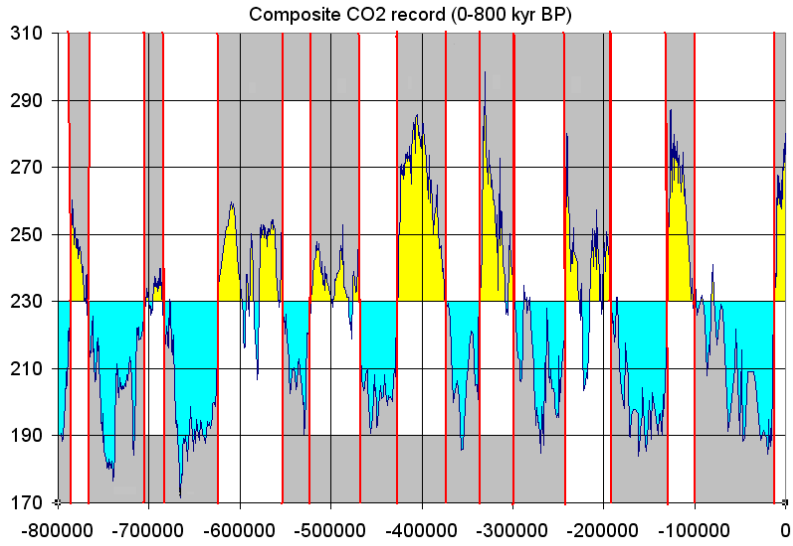


Figure 6.7.9: Composite carbon dioxide record from the last 800,000 years based on ice core data from EPICA Dome C Ice Core.

Oceanic Microfossils

Microfossils, like foraminifera, diatoms, and radiolarians, can be used to interpret past climate records. In sediment cores, different species of microfossils are found in different layers. Groups of these microfossils are called assemblages. One assemblage consists of species that lived in cooler ocean water (in glacial times) and another assemblage found at a different level in the same sediment core is made of warmer water species [49].

Tree Rings



Figure 6.7.10: Tree rings form every year. Rings that are farther apart are from wetter years and rings that are closer together are from dryer years.

Every year a tree will grow one ring with a light section and dark section (Figure 6.7.10).. The rings vary in width. Since trees need a lot of water to survive, narrower rings indicate colder and drier climates. Since some trees can be several thousands years old, we can use their rings for regional paleoclimatic reconstructions. Further, dead trees such as those used in Puebloan ruins can be used to extend this proxy indicator, which showed long term droughts in the region and why their villages were abandoned (Figure 6.7.11)..

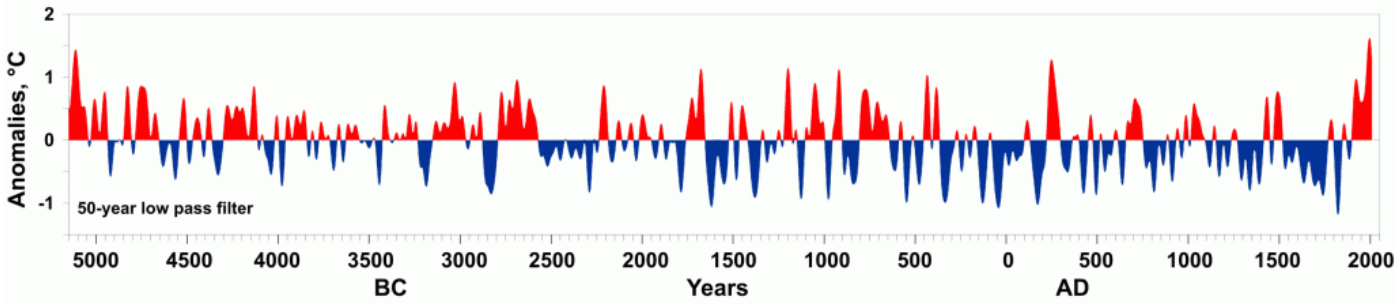


Figure 6.7.11: Summer temperature anomalies for the past 7000 years (Source: R.M.Hantemirov)

Pollen

Flowering plants produce pollen grains. Pollen is distinctive when viewed under a microscope (Figure 6.7.5). Sometimes pollen can be preserved in lake sediments that accumulate every year. Coring of lake sediments can reveal ancient pollen. Fossil pollen assemblages are groups of pollen from multiple species such as spruce, pine, and oak. Through time (via the sediment cores and radiometric age-dating techniques), the pollen assemblage will change revealing the plants that lived in the area at the time. Thus the pollen assemblages are an indicator of past climate since different plants will prefer different climates [50]. For example, in the Pacific Northwest east of the Cascades, a region close to the border of grasslands and forest, a study tracked pollen over the last 125,000 years covering the last two glaciations. As shown in the figure (Fig. 2 from reference Whitlock and Bartlein 1997 [51]), pollen assemblages with more pine tree pollen are found during glaciations and pollen assemblages with less pine tree pollen are found during interglacial times [51].

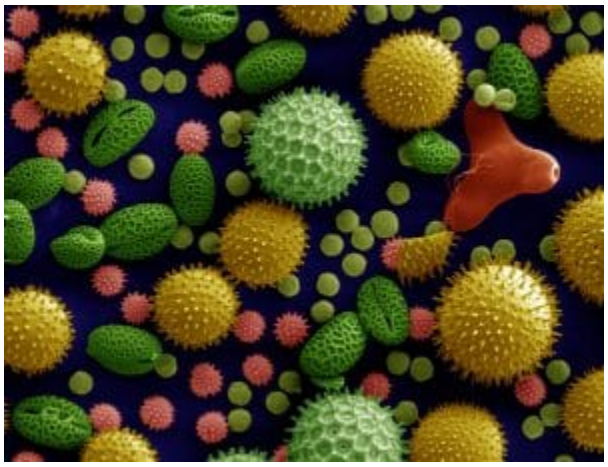


Figure 6.7.12: Scanning electron microscope image of modern pollen with false color added to distinguish plant species. (Source: Dartmouth Electron Microscope Facility, Dartmouth College)

Other Proxy Indicators

Paleoclimatologists study many other phenomena to understand past climates such as human historical accounts, human instrument record from the recent past, lake sediments, cave deposits of calcium carbonates, and corals (both oxygen isotopes and growth rings).

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6.8: Anthropogenic Climate Change

When we talk about anthropogenic climate change, we are generally thinking of the industrial era, which really got going when we started using fossil fuels (coal to begin with) to drive machinery and trains. That was around the middle of the 18th century. The issue with fossil fuels is that they involve burning carbon that was naturally stored in the crust over hundreds of millions of years. Some climate scientists argue that anthropogenic climate change actually goes back much further than the industrial era, and that humans began to impact the climate by clearing land to grow grains in Europe and the Middle East around 8,000 years BCE and by creating wetlands to grow rice in Asia around 5,000 years BCE. Clearing forests for crops is a type of climate-forcing because the CO_2 storage capacity of the crops is generally lower than that of the trees they replace, and creating wetlands is a type of climate forcing because the anaerobic bacterial decay of organic matter within wetlands produces CH_4.

In fact, whether anthropogenic climate change started with the agricultural revolution or the industrial revolution is not important, because the really significant climate changes didn't start until the early part of the 20th century, and although our activities are a major part of the problem, our increasing numbers are a big issue as well. Figure 6.8.1 shows the growth of the world population from around 5 million, when we first started growing crops, to about 18 million when wetland rice cultivation began, to over 800 million at the start of the industrial revolution, to over 7,700 million in 2019. A big part of the incredible growth in our population is related to the availability of the cheap and abundant energy embodied in fossil fuels, which we use for transportation, heating and cooling, industry, and food production.

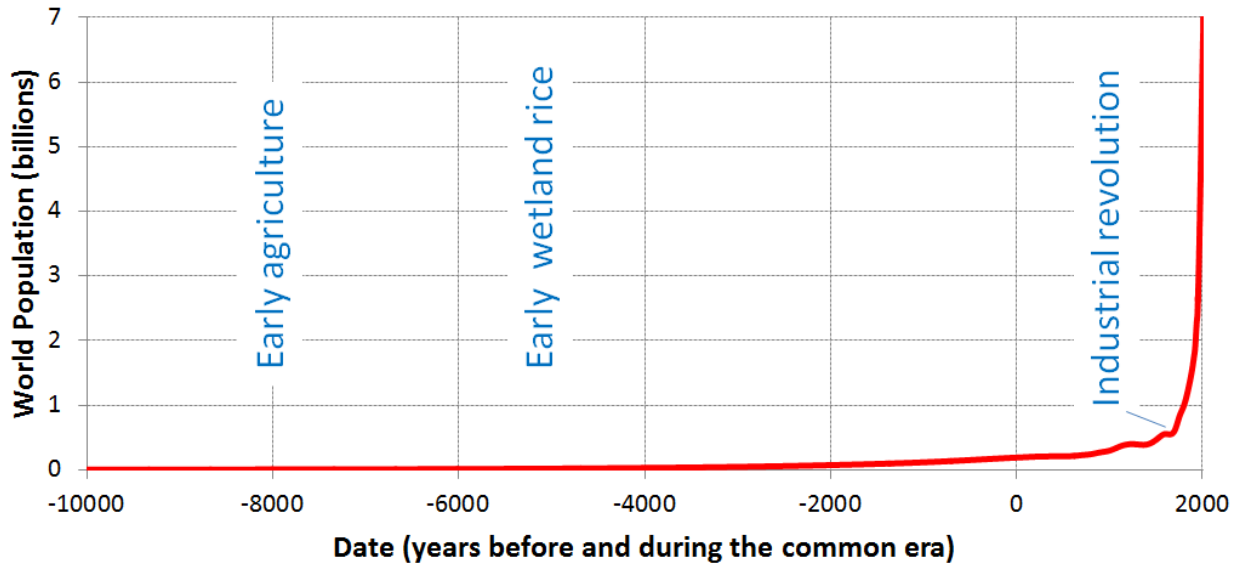


Figure 6.8.1: World population growth over the past 12,000 years.
© Steven Earle. CC BY. Based on World Population Annual 12000 years data.

A rapidly rising population, the escalating level of industrialization and mechanization of our lives, and an increasing dependence on fossil fuels for transportation and energy generation have driven the anthropogenic climate change of the past century. The trend of mean global temperatures since 1880 is shown in Figure 6.8.2. For approximately the past 55 years, the temperature has increased at a relatively steady and rapid rate, especially compared to past changes. The average temperature now is approximately 1.0°C higher than before industrialization, and two-thirds of this warming has occurred since 1975.

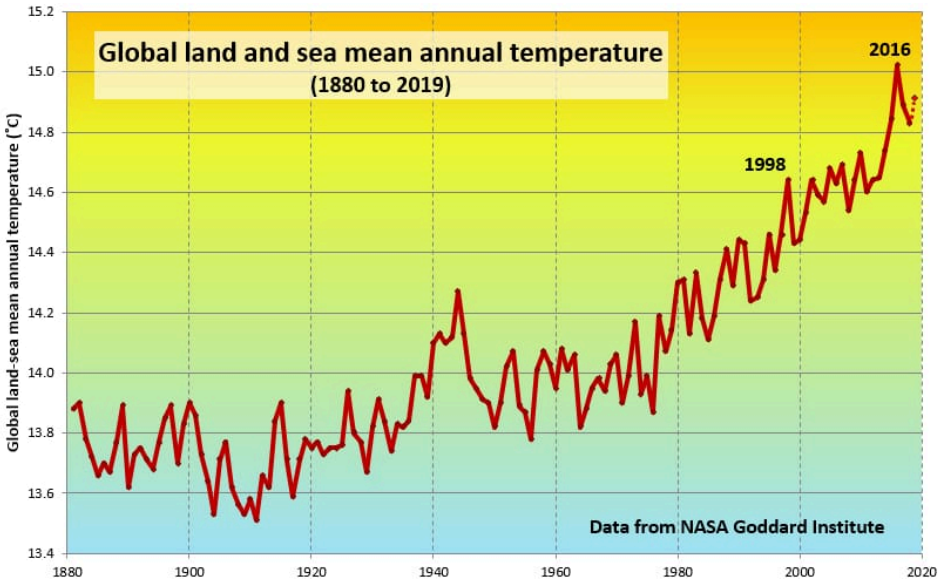


Figure 6.8.2: Global mean annual temperatures for the period from 1880 to 2019. The value for 2019 is projected, based on only 6 months of data. 1998 and 2016 were strong El Niño years.
© Steven Earle. CC BY. Based on data from NASA.

Changes in land surface or ocean surface temperatures can be expressed as temperature **anomalies**. A temperature anomaly is the difference in average temperature measurement from a predetermined datum (or baseline). This datum is the average temperature of a particular date range, for example, 1951 to 1980. Another common datum is the last century (1900-2000). Therefore, an anomaly of 1.25 ℃ for 2015 (last century datum) means that the average temperature for 2015 was 1.25 ℃ greater than the 1900-2000 average. In 1950, the temperature anomaly was -0.28 ℃, so this is -0.28 ℃ lower than the 1900-2000 average [3]. These temperatures are annual average surface temperatures. Figure 6.8.3 shows the global mean temperature estimates for the period of 1880 to 2020 using the datum of the 1951-1980 average temperature.

Figure 6.8.3: Land-ocean temperature index, 1880 to present, with a base time 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling.
[From https://opengeology.org/textbook/15-...limate-change/ Adapted from *Source: National Climate Data Center*]

Since 1880, average global surface temperatures have trended upward and most of that warming has occurred since 1970 (see this NASA animation). Since the ocean is absorbing a lot of the additional trapped heat, surface temperatures include both land surface and ocean temperatures [13]. This video figure also shows worldwide temperature changes since 1880. The more blue, the cooler; the more yellow and red, the warmer.

Scientific Consensus: Global Climate Change is Real

The **Intergovernmental Panel on Climate Change** (IPCC)—established by the United Nations Environment Programme and the World Meteorological Organization in 1988—is responsible for reviewing the scientific literature on climate change and issuing periodic reports on several topics, including the scientific basis for understanding climate change, our vulnerability to observed and predicted climate changes, and what we can do to limit climate change and minimize its impacts. The IPCC uses this information to evaluate current impacts and future risks, in addition to providing policymakers with assessments. These assessments are released about once every every six years. The most recent report, the 5th Assessment, was released in 2013. Hundreds of leading scientists from around the world are chosen to author these reports. Over the history of the IPCC, these scientists have reviewed thousands of peer-reviewed, publicly available studies. The scientific consensus according to the last IPCC assessment is clear: global climate change is real and humans are very likely the cause for this change.

Additionally, the major scientific agencies of the United States, including the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), also agree that climate change is occurring and that humans are driving it. In 2010, the US National Research Council concluded that “Climate change is occurring, is very likely caused by human activities, and poses significant risks for a broad range of human and natural systems”. Many independent scientific organizations have released similar statements, both in the United States and abroad. This doesn’t necessarily mean

that every scientist sees eye to eye on each component of the climate change problem, but broad agreement exists that climate change is happening and is primarily caused by excess greenhouse gases from human activities.

The historical record shows that the climation (NASA) and the National Oceanic and Atmospheric Administration (NOAA), also agree that climate change is occurring and that humans are driving it. In 2010, tate varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. Recent changes in climate**,** however, cannot be explained by natural causes alone. Research indicates that natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, human activities, especially our combustion of fossil fuels, explains the current warming (figure 6.8.4). The scientific consensus is clear: through alterations of the carbon cycle, humans are changing the global climate by increasing the effects of something known as the greenhouse effect.

Figure 6.8.4**:** This graph shows the predicted temperatures from two climate models and observed temperatures from 1880 to 2020. The first model considered only natural factors that could influence temperature and is represented by the green line (bottom). It shows some fluctuations in temperature by no overall increase or decrease. The second model considered both human and natural factors and is represented by the orange line (top). It shows an overall increase in temperature. Actual observations (black, jagged line; middle) more closely match the second model. Overall, temperature has increased about 1.2 degrees Celsius (2.1 degrees Fahrenheit) since pre-industrial times. Image relabeled from Efbrazil (CC-BY-SA).

Human Impact on Greenhouse Gases

Recall that greenhouse gases are probably the most significant drivers of the climate. The greenhouse gases that affect Earth include carbon dioxide, methane, water vapor, nitrous oxide, and ozone. Approximately half of the radiation from the sun passes through these gases in the atmosphere and strikes the Earth. This radiation is converted into thermal radiation on the Earth's surface, and then a portion of that energy is re-radiated back into the atmosphere as thermal energy. Greenhouse gases absorb much of the thermal energy near the Earth's surface so the more greenhouse gases there are in the atmosphere, the more thermal energy is retained by the Earth.

Water vapor is the most abundant greenhouse gas and also the most important in terms of its contribution to the natural greenhouse effect, despite having a short atmospheric lifetime. Some human activities can influence local water vapor levels. However, on a global scale, the concentration of water vapor is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, the global concentration of water vapor is not substantially affected by direct human emissions.

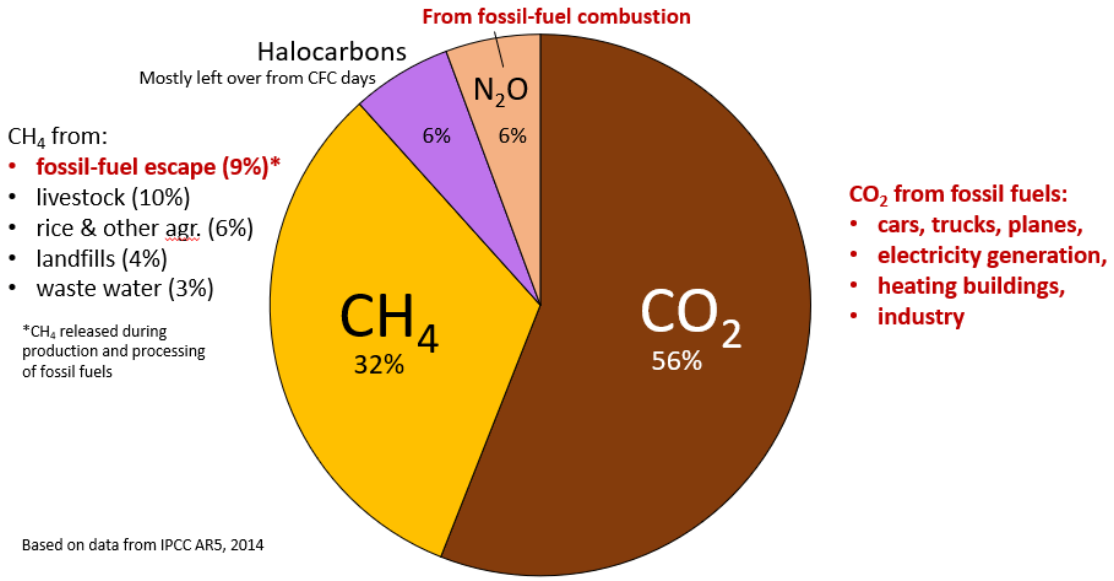


Figure 6.8.5: The relative climate-warming effects of the various greenhouse gases. (Effects listed in red are all related to fossil fuels.)
© Steven Earle. CC BY. Based on data in IPCC AR 5, 2014.

Figure 6.8.5, which is based on data from the fifth assessment report of the IPCC, issued in 2014, shows the relative contributions of various long-lasting anthropogenic GHGs to current climate forcing, based on the changes from levels that existed in 1750. Human activity releases carbon dioxide and methane, two of the most important greenhouse gases, into the atmosphere in several ways. The biggest anthropogenic contributor to warming is CO_2, which accounts for 56% of positive forcing. The primary mechanism that releases carbon dioxide is the burning of fossil fuels, such as gasoline, coal, and natural gas (Figure 6.8.6). CH_4 accounts for 32%, and the halocarbon gases (mostly leaked from older air-conditioning appliances that still contain CFCs) and nitrous oxide (N_2O) (from burning fossils fuels) account for 6% each. CO_2 emissions come mostly from coal- and gas-fired power stations, motorized vehicles (cars, trucks, and aircraft), and industrial operations (e.g., smelting). CH_4 emissions come from production of fossil fuels (escape from coal mining and from gas and oil production and processing), livestock farming (mostly beef), landfills, waste water, and wetland rice farming. N_2O is derived almost entirely from the combustion of fossil fuels. In summary, most (by far) of our current GHG emissions come from fossil fuel production and use.



Figure 6.8.6: The burning of fossil fuels in industry and by vehicles releases carbon dioxide and other greenhouse gases into the atmosphere. (credit: "Pöllö"/Wikimedia Commons)

Carbon Dioxide

Carbon dioxide (CO_2) is the primary greenhouse gas that is contributing to recent global climate change. CO_2 is a natural component of the carbon cycle, involved in such activities as photosynthesis, respiration, volcanic eruptions, and ocean-atmosphere exchange. Human activities, primarily the burning of fossil fuels and changes in land use, release very large amounts of CO_2 to the atmosphere, causing its concentration in the atmosphere to rise. Deforestation, cement manufacture, animal agriculture, the clearing of land, and the burning of forests are other human activities that release carbon dioxide.

Scientists look at patterns in data and try to explain differences or deviations from these patterns. The atmospheric carbon dioxide data reveal a historical pattern of carbon dioxide increasing and decreasing, cycling between a low of 180 ppm and a high of 300 ppm (Figure 6.8.4). Scientists have concluded that it took around 50,000 years for the atmospheric carbon dioxide level to increase from its low minimum concentration to its higher maximum concentration.

**Figure 6.8.7: ** Graph of change in temperature in degrees Celsius (top, blue line) and carbon dioxide concentration in parts per million by volume (bottom, green line) measured from the Vostok, Antarctica ice core. These have been associated for over 400,000 years. As carbon dioxide concentration increased, so did temperature. As carbon dioxide concentration decreased, so did temperature. These data were collected in 1999. Since then, carbon dioxide concentrations have increased to 409.8 ppm (2019 average). Image and caption (modified) by NOAA/Autopilot (CC-BY-SA)

However, starting recently, atmospheric carbon dioxide concentrations have increased beyond the historical maximum of 300 ppm (figure 6.8.8 – 9). Atmospheric CO_2 concentrations have increased by 45% since pre-industrial times, from approximately 280 parts per million (ppm) in the 18th century to 409.8 ppm in 2019 (figure 6.8.8 – 9).

Figure 6.8.8**:** Monthly mean carbon dioxide concentration in parts per million (ppm) measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. The fluctuating red line represents the monthly mean values, centered on the middle of each month. Carbon dioxide concentrations dip every summer due to increased photosynthesis. The smoother black line represents the same, after correction for the average seasonal cycle. Image and caption (modified) by NOAA (public domain).

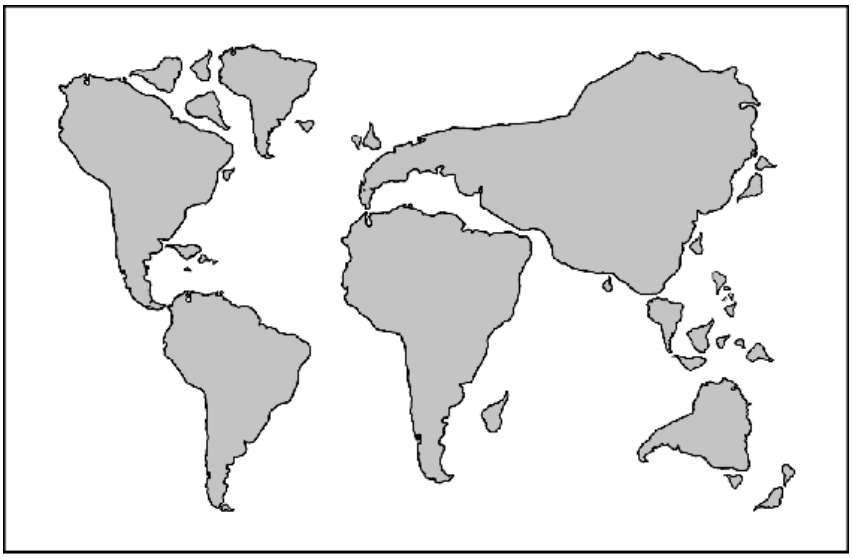


Figure 6.8.9**:** This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO2 has increased since the Industrial Revolution. On the x-axis are the years before today (0 = 1950). It begins 400,000 years prior to 1950. On the y-axis is the carbon dioxide level in parts per million. Carbon dioxide levels have fluctuated over the years, but they never exceeded 300 parts per million until 1950. In 2018, carbon dioxide levels reached 409.8 ppm. (This graph is a few years old and shows the current CO_2 level at 400 ppm; Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record.)

The current CO_2 level is higher than it has been in at least 800,000 years, based on evidence from ice cores that preserve ancient atmospheric gases. The current increases in atmospheric carbon dioxide have happened very quickly—in a matter of hundreds of years rather than thousands of years. What is the reason for this difference in the rate of change and the amount of increase in carbon dioxide? A key factor that must be recognized when comparing the historical data and the current data is the presence of modern human society; no other driver of climate change has yielded changes in atmospheric carbon dioxide levels at this rate or to this magnitude. Human activities currently release over 30 billion tons of CO_2 into the atmosphere every year. While some volcanic eruptions released large quantities of CO_2 in the distant past, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much CO_2 as volcanoes each year. This human-caused build-up of CO_2 in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

The following video shows how atmospheric CO_2 has varied recently and also over the last 800,000 years as determined by many CO_2 monitoring stations (shown on the insert map). It is also instructive to watch the CO_2 variation of the Keeling portion of the video by latitude. This shows that most of the human sources of CO_2 are in the Northern Hemisphere.

Methane

Although this concentration is far less than that of CO_2, **methane** (CH_4) is 28 times as potent a greenhouse gas. Methane is produced when bacteria break down organic matter under anaerobic conditions and can be released due to natural or anthropogenic processes. Anaerobic conditions can happen when organic matter is trapped underwater (such as in rice paddies) or in the intestines of herbivores. Anthropogenic causes now account for 60% of total methane release. Examples include agriculture, fossil fuel extraction and transport, mining, landfill use, and burning of forests. Methane can also be released from natural gas fields and the decomposition that occurs in landfills. Specifically, raising cattle releases methane due to fermentation

in their rumens produces methane that is expelled from their GI tract. Methane is more abundant in Earth's atmosphere now than at any time in at least the past 650,000 years, and CH_4 concentrations increased sharply during most of the 20th century. They are now more than two and-a-half times pre-industrial levels (1.9 ppm), but the rate of increase has slowed considerably in recent decades.

Another source of methane is the melting of clathrates. Clathrates are frozen chunks of ice and methane found at the bottom of the ocean. When water warms, these chunks of ice melt and methane is released. As the ocean's water temperature increases, the rate at which clathrates melt is increasing, releasing even more methane. This leads to increased levels of methane in the atmosphere, which further accelerates the rate of global warming. This is an example of the positive feedback loop that is leading to the rapid rate of increase of global temperatures.

Other Greenhouse Gases

Nitrous oxide (N_2O) is produced through natural and human activities, mainly through agricultural activities and natural biological processes. Fuel burning and some other processes also create N_2O. Concentrations of N_2O have risen approximately 18% since the start of the Industrial Revolution, with a relatively rapid increase towards the end of the 20th century. [3] In contrast, the atmospheric concentration of N_2O varied only slightly for a period of 11,500 years before the onset of the industrial period, as shown by ice core samples.

Ground-level ozone (O_3), which also has a short atmospheric lifetime, is a potent greenhouse gas. Chemical reactions create ozone from emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight. In addition to trapping heat, ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6), together called F-gases, are often used in coolants, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants. Unlike water vapor and ozone, these F-gases have a long atmospheric lifetime, and some of these emissions will affect the climate for many decades or centuries.

Human Induced Changes in Albedo

When sunlight energy reaches Earth it can be reflected or absorbed. The amount that is reflected or absorbed depends on Earth's surface and atmosphere. Light-colored objects and surfaces, like snow and clouds, tend to reflect most sunlight, while darker objects and surfaces, like the ocean and forests, tend to absorb more sunlight. The term **albedo** refers to the amount of solar radiation reflected from an object or surface, often expressed as a percentage. Earth as a whole has an albedo of about 30%, meaning that 70% of the sunlight that reaches the planet is absorbed. Sunlight that is absorbed warms Earth's land, water, and atmosphere.

Albedo is also affected by aerosols. **Aerosols** are small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight. Unlike greenhouse gases (GHGs), the climate effects of aerosols vary depending on what they are made of and where they are emitted. Those aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect. In addition, human activities have generally increased the number of aerosol particles in the atmosphere. Overall, human-generated aerosols have a net cooling effect offsetting about one-third of the total warming effect associated with human greenhouse gas emissions. Reductions in overall aerosol emissions can therefore lead to more warming. However, targeted reductions in black carbon emissions can reduce warming.

Human changes in land use and land cover have changed Earth's albedo. Processes such as deforestation, reforestation, desertification, and urbanization often contribute to changes in climate in the places they occur. These effects may be significant regionally, but are smaller when averaged over the entire globe.

Climate Feedbacks

When sea ice melts, as it has done in the Arctic Ocean at a disturbing rate over the past decade, the albedo of the area affected changes dramatically, from around 80% down to less than 10%. This is a positive feedback because much more solar energy is absorbed by the water than by the pre-existing ice, and the temperature increase is amplified. The same applies to ice and snow

on land, but the difference in albedo is not as great.

When ice and snow on land melt, sea level rises. (Sea level is also rising because the oceans are warming and that increases their volume.) A higher sea level means a larger proportion of the planet is covered with water, and since water has a lower albedo than land, more heat is absorbed and the temperature goes up a little more. Since the last glaciation, sea-level rise has been about 125 m; a huge area that used to be land is now flooded by heat-absorbent seawater. During the current period of anthropogenic climate change, sea level has risen only about 20 cm, and although that doesn't make a big change to albedo, sea-level rise is accelerating.

Figure 6.8.10: A degrading permafrost site on the north coast of Alaska.

Most of northern Canada has a layer of permafrost that ranges from a few centimeters to hundreds of meters in thickness; the same applies in Alaska, Russia, and Scandinavia. Permafrost is a mixture of soil and ice (Figure 6.8.10), and it also contains a significant amount of trapped organic carbon that is released as CO_2 and CH_4 when the permafrost breaks down. Because the amount of carbon stored in permafrost is in the same order of magnitude as the amount released by burning fossil fuels, this is a feedback mechanism that has the potential to equal or surpass the forcing that has unleashed it.

In some polar regions, including northern Canada, permafrost includes methane hydrate, a highly concentrated form of CH_4 trapped in solid form. Breakdown of permafrost releases this CH_4. Even larger reserves of methane hydrate exist on the sea floor, and while it would take significant warming of ocean water down to a depth of hundreds of meters, this too is likely to happen in the future if we don't limit our impact on the climate. There is strong isotopic evidence that the Paleocene-Eocene thermal maximum was caused, at least in part, by a massive release of sea-floor methane hydrate.

There is about 45 times as much carbon in the ocean (as dissolved bicarbonate ions, HCO_3^-) as there is in the atmosphere (as CO_2), and there is a steady exchange of carbon between the two reservoirs. But the solubility of CO_2 in water decreases as the temperature goes up. In other words, the warmer it gets, the more of that oceanic bicarbonate gets transferred to the atmosphere as CO_2. That makes CO_2 solubility another positive feedback mechanism.

Vegetation growth responds positively to both increased temperatures and elevated CO_2 levels, and so in general, it represents a negative feedback to climate change because the more the vegetation grows, the more CO_2 is taken from the atmosphere. But it's not quite that simple because when trees grow bigger and more vigorously, forests become darker (they have lower albedo) so they absorb more heat. Furthermore, climate warming isn't necessarily good for vegetation growth; some areas have become too hot, too dry, or even too wet to support the plant community that was growing there, and it might take centuries for something to replace it successfully.

All of these positive (and negative) feedbacks work both ways. For example, during climate cooling, growth of glaciers leads to higher albedos, and formation of permafrost results in storage of carbon that would otherwise have returned quickly to the atmosphere.

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Further "Reading"

For more information, watch this six-minute video on climate change by two professors at a North Carolina State University.

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6.9: Implications of Climate Change

Past and Present-day GHG Emissions Will Affect Climate Far into the Future

Many greenhouse gases stay in the atmosphere for long periods of time. As a result, even if emissions stopped increasing, atmospheric greenhouse gas concentrations would continue to remain elevated for hundreds of years. Moreover, if we stabilized concentrations and the composition of today's atmosphere remained steady (which would require a dramatic reduction in current greenhouse gas emissions), surface air temperatures would continue to warm. This is because the oceans, which store heat, take many decades to fully respond to higher greenhouse gas concentrations. The ocean's response to higher greenhouse gas concentrations and higher temperatures will continue to impact climate over the next several decades to hundreds of years.

Figure 6.9.1: Temperature increases have been most pronounced in northern latitudes and over land masses. The colors represent the temperature difference between the 2011-2020 average and the 1951-1980 baseline, with warmer colors (yellow, orange, red) representing increases, and cool colors (green, blue) representing decreases. The image uses longer term averages of at least a decade to smooth out climate variability due to factors such as El Niño. Grey areas in the image have insufficient data for rendering. Image and caption (modified) from NASA's Scientific Visualization Studio/Eric Fisk (public domain).

Future Temperature Changes

Climate models project the following key temperature-related changes:

- Average global temperatures are expected to increase by 2°F to 11.5°F by 2100, depending on the level of future greenhouse gas emissions, and the outcomes from various climate models.
- By 2100, global average temperature is expected to warm at least twice as much as it has during the last 100 years.
- Ground-level air temperatures are expected to continue to warm more rapidly over land than oceans.
- Some parts of the world are projected to see larger temperature increases than the global average.

These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. The magnitude and rate of future climate change will primarily depend on the following factors:

- The rate at which levels of greenhouse gas concentrations in our atmosphere continue to increase,
- How strongly features of the climate (e.g., temperature, precipitation, and sea level) respond to the expected increase in greenhouse gas concentrations,
- Natural influences on climate (e.g., from volcanic activity and changes in the sun's intensity) and natural processes within the climate system (e.g., changes in ocean circulation patterns).

Future Precipitation and Storm Events

Patterns of precipitation and storm events, including both rain and snowfall are likely to change. However, some of these changes are less certain than the changes associated with temperature. Because warm air is able to hold more water than cold air, the general global trend over the past century has been one of increasing precipitation (Figure 6.9.2).

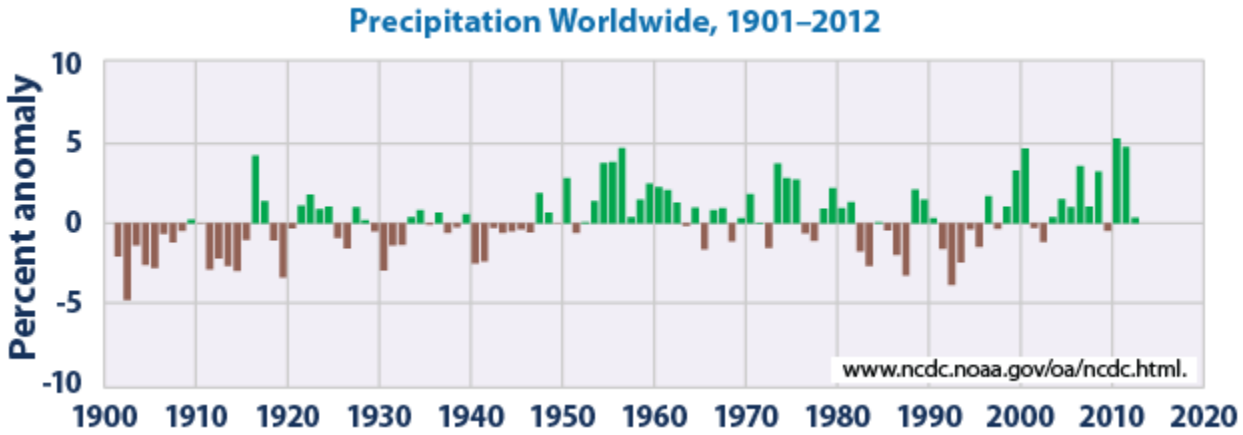


Figure 6.9.2**:** *Global precipitation anomalies compared with the average over the period from 1901 to 2012.* ["Precipitation Worldwide, 1901-2013" by NASA. Public domain.]

Projections show that future precipitation and storm changes will vary by season and region. Some regions may have less precipitation, some may have more precipitation, and some may have little or no change. The amount of rain falling in heavy precipitation events is likely to increase in most regions, while storm tracks are projected to shift towards the poles. Climate models project the following precipitation and storm changes:

- Global average annual precipitation through the end of the century is expected to increase, although changes in the amount and intensity of precipitation will vary by region.
- The intensity of precipitation events will likely increase on average. This will be particularly pronounced in tropical and high-latitude regions, which are also expected to experience overall increases in precipitation.
- The strength of the winds associated with tropical storms is likely to increase. The amount of precipitation falling in tropical storms is also likely to increase.
- Annual average precipitation is projected to increase in some areas and decrease in others.

Occurrence and intensity of extreme weather events such as hurricanes, precipitation, and heatwaves are increasing [3; 6]. Since the 1980s, hurricanes, which are generated from warm ocean water, have increased in frequency, intensity, and duration and connections to a warmer climate are likely. Since 1910, average precipitation has increased by 10% in the contiguous United States, and much of this increase is associated with heavy precipitation events like storms [18]. However, the distribution is not even and more precipitation is projected for the northern United States while less precipitation is projected for the already dry southwest [3]. Further, heatwaves have increased and rising temperatures are already affecting crop yields in northern latitudes [6]. Increased heat allows for greater moisture capacity in the atmosphere, increasing the potential for more extreme events [19].

One of the other risks for coastal populations, besides sea-level rise, is that climate warming is also associated with an increase in the intensity of tropical storms (e.g., hurricanes or typhoons), which almost always bring serious flooding from intense rain and storm surges. Some recent examples are New Orleans in 2005 with Hurricane Katrina, and New Jersey and New York in 2012 with Hurricane Sandy (Figure 6.9.3).



Figure 6.9.3: Damage to the Casino Pier, Seaside Heights, New Jersey, from Hurricane Sandy, November 2012
["Hurricane Sandy New Jersey Pier" © Master Sgt. Mark C. Olsen/U.S. Air Force/New Jersey National Guard. CC BY.]

Tropical storms get their energy from the evaporation of warm seawater in tropical regions. In the Atlantic Ocean, this takes place between 8° and 20° N in the summer. Figure 6.9.4 shows the variations in the sea-surface temperature (SST) of the tropical Atlantic Ocean (in blue) versus the amount of power represented by Atlantic hurricanes between 1950 and 2008 (in red). Not only has the overall intensity of Atlantic hurricanes increased with the warming since 1975, but the correlation between hurricanes and sea-surface temperatures is very strong over that time period.

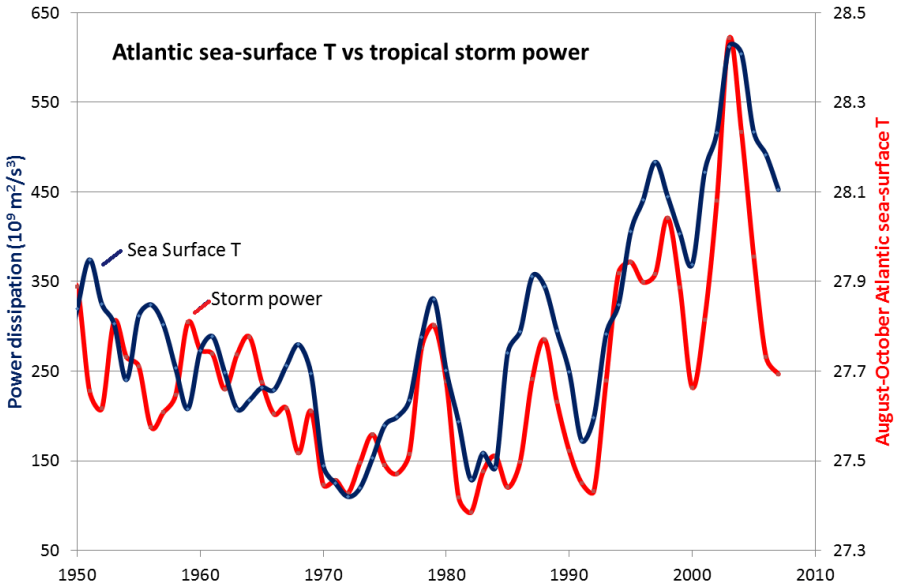


Figure 6.9.4: Relationship between Atlantic tropical storm cumulative annual intensity and Atlantic sea-surface temperatures
["Atlantic sea-surface T vs. tropical storm power" © Steven Earle. CC BY.
Based on data from Papers, Data, and Graphics Pertaining to Tropical Cyclone Trends and Variability.]

For several weeks in July and August of 2010, a massive heat wave affected western Russia, especially the area southeast of Moscow, and scientists have stated that climate change was a contributing factor. Temperatures soared to over 40°C, as much as 12°C above normal over a wide area, and wildfires raged in many parts of the country. Over 55,000 deaths are attributed to the heat and to respiratory problems associated with the fires. A summary of the impacts of climate change on natural disasters is given in Figure 6.9.5. The major types of disasters related to climate are floods and storms, but the health implications of extreme temperatures are also becoming a great concern. In the decade 1971 to 1980, extreme temperatures were the fifth most common

natural disasters; by 2001 to 2010, they were the third most common.

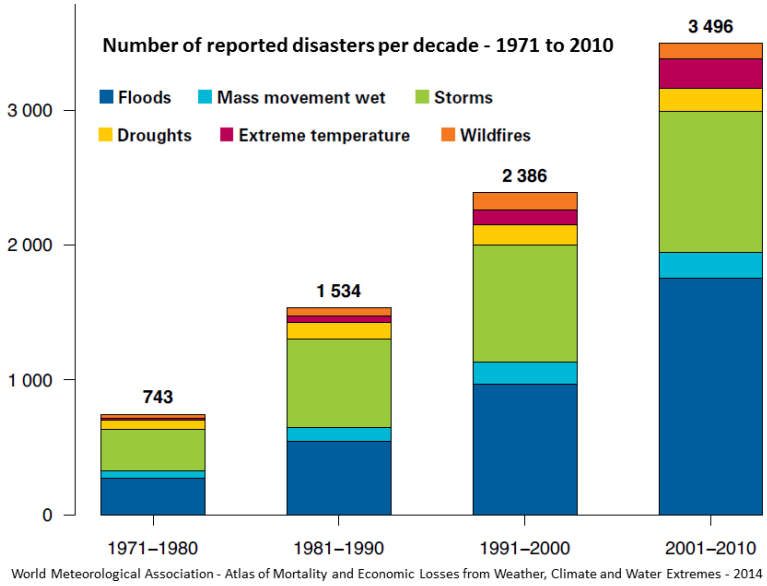


Figure 6.9.5: Numbers of various types of disasters between 1971 and 2010 (WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes, 2014. CC BY-NC-ND).

We've all experienced the effects of climate change over the past decade. However, it's not straightforward for climatologists to make the connection between a warming climate and specific weather events, and most are justifiably reluctant to ascribe any specific event to climate change. In this respect, the best measures of climate change are those that we can detect over several decades, such as the temperature changes shown in Figure 6.9.1, or the sea level rise shown in Figure 6.9.8.

Future Ice, Snowpack, and Permafrost

Arctic sea ice is already declining. The area of snow cover in the Northern Hemisphere has decreased since 1970. Permafrost temperature has increased over the last century, making it more susceptible to thawing. Over the next century, it is expected that sea ice will continue to decline, glaciers will continue to shrink, snow cover will continue to decrease, and permafrost will continue to thaw.

For every 2°F of warming, models project about a 15% decrease in the extent of annually averaged sea ice and a 25% decrease in September Arctic sea ice. The coastal sections of the Greenland and Antarctic ice sheets are expected to continue to melt or slide into the ocean. If the rate of this ice melting increases in the 21st century, the ice sheets could add significantly to global sea level rise. Glaciers are expected to continue to decrease in size. The rate of melting is expected to continue to increase, which will contribute to sea level rise.

Glaciers are ice on top of the land. Alpine glaciers, ice sheets, and sea ice are all melting. Almost all major alpine glaciers are shrinking, deflating, and retreating and the rate of ice mass loss is unprecedented (never observed before) since the 1940's when quality records for most began.Before anthropogenic warming, glacial activity was variable with some retreating and some advancing [17]. The extent of spring snow cover has decreased. Satellites have recorded that Antarctica is melting at 118 gigatons per year and Greenland is melting at 281 gigatons per year (1 gigaton is over 2 trillion pounds) (Figure 6.9.6).

Figure 6.9.6: Decline of Antarctic ice mass from 2002 to 2016

In addition, the extent of sea ice is shrinking. Sea ice is ice floating in the ocean (not on land like a glacier). Most sea ice is at the North Pole which is only occupied by the Arctic Ocean and sea ice [3; 6]. Below, the NOAA animation shows how perennial sea ice has declined from 1987 to 2015. The oldest ice is white and the youngest (seasonal) ice is dark blue. The amount of old ice has declined from 20% in 1985 to 3% in 2015.

This loss of ice is leading to increases in the global sea level. On average, the sea is rising at a rate of 1.8 mm per year. However, between 1993 and 2010 the rate of sea level increase ranged between 2.9 and 3.4 mm per year. A variety of factors affect the volume of water in the ocean, including the temperature of the water (the density of water is related to its temperature) and the amount of water found in rivers, lakes, glaciers, polar ice caps, and sea ice. As glaciers and polar ice caps melt, there is a significant contribution of liquid water that was previously frozen.

A number of global events have occurred that may be attributed to climate change during our lifetimes. Explore melting glaciers at NASA's interactive Global Ice Viewer. Glacier National Park in Montana is undergoing the retreat of many of its glaciers, a phenomenon known as glacier recession. In 1850, the area contained approximately 150 glaciers. By 2010, however, the park contained only about 24 glaciers greater than 25 acres in size. One of these glaciers is the Grinnell Glacier (Figure 6.9.7) at Mount Gould. Between 1966 and 2005, the size of Grinnell Glacier shrank by 40 percent. Similarly, the mass of the ice sheets in Greenland and the Antarctic is decreasing: Greenland lost 150–250 km^3 of ice per year between 2002 and 2006. In addition, the size and thickness of the Arctic sea ice is decreasing.



Figure 6.9.7: The effect of global warming can be seen in the continuing retreat of Grinnel Glacier. The mean annual temperature in the park has increased 1.33 °C since 1900. The loss of a glacier results in the loss of summer meltwaters, sharply reducing seasonal water supplies and severely affecting local ecosystems. (credit: modification of work by USGS)

Future Sea Level Change

Warming temperatures contribute to sea level rise by expanding ocean water, melting mountain glaciers and ice caps, and causing portions of the Greenland and Antarctic ice sheets to melt or flow into the ocean. Since 1870, global sea level has risen by about 8 inches. Estimates of future sea level rise vary for different regions, but global sea level for the next century is expected to rise at a greater rate than during the past 50 years. The contribution of thermal expansion, ice caps, and small glaciers to sea level rise is relatively well-studied, but the impacts of climate change on ice sheets are less understood and represent an active area of research. Thus, it is more difficult to predict how much changes in ice sheets will contribute to sea level rise. Greenland and Antarctic ice sheets could contribute an additional 1 foot of sea level rise, depending on how the ice sheets respond.

Sea-level is rising 3.4 millimeters (0.13 inches) per year and has risen 0.19 meters (7.4 inches) from 1901 to 2010 (Figure 6.9.8). This is thought largely to be from both the melting of glaciers and thermal expansion. Thermal expansion means that as objects such as solids, liquids, and gases heat up, they expand in volume. Since 1970, the melting of glaciers and thermal expansion account for 75% of the sea-level rise [6].

Figure 6.9.8: Sea height variation (mm) over time. Sea height has increased about 3.3 millimeters per year on average since 1993. Data is from satellite sea level observations by the NASA Goddard Space Flight Center. Image by NASA (public domain).

Projections for sea level rise to the end of this century vary widely. This is in large part because we do not know which of the above climate change scenarios (Figure 6.9.9) we will most closely follow, but many are in the range from 0.5 m to 2.0 m. One of the problems in predicting sea level rise is that we do not have a strong understanding of how large ice sheets, such as Greenland and Antarctica, will respond to future warming. Another issue is that the oceans don't respond immediately to warming. For example, with the current amount of warming, we are already committed to a future sea level rise of between 1.3 m and 1.9 m, even if we could stop climate change today. This is because it takes decades to centuries for the existing warming of the atmosphere to be transmitted to depth within the oceans and to exert its full impact on large glaciers. Most of that committed rise would take place over the next century, but some would be delayed longer. And for every decade that the current rates of climate change continue, that number increases by another 0.3 m. In other words, if we don't make changes quickly, by the end of this century we'll be locked into 3 m of future sea level rise. In a 2008 report, the Organization for Economic Co-operation and Development (OECD) estimated that by 2070 approximately 150 million people living in coastal areas could be at risk of flooding due to the combined effects of sea level rise, increased storm intensity, and land subsidence. The assets at risk (buildings, roads, bridges, ports, etc.) are in the order of $35 trillion ($35,000,000,000,000). Countries with the greatest exposure of population to flooding are China, India, Bangladesh, Vietnam, U.S.A., Japan, and Thailand. Some of the major cities at risk include Shanghai, Guangzhou, Mumbai, Kolkata, Dhaka, Ho Chi Minh City, Tokyo, Miami, and New York.

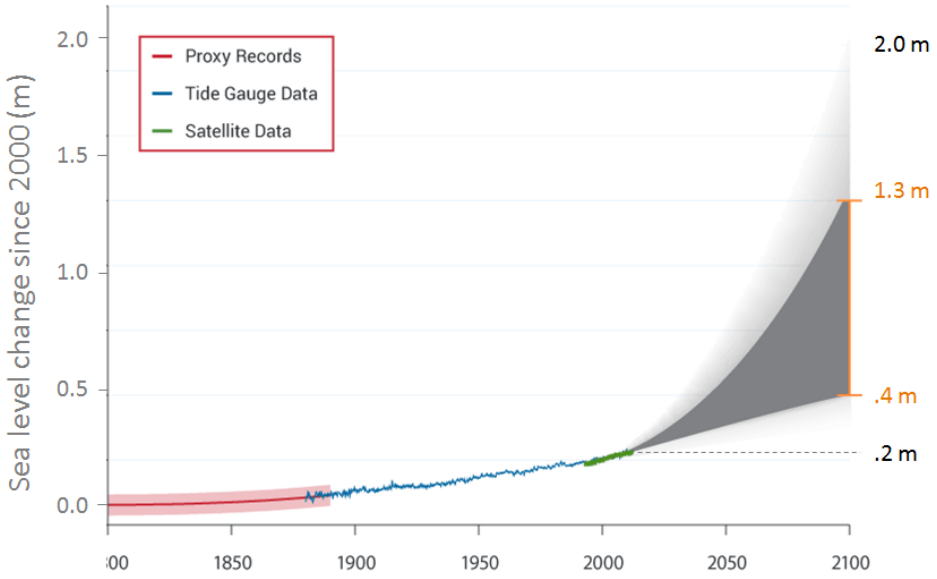


Figure 6.9.9: Projected sea-level increases to 2100, showing likely range (grey) and possible maximum
[Adapted by Steven Earle from "Past and Projected Changes in Global Sea Level Rise"
based on data from Parris et al. 2012 with input from NASA Jet Propulsion Laboratory.]

Regional and local factors will influence future relative sea level rise for specific coastlines around the world (Figure 6.9.10). For example, relative sea level rise depends on land elevation changes that occur as a result of subsidence (sinking) or uplift (rising). Relative sea level rise also depends on local changes in currents, winds, salinity, and water temperatures, as well as proximity to thinning ice sheets. Assuming that these historical geological forces continue, a 2-foot rise in global sea level by 2100 would result in the following relative sea level rise:

- 2.3 feet at New York City
- 2.9 feet at Hampton Roads, Virginia
- 3.5 feet at Galveston, Texas
- 1 foot at Neah Bay in Washington state

Figure 6.9.10: The United States government paid for the residents of Isle De Jean Charles, an island south of Louisiana (that is also part of Louisiana), to relocate when it became inhabitable due to sea level rise. Image by Karen Apricot (CC-BY-SA).

Future Ocean Acidification

Since 1750, about 40% of the new anthropogenic carbon dioxide has remained in the atmosphere. The remaining 60%

gets absorbed by the ocean and vegetation. Therefore, the ocean has absorbed about 30% of new anthropogenic carbon dioxide. When carbon dioxide gets absorbed in the ocean, it creates carbonic acid which makes the ocean more acidic. **Ocean acidification** is the process of ocean waters decreasing in pH. Oceans become more acidic as carbon dioxide (CO_2) emissions in the atmosphere dissolve in the ocean. This change is measured on the pH scale, with lower values being more acidic. The pH level of the oceans has decreased by approximately 0.1 pH units since pre-industrial times, which is equivalent to a 25% increase in acidity. The pH level of the oceans is projected to decrease even more by the end of the century as CO_2 concentrations are expected to increase for the foreseeable future. Ocean acidification adversely affects many marine species, including plankton, mollusks, shellfish, and corals. As ocean acidification increases, the availability of calcium carbonate will decline. Calcium carbonate is a key building block for the shells and skeletons of many marine organisms. Acidification combined with warmer temperature and lower oxygen levels is expected to have severe impacts on marine ecosystems and human-used fisheries, possibly affecting our ocean-derived food sources [6].

Corals require the right combination of temperature, light, and the presence of calcium carbonate (which they use to build their skeletons). As atmospheric carbon dioxide (CO_2) levels rise, some of the excess CO_2 dissolves into ocean water, reducing its calcium carbonate saturation. Calcium carbonate saturation has already been reduced considerably from its pre-industrial level, and model projections suggest much greater reductions in the future. If atmospheric CO_2 concentrations double, coral calcification rates are projected to decline by more than 30%. If CO_2 concentrations continue to rise at their current rate, corals could become rare on tropical and subtropical reefs by 2050. Under projections for the future, it is very unlikely that calcium carbonate saturation levels will be adequate to support coral reefs in any U.S. waters.

Plant Productivity

Watch this NASA video to discover the mixed effects of global warming on plant growth. While scientists found that warmer temperatures in the 1980s and 1990s caused an increase in plant productivity, this advantage has since been counteracted by more frequent droughts.

Mismatched Interactions

In addition to some abiotic conditions changing in response to climate change, many organisms are also being affected by the changes in temperature. Temperature and precipitation play key roles in determining the *geographic distribution* and *phenology* of plants and animals. **Phenology** is the study of the effects of climatic conditions on the timing of periodic life cycle events, such as flowering in plants or migration in birds.

Researchers have shown that 385 plant species in Great Britain are flowering 4.5 days sooner than was recorded earlier during the previous 40 years. In addition, insect-pollinated species were more likely to flower earlier than wind-pollinated species. The impact of changes in flowering date would be mitigated if the insect pollinators emerged earlier. This mismatched timing of plants and pollinators could result in injurious ecosystem effects because, for continued survival, insect-pollinated plants must flower when their pollinators are present. Likewise, migratory birds rely on daylength cues, which are not influenced by climate change. Their insect food sources, however, emerge earlier in the year in response to warmer temperatures. As a result, climate change decreases food availability for migratory bird species.

Spread of Disease

This rise in global temperatures will increase the range of disease-carrying insects and the viruses and pathogenic parasites they harbor. Thus, diseases will spread to new regions of the globe. This spread has already been documented with dengue fever, a disease the affects hundreds of millions per year, according to the World Health Organization. Colder temperatures typically limit the distribution of certain species, such as the mosquitoes that transmit malaria, because freezing temperatures destroy their eggs. West Nile virus and Lyme disease are two examples that already directly affect North Americans, while dengue fever could be an issue in the future (dengue became a “nationally notifiable condition” in the United States in 2010).

Not only will the range of some disease-causing insects expand, the increasing temperatures will also accelerate their lifecycles, which allows them to breed and multiply quicker, and perhaps evolve pesticide resistance faster. In addition to dengue fever, other diseases are expected to spread to new portions of the world as the global climate warms. These include malaria, yellow fever, West Nile virus, zika virus, and chikungunya.

Climate change does not only increase the spread of diseases in humans. Rising temperatures are associated with greater amphibian mortality due to chytridiomycosis (see Invasive Species). Similarly, warmer temperatures have exacerbated bark beetle

infestations of coniferous trees, such as pine an spruce.

Climate Change Affects Everyone

Our lives are connected to the climate**.** Human societies have adapted to the relatively stable climate we have enjoyed since the last ice age which ended several thousand years ago. A warming climate will bring changes that can affect our water supplies, agriculture, power and transportation systems, the natural environment, and even our own health and safety. Carbon dioxide can stay in the atmosphere for nearly a century, on average, so Earth will continue to warm in the coming decades. The warmer it gets, the greater the risk for more severe changes to the climate and Earth's system. Although it's difficult to predict the exact impacts of climate change, what's clear is that the climate we are accustomed to is no longer a reliable guide for what to expect in the future

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Suggested Supplementary Reading

Intergovernmental Panel on Climate Change. 2013. 5th Assessment: Summary for Policymakers.

NASA. 2018. Global Climate Change: Vital Signs of the Planet. This website by NASA provides a multi-media smorgasbord of engaging content. Learn about climate change using data collected by NASA satellites and more.

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7: UNIVERSE AND SOLAR SYSTEM

7.1: Introduction to the Universe and Objectives

7.2: The Universe

7.3: Galaxies and Stars

7.4: The Solar System

7.5: The Sun

7.6: Terrestrial Planets

7.7: Gas Giants

7.8: Other Objects in the Solar System

7.9: Attributions and References

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7.1: Introduction to the Universe and Objectives

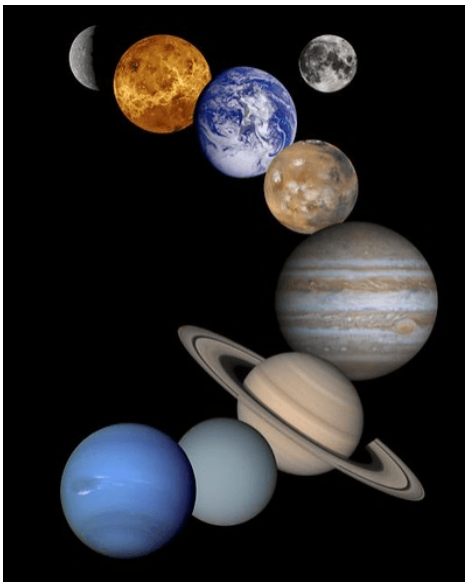
Introduction to the Universe & Solar System

Prepare to embark on a virtual journey through the cosmos as we explore the universe and our solar system in this chapter. Our adventure begins by understanding the universe in the context of Earth Science, revealing the connections between celestial phenomena and the planet we call home. We'll delve into the vast expanse of galaxies, where billions of stars, including our Sun, form complex systems that illuminate the night sky and provide the energy essential for life on Earth.

Our exploration continues with an in-depth look at our solar system, starting with the Sun, the dynamic heart that governs the motion of planets and other celestial bodies. We'll traverse the rocky terrain of terrestrial planets like Mercury, Venus, Earth, and Mars, before venturing to the distant gas giants—Jupiter, Saturn, Uranus, and Neptune—with their mesmerizing rings and myriad moons. Beyond the planets, we'll uncover the mysteries of other objects in the solar system, including dwarf planets, asteroids, and comets, each holding clues to the origins of our cosmic neighborhood. Get ready to expand your understanding of the universe and appreciate the extraordinary place our solar system holds within it.

Learning Objectives

1. Explain the relationship between the universe and Earth Science, including how celestial phenomena impact our planet.
2. Describe the structure and components of galaxies, focusing on the formation and characteristics of stars, including our Sun.
3. Analyze the features and dynamics of the solar system, highlighting the differences between terrestrial planets and gas giants.
4. Evaluate the role and significance of other objects in the solar system, such as dwarf planets, asteroids, and comets.
5. Understand the Sun's influence on the solar system and its importance in governing the motion and behavior of celestial bodies.



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7.2: The Universe

The Expanding Universe

The ancient Greeks believed that the universe contained Earth at the center and that the sun, moon, and stars were connected around the planet. This idea held for many centuries until Galileo's telescope helped allow people to realize that Earth is not the center of the universe. They also found out that there are many more stars than were visible to the naked eye. All of those stars were in the Milky Way Galaxy.

In the early 20th century, an astronomer named Edwin Hubble discovered that what scientists called the Andromeda Nebula was over 2 million light-years away, many times farther than the farthest distances that had ever been measured. Hubble realized that many of the objects that astronomers called nebulas were not clouds of gas, but were collections of millions or billions of stars that we now call galaxies.

Hubble showed that the universe was much larger than our galaxy. The general consensus among astronomers today is that there are at least several hundred billion galaxies in the universe. The number of stars in our Milky Way Galaxy are estimated to be between 100 billion to 400 billion. Edwin Hubble went on to measure the distance to hundreds of galaxies after discovering that there are galaxies beyond the Milky Way. His data would eventually show how the universe is changing, and would even yield clues as to how the universe formed. Our best estimates today are that the universe is approximately 14 billion years old.

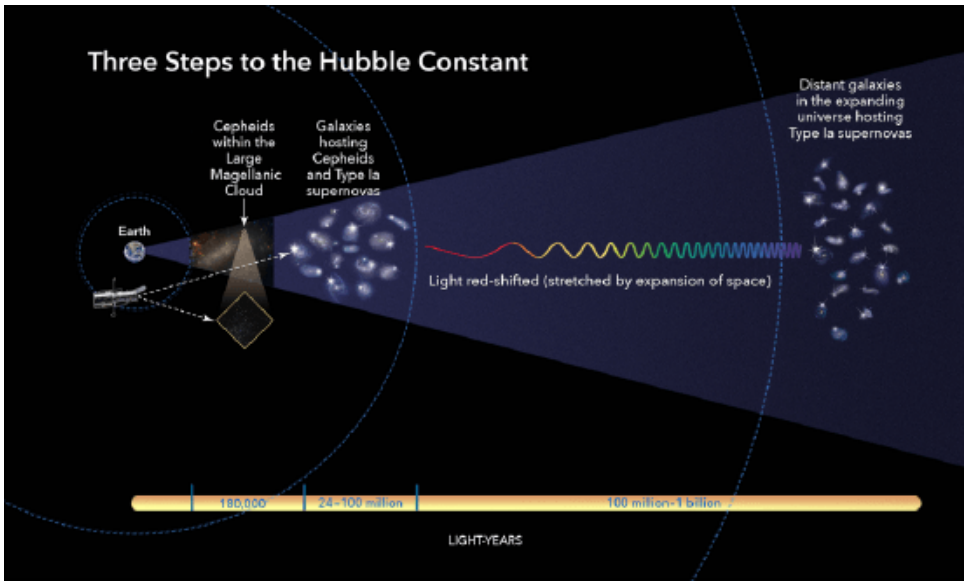
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Redshift

If we look at a star through a prism, we will see a spectrum or a range of colors through the rainbow. The spectrum will have specific dark bands where elements in the star absorb light of particular energies. By examining the arrangement of these dark absorption lines, astronomers can determine the composition of elements that make up a distant star. The element helium was first discovered in our Sun, not on Earth, by analyzing the absorption lines in the spectrum of the Sun.

While studying the spectrum of light from distant galaxies, astronomers noticed something strange. The dark lines in the spectrum were in the patterns they expected, but they were shifted toward the red end of the spectrum. This shift of absorption bands toward the red end of the spectrum is known as redshift.



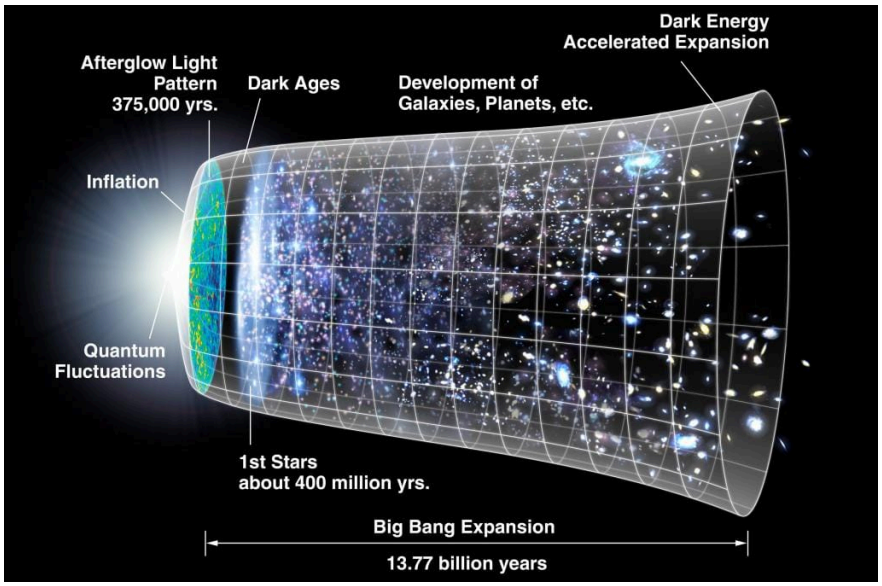
"Three Steps to the Hubble Constant" by NASA is licensed as Public Domain.

Redshift occurs when the light source is moving away from the observer or when the space between the observer and the source is stretched. What does it mean that stars and galaxies are redshifted? When astronomers see redshift in the light from a galaxy, they know that the galaxy is moving away from Earth. What astronomers are noticing is that all the galaxies have a redshift, strongly indicating that all galaxies are moving away from each other, causing the Universe to expand.

Redshift can occur with other types of waves, too, called the **Doppler Effect**. An analogy to redshift is the noise a siren makes as it passes. As it passes by, the ambulance will seem to lower the pitch of its siren. This is because the sound waves shift towards a lower pitch when the ambulance speeds away. Though redshift involves light instead of sound, a similar principle operates in both situations.

The Expanding Universe

Edwin Hubble combined his measurements of the distances to galaxies with other astronomers' measurements of redshift. From this data, he noticed a relationship, called **Hubble's Law,** that states that the farther away a galaxy is, the faster it is moving away from us. What this leads to is the hypothesis that the universe is expanding.



"Timeline of the Expanding Universe" by NASA is licensed as Public Domain.

The figure above by NASA shows a simplified diagram of the expansion of the universe. If we look closely at the diagram, the formation of the universe and the energy is relatively high. Over the 13.7 billion years, the energy begins to cool enough to create trillions of stars and, over time, develop into galaxies. Over time, the galaxies continue to cool and expand farther apart from each other.

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Formation of the Universe

Before Hubble, most astronomers thought that the universe did not change. However, if the universe is expanding, what does that say about where it was in the past? If the universe is expanding, the next logical thought is that it had to have been smaller in the past.

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The Big Bang Theory

The **Big Bang Theory** is the most widely accepted cosmological explanation of how the universe formed. According to the Big Bang theory, the universe began about 13.7 billion years ago. Everything that is now in the universe was squeezed into a tiny volume of hot, chaotic mass. An enormous explosion, a big bang – caused the universe to start expanding rapidly. All the matter and energy in the universe and even space itself came out of this explosion. Currently, there is not a way for scientists to know since there is no remaining evidence.

After the Big Bang

In the first few moments after the Big Bang, the universe was unimaginably hot and dense. As the universe expanded, it became less dense and began to cool. After only a few seconds, protons, neutrons, and electrons formed. After a few minutes, those subatomic particles came together to create hydrogen. The energy in the universe was significant enough to initiate nuclear fusion, and hydrogen nuclei were fused into helium nuclei. The first neutral atoms that included electrons did not form until about 380,000 years later.

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The matter in the early universe was not smoothly distributed across space. Dense clumps of matter held close together by gravity were spread around. Eventually, these clumps formed countless trillions of stars, billions of galaxies, and other structures that now form most of the universe's visible mass. If we look at an image of galaxies at the far edge of what we can see, we are looking at great distances. However, we are also looking across a different type of distance. Because it takes so long for light from so far away to reach us, we are also looking back in time.

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Dark Matter and Dark Energy

The Big Bang Theory is still the best scientific model we have for explaining the formation of the universe, and many lines of evidence support it. However, recent discoveries continue to shake up our understanding of the universe. Astronomers and other scientists are now wrestling with some unanswered questions about what the universe is made of and why it is expanding. Many cosmologists create mathematical models and computer simulations to account for these unknown phenomena, such as **dark energy** and **dark matter**.

The things we observe in space are objects that emit electromagnetic radiation. However, scientists think that matter that emits light makes up only a small part of the matter in the universe. The rest of the matter, about 80 percent, is dark matter. Dark matter emits no electromagnetic radiation, so we cannot observe it directly. However, astronomers know that dark matter exists because its gravity affects the motion of objects around it. When astronomers measure how spiral galaxies rotate, they find that the outside edges of a galaxy rotate at the same speed as parts closer to the center. This can only be explained if there is a lot more matter in the galaxy than they can see.

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Gravitational lensing occurs when light is bent from a very distant bright source around a supermassive object. To explain strong gravitational lensing, more matter than is observed must be present. With so little to go on, astronomers do not know much about the nature of dark matter. One possibility is that it could just be ordinary matter that does not emit radiation in objects such as black holes, neutron stars, and brown dwarfs, objects more massive than Jupiter but smaller than the smallest stars. However, astronomers cannot find enough of these types of objects, which they have named MACHOS (massive astrophysical compact halo object), to account for all the dark matter, so they are thought to be only a small part of the total.

Another possibility is that the dark matter is thought to be much different from the ordinary matter we see. Some appear to be particles that have gravity, but do not otherwise appear to interact with other particles. Scientists call these theoretical particles WIMPs, which stands for Weakly Interactive Massive Particles. Most scientists who study dark matter think that the dark matter in the universe is a combination of massive astrophysical compact halo objects (MACHOS) and some exotic matter such as weakly-interacting massive particles (WIMPs). Researching dark matter is an active area of scientific research, and astronomers' knowledge about dark matter is changing rapidly.

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Astronomers who study the expansion of the universe are interested in knowing the rate of that expansion. Is the rate fast enough to overcome the attractive pull of gravity? If yes, then the universe will expand forever, although the expansion will slow down over time. If no, then the universe would someday start to contract, and eventually get squeezed together in a big crunch, the opposite of the Big Bang. Observations of the universe show that it is expanding faster now than ever before, and in the future, it will expand even faster. So now, astronomers think that the universe will keep expanding forever. However, it also proposes a problematic new question: What is causing the expansion of the universe to accelerate? One possible hypothesis involves a new, hypothetical form of energy called dark energy. Some scientists think that dark energy makes up as much as 72 percent of the total energy content of the universe.

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Star Systems

"**Stars** are the most widely recognized astronomical objects, and represent the most fundamental building blocks of galaxies. The age, distribution, and composition of the stars in a galaxy trace the history, dynamics, and evolution of that galaxy. Moreover, stars are responsible for the manufacture and distribution of heavy elements such as carbon, nitrogen, and oxygen, and their characteristics are intimately tied to the characteristics of the planetary systems that may coalesce about them. Consequently, the study of the birth, life, and death of stars is central to the field of astronomy." (Stars | Science Mission Directorate, n.d.)

Although constellations have stars that usually only appear to be close together, stars may be found in the same portion of space. Stars that are grouped tightly together are called **star systems**. Larger groups of hundreds or thousands of stars are called **star clusters**. The image shown here is a famous star cluster known as Pleiades, which can be seen with the naked autumn sky.



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Although the star humans know best is a single star, many stars – in fact, more than half of the bright stars in our galaxy – are star systems. A system of two stars orbiting each other is a binary star. A system with more than two stars orbiting each other is a multiple star system. The stars in a binary or multiple star system are often so close together that they appear as only through a telescope can the pair be distinguished.

Star clusters are divided into two main types, open clusters and globular clusters. **Open clusters** are groups of up to a few thousand stars that are loosely held together by gravity. Pleiades is an open cluster that is also called the Seven Sisters. Open clusters tend to be blue and often contain glowing gas and dust and are made of young stars formed from the same nebula. The stars may eventually be pulled apart by gravitational attraction to other objects.

Globular clusters are groups of tens to hundreds of thousands of stars held tightly together by gravity. Globular clusters have a definite, spherical shape and contain mostly reddish stars. The stars are closer together, closer to the center of the cluster. Globular clusters do not have much dust in them — the dust has already formed into stars.

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7.3: Galaxies and Stars

Types of Galaxies

Galaxies are the most prominent groups of stars and can contain anywhere from a few million stars to many billions of stars. Every star that is visible in the night sky is part of the Milky Way Galaxy. To the naked eye, the closest major galaxy, the Andromeda Galaxy, looks like only a dim, fuzzy spot, but that fuzzy spot contains one trillion stars.

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Spiral and Elliptical Galaxies

Spiral galaxies spin, so they appear as a rotating disk of stars and dust, with a bulge in the middle, like the Sombrero Galaxy. Several arms spiral outward in the Pinwheel Galaxy and are appropriately called spiral arms. Spiral galaxies have lots of gas and dust and lots of young stars.

Other galaxies are egg-shaped and called an **elliptical galaxy**. The smallest elliptical galaxies are as small as some **globular clusters**. Giant elliptical galaxies, on the other hand, can contain over a trillion stars. Elliptical galaxies are reddish to yellowish because they contain mostly old stars. Most elliptical galaxies contain very little gas and dust because they had already formed. However, some elliptical galaxies contain lots of dust. Why might some elliptical galaxies contain dust?

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Irregular and Dwarf Galaxies

Galaxies that are not elliptical galaxies or spiral galaxies are **irregular galaxies**. Most irregular galaxies were once spiral or elliptical galaxies that were then deformed either by gravitational attraction to a more massive galaxy or by a collision with another galaxy.

Dwarf galaxies are small galaxies containing only a few million to a few billion stars. Dwarf galaxies are the most common type in the universe. However, because they are relatively small and dim, we do not see as many dwarf galaxies from Earth. Most dwarf galaxies are irregular in shape. However, there are also dwarf elliptical galaxies and dwarf spiral galaxies.

Look back at the picture of the spiral galaxy, Andromeda. Next to our closest galaxy neighbor are two dwarf elliptical galaxies that are companions to the Andromeda Galaxy. One is a bright sphere to the left of center, and the other is a long ellipse below and to the center's right. Dwarf galaxies are often found near more massive galaxies. They sometimes collide with and merge into their larger neighbors.

Milky Way Galaxy

On a dark, clear night, a milky band of light will stretch across the sky. This band is the disk of a galaxy, the **Milky Way Galaxy** is our galaxy and is made up of millions of stars along with a lot of gas and dust. Although it is difficult to know what the shape of the Milky Way Galaxy is because we are inside of it, astronomers have identified it as a typical spiral galaxy containing about 100 billion to 400 billion stars.

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Like other spiral galaxies, our galaxy has a disk, a central bulge, and spiral arms. The disk is about 100,000 light-years across and 3,000 light-years thick. Most of the Galaxy's gas, dust, young stars, and open clusters are in the disk. Scientists know that the Milky Way is a spiral galaxy because of the shape of the galaxy as from Earth's perspective, the velocities of stars and gas in the galaxy show a rotational motion, and the gases, color, and dust are typical of spiral galaxies.

The central bulge is about 12,000 to 16,000 light-years wide and 6,000 to 10,000 light-years thick. The central bulge contains mostly older stars and globular clusters. Some recent evidence suggests the bulge might not be spherical, but is instead shaped like a bar. The bar might be as long as 27,000 light-years long. The disk and bulge are surrounded by a faint, spherical halo, which also includes old stars and globular clusters. Astronomers have discovered that there is a gigantic black hole at the center of the galaxy.

The Milky Way Galaxy is a significant place. Our solar system, including the Sun, Earth, and all the other planets, is within one of the spiral arms in the disk of the Milky Way Galaxy. Most of the stars we see in the sky are relatively nearby stars that are also in this spiral arm. Earth is about 26,000 light-years from the center of the galaxy, a little more than halfway out from the center of the galaxy to the edge.

Just as Earth orbits the Sun, the Sun and solar system orbit the center of the Milky Way Galaxy. One orbit of the solar system takes about 225 to 250 million years. The solar system has orbited 20 to 25 times since it formed 4.6 billion years ago. Astronomers have recently found that at the center of the Milky Way, and most other galaxies, is a supermassive black hole, though a black hole cannot be seen.

https://youtu.be/O37DrGZxDyw

Nuclear Fusion within Stars

The Sun is Earth's primary source of energy, yet the planet only receives a small portion of its energy, and the Sun is just an ordinary star. Many stars produce much more energy than the Sun. The energy source for all stars is **nuclear fusion**.

Stars are made mostly of hydrogen and helium, which are packed so densely in a star that is the star's center. The pressure is enormous enough to initiate nuclear fusion reactions. In a nuclear fusion reaction, the nuclei of two atoms combine to create a new atom. Most commonly, two hydrogen atoms fuse to become a helium atom in the core of a star. Although nuclear fusion reactions require much energy to get started, they produce enormous amounts of energy once they are going.

In a star, the energy from fusion reactions in the core pushes outward to balance the inward pull of the star's gravity. This energy moves outward through the star's layers until it finally reaches the star's outer surface. The star's outer layer glows brightly, sending the energy into space as **electromagnetic radiation**, including visible light, heat, ultraviolet light, and radio waves.

In particle accelerators, subatomic particles are propelled until they have attained almost the same amount of energy as found in the core of a star. When these particles collide head-on, new particles are created. This process simulates the nuclear fusion that takes place in the cores of stars. The process also mimics the conditions that allowed for the first helium atom to be produced from the collision of two hydrogen atoms in the first few minutes of the universe.

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Star Classification

Think about how the color of a piece of metal changes with temperature. A coil of an electric stove will start black, but with added heat will start to glow a dull red. With more heat, the coil turns a brighter red, then orange. At extremely high temperatures, the coil will turn yellow-white or even blue-white. A star's color is also determined by the temperature of the star's surface. Relatively cool stars are red, warmer stars are orange or yellow, and extremely hot stars are blue or blue-white.

Color is the most common way to classify stars. A star's class is given by a letter, where each letter corresponds to a color and temperature range. Note that these letters do not match the color names; they are leftover from an older system that is no longer used. For most stars, the surface temperature is also related to size. Bigger, bluish-white stars produce more energy and have hotter surfaces than smaller, yellow stars that produce less energy, so their surfaces are hotter than smaller stars. These stars tend toward bluish-white.

Stars have a life cycle that is expressed similarly to the life cycle of a living creature: they are born, grow, change over time, and eventually die. Most stars vary in size, color, and class at least once in their lifetime. What astronomers know about the life cycles of stars is because of data gathered from visual, radio, and X-ray telescopes.

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Main Sequence Stars

For most of a star's life, nuclear fusion in the core produces helium from hydrogen, a stage called a **main-sequence star**. This term comes from the **Hertzsprung-Russell diagram** shown below. For stars on the main sequence, the temperature is directly related to brightness. A star is on the main sequence as long as it can balance the inward force of gravity with the outward force of nuclear fusion in its core. The more massive a star, the more it must burn hydrogen fuel to prevent internal gravitational collapse. Because they burn more fuel, massive stars have higher temperatures, but run out of hydrogen sooner than smaller stars.

Our Sun, a yellow star, has been a main-sequence star for about 5 billion years and will continue on the main sequence for about 5 billion more years. Massive stars may be on the main sequence for only 10 million years. Tiny stars may last tens to hundreds of billions of years.

Red Giants and White Dwarfs

As a star begins to use up its hydrogen, it fuses helium atoms into heavier atoms such as carbon. A blue giant star has exhausted its hydrogen fuel and is a transitional phase. When the light elements are mostly used up, the star can no longer resist gravity, and it starts to collapse inward. The outer layers of the star grow outward and cool. The larger, cooler star turns red, and so is called a **red giant**.

Eventually, a red giant burns up all of the helium in its core. What happens next depends on how massive the star is. A typical star, such as the Sun, stops fusion completely. Gravitational collapse shrinks the star's core to a white, glowing object about Earth's size, called a **white dwarf**, which will ultimately fade out.



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Low Mass Stars



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High Mass Stars

A star that runs out of helium will end its life much more dramatically. When very massive stars leave the main sequence, they become **redsupergiants**. Unlike a red giant, when all the helium in a red supergiant is gone, fusion continues. Lighter atoms fuse into heavier atoms up to iron atoms. Creating elements heavier than iron through fusion uses more energy than it produces, so stars do not ordinarily form any heavier elements. When there are no more elements for the star to fuse, the core succumbs to gravity and collapses, creating an explosion called a **supernova**.

A supernova explosion contains so much energy that atoms can fuse to produce heavier elements such as gold, silver, and uranium. A supernova can shine as brightly as an entire galaxy for a short time. Nuclear fusion in stars created all elements with

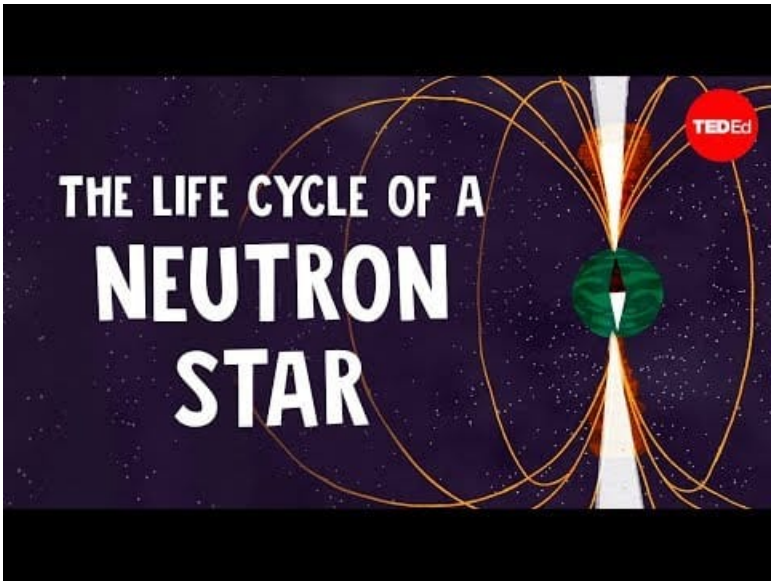
an atomic number more significant than that of lithium.



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Neutron Stars and Black Holes

After a supernova explosion, the leftover material in the core is incredibly dense. If the core is less than about four times the mass of the Sun, the star becomes a **neutron star**. A neutron star is made almost entirely of neutrons, relatively large particles that have no electrical charge.



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If the core remaining after a supernova is more than about five times the mass of the Sun, the core collapses into a black hole. **Black holes** are so dense that not even light can escape their gravity. With no light, a black hole cannot be observed directly. However, a black hole can be identified by the effect that it has on objects around it, and by radiation that leaks out around its edges.



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Observing and Measuring Stars

Astronomical Observations



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Telescopes



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Parallax

Parallax is an apparent shift in position that takes place when the position of the observer changes. To see an example of parallax, try holding your finger about 30 cm (1 foot) in front of your eyes. Now, while focusing on your finger, close one eye and then the other. Alternate back and forth between eyes, and pay attention to how your finger appears to move. The shift in the position of your finger is an example of parallax. Now try moving your finger closer to your eyes, and repeat the experiment and notice any differences. The closer your finger is to your eyes, the more significant the position changes because of parallax.

Astronomers use this same principle to measure the distance to stars. Instead of a finger, they focus on a star, and instead of switching back and forth between eyes, they switch between the most significant possible differences in observing position. To do this, an astronomer first looks at the star from one position and notes where the star is relative to more distant stars. Now, where will the astronomer go to observe the most significant distance from the first observation? In six months, after Earth moves from one side of its orbit around the Sun to the other side, the astronomer looks at the star again. This time parallax causes the star to appear in a different position relative to more distant stars. From the size of this shift, astronomers can calculate the distance to the star.

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Using NASA's Hubble Space Telescope, astronomers now can precisely measure the distance of stars up to 10,000 light-years away, ten times farther than previously possible. Astronomers have developed yet another novel way to use the 24-year-old space telescope by employing a technique called spatial scanning, which dramatically improves Hubble's accuracy for making angular measurements. The technique, when applied to the age-old method for gauging distances called astronomical parallax, extends Hubble's tape measure ten times farther into space. "This new capability is expected to yield new insight into the nature of dark energy, a mysterious component of space that is pushing the universe apart at an ever-faster rate," said Noble laureate Adam Riess of the Space Telescope Science Institute (STScI) in Baltimore, Md.

Parallax, a trigonometric technique, is the most reliable method for making astronomical distance measurements, and a practice long employed by land surveyors here on Earth. Earth's orbit's diameter is the base of a triangle, and the star is the apex where the triangle's sides meet. The lengths of the sides are calculated by accurately measuring the three angles of the resulting triangle. Astronomical parallax works reliably well for stars within a few hundred light-years of Earth. (Northon, 2014)

For example, measurements of the distance to Alpha Centauri, the star system closest to our sun, vary only by one arc second. This variance in distance is equal to the apparent width of a dime seen from two miles away. Stars farther out have much smaller angles of apparent back-and-forth motion that are extremely difficult to measure. (Northon, 2014)

Astronomers have pushed to extend the parallax yardstick ever deeper into our galaxy by measuring smaller angles more accurately. This new long-range precision was proven when scientists successfully used Hubble to measure the distance of a particular class of bright stars called Cepheid variables, approximately 7,500 light-years away in the northern constellation Auriga. The technique worked so well; they are now using Hubble to measure the distances of other far-flung Cepheids. Such measurements will be used to provide a firmer footing for the so-called cosmic “distance ladder.” This ladder’s “bottom rung” is built on measurements to Cepheid variable stars that, because of their known brightness, have been used for more than a century to gauge the size of the observable universe. They are the first step in calibrating far more distant extra-galactic milepost markers such as Type Ia supernovae.

Riess and the Johns Hopkins University in Baltimore, Md., in collaboration with Stefano Casertano of STScI, developed a technique to use Hubble to make measurements as small as five-billionths of a degree. To make a distance measurement, two exposures of the target Cepheid star were taken six months apart, when Earth was on opposite sides of the sun. A very subtle shift in the star’s position was measured to an accuracy of 1/1,000 the width of a single image pixel in Hubble’s Wide Field Camera 3, which has 16.8 megapixels total. A third exposure was taken after another six months to allow for the team to subtract the effects of the subtle space motion of stars, with additional exposures used to remove other sources of error.

Riess shares the 2011 Nobel Peace Prize in Physics with another team for his leadership in the 1998 discovery the universe’s expansion rate is accelerating — a phenomenon widely attributed to a mysterious, unexplained dark energy filling the universe. This new high-precision distance measurement technique is enabling Riess to gauge just how much the universe is stretching. His goal is to refine estimates of the universe’s expansion rate to the point where dark energy can be better characterized. (Northon, 2014)

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7.4: The Solar System

Geocentric Model

Humans' view of the **solar system** has evolved as technology and scientific knowledge has increased. The ancient Greeks identified five of the planets, and they were the only planets known for many centuries. Since then, scientists have discovered two more planets, many other solar-system objects, and even planets found outside our solar system. (Introduction to the Solar System | Earth Science, n.d.)

The ancient Greeks believed that Earth was at the center of the universe. This view is called the **geocentric "**Earth-centered" **model**. In the geocentric model, the sky, or heavens, are a set of spheres layered on top of one another. Each object in the sky is attached to a sphere and moves around Earth as that sphere rotates. From Earth outward, these spheres contain the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. An outer sphere holds all the stars. Since the planets appear to move much faster than the stars, the Greeks placed them closer to Earth.

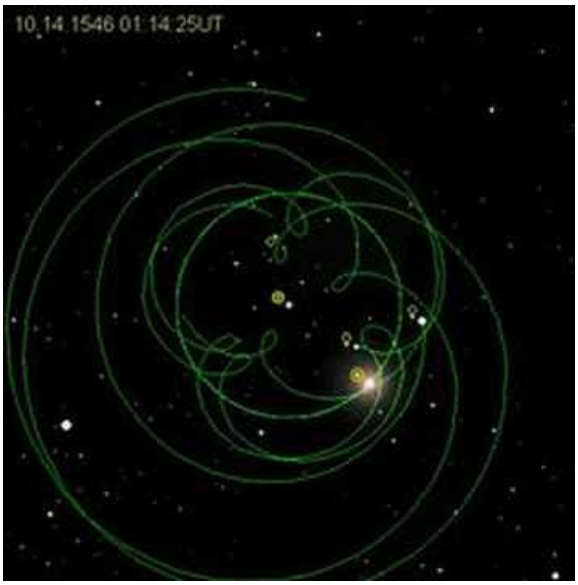
The geocentric model worked well by explaining why all the stars appear to rotate around Earth once per day. The model also explained why the planets move differently from the stars and each other. One problem with the geocentric model is that some planets seem to move backward, in retrograde, instead of in their usual forward motion around Earth.

Around 150 A.D., the astronomer Ptolemy resolved this problem by using a system of circles to describe the motion of planets. In Ptolemy's system, a planet moves in a small circle, called an **epicycle**. This circle moves around Earth in a larger circle, called a **deferent**. Ptolemy's version of the geocentric model worked so well that it remained the accepted model of the universe for more than a thousand years.

Heliocentric Model

Ptolemy's geocentric model worked, but it was not only complicated, it occasionally made errors in predicting the movement of planets. At the beginning of the 16th century A.D., Nicolaus Copernicus proposed that Earth and all the other planets orbit the Sun. With the Sun at the center, this model is called the heliocentric or "sun-centered" model of the universe. Copernicus' model explained the motion of the planets, as well as Ptolemy's model, did, but it did not require complicated additions like epicycles and deferents.

Although Copernicus' model worked more simply than Ptolemy's, it still did not entirely describe the motion of the planets because, like Ptolemy, Copernicus thought planets moved in perfect circles. Not long after Copernicus, Johannes Kepler refined the heliocentric model so that the planets moved around the Sun in ellipses (ovals), not circles. Kepler's model matched observations perfectly.



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Because people were so used to thinking of Earth at the center of the universe, the heliocentric model was not widely accepted at first. However, when Galileo Galilei first turned a telescope to the heavens in 1610, he made several striking discoveries. Galileo discovered that the planet Jupiter has moons orbiting around it. This provided the first evidence that objects could orbit something besides Earth. Galileo also discovered that Venus has phases like the Moon, which provides direct proof that Venus orbits the Sun.

Galileo's discoveries caused many more people to accept the heliocentric model of the universe, although Galileo himself was found guilty of heresy for his ideas. The shift from an Earth-centered view to a Sun-centered view of the universe is referred to as the Copernican Revolution.

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Watch this animation of the Ptolemaic and Copernican models of the solar system. Ptolemy made the best model he could with the assumption that Earth was the center of the universe, but by letting that assumption go, Copernicus came up with a much simpler model. Before people would accept that Copernicus was right, they needed to accept that the Sun was the center of the solar system.

Today we know that just as Earth orbits the Sun, the Sun and solar system orbit the center of the Milky Way galaxy. The center of the Milky Way may likely be a massive black hole. One orbit of the solar system takes about 225 to 250 million years. It is believed that the solar system has orbited 20 to 25 times since it formed 4.6 billion years ago.

Modern Solar System

Today, we know that our **solar system** is just one tiny part of the universe. Neither Earth nor the Sun is at the center of the universe. However, the heliocentric model accurately describes the solar system. In our modern view of the solar system, the Sun is at the center, with the planets moving in elliptical orbits around the Sun. The planets do not emit their light, but instead, reflect light from the Sun.

The Environmental Research Institute (ESRI) has created an excellent story map called the Solar System Atlas. NASA has created a great website called Solar System Exploration, and National Geographic has created a great resource called Solar System. These several websites are splendid sources to introduce yourself to our solar system.

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Exoplanets

Since the early 1990s, astronomers have discovered other solar systems, with planets orbiting stars other than our own Sun, called **extrasolar planets** or simply, **exoplanets**. Some extrasolar planets have been directly observed, but indirect methods have discovered most. One technique involves detecting a star's very slight motion periodically moving toward and away from us along our line-of-sight, known as a star's **radial velocity**. This periodic motion can be attributed to the gravitational pull of a planet or, sometimes, another star orbiting the star.

A planet may also be identified by measuring a star's brightness over time. A temporary, periodic decrease in light emitted from a star can occur when a planet crosses in front of the star it is orbiting, called a **transit**, momentarily blocking out some of the starlight. More than 3,600 extrasolar planets have been identified, and the rate of discovery is increasing rapidly.

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Planets and Their Motions

Since the time of Copernicus, Kepler, and Galileo, we have learned a lot more about our solar system. Astronomers have discovered two more planets (Uranus and Neptune), four dwarf planets (Ceres, Pluto, Makemake, Haumea, and Eris), more than 150 moons, and many, many asteroids and other small objects.

Although the Sun is just an average star compared to other stars, it is by far the most massive object in the solar system. The Sun is more than 500 times the mass of everything else in the solar system combined. The table below gives data on the sizes of the Sun and planets relative to Earth. (Introduction to the Solar System | Earth Science, n.d.)

Object	Mass (Relative to Earth	Diameter of Planet (Relative to Earth)
Sun	333,000 Earth's mass	109.2 Earth's diameter
Mercury	0.06 Earth's mass	0.39 Earth's diameter
Venus	0.82 Earth's mass	0.95 Earth's diameter
Earth	1.00 Earth's mass	1.00 Earth's diameter
Mars	0.11 Earth's mass	0.53 Earth's diameter

Jupiter	317.8 Earth's mass	11.21 Earth's diameter
Saturn	95.2 Earth's mass	9.41 Earth's diameter
Uranus	4.6 Earth's mass	3.98 Earth's diameter
Neptune	7.2 Earth's mass	.81 Earth's diameter

Size and Shape of Planetary Orbits

The figure below shows the relative sizes of the orbits of the major planets within our solar system. In general, the farther away from the Sun, the higher the distance from one planet's orbit to the next. The orbits of the planets are not circular but slightly elliptical with the Sun located at one of the foci.

While studying the solar system, Johannes Kepler discovered the relationship between the time it takes a planet to make one complete orbit around the Sun, its "orbital period," and the distance from the Sun to the planet. If the orbital period of a planet is known, it is possible to determine the planet's distance from the Sun. This is how astronomers without modern telescopes could determine the distances to other planets within the solar system.

Distances in the solar system are often measured in astronomical units (AU). One astronomical unit is defined as the distance from Earth to the Sun. 1 AU equals about 150 million kilometers or 93 million miles. The table below shows the distances to the planets (the average radius of orbits) in AU. The table also indicates how long it takes each planet to spin on its axis (the length of a day) and how long it takes each planet to complete an orbit (the length of a year); in particular, notice how slowly Venus rotates relative to Earth.

Planet	Average Distance from Sun	Length of Day	Length of Year
Mercury	0.39 Astronomical Units (AU)	56.84 (In Earth Days)	0.24 (In Earth Years)
Venus	0.72	243.02	0.62
Earth	1.00	1.00	1.00
Mars	1.52	1.03	1.88
Jupiter	5.2	0.41	11.86
Saturn	9.54	0.43	29.46
Uranus	19.22	0.72	84.01
Neptune	30.06	0.67	164.8

The Role of Gravity

Isaac Newton was one of the first scientists to explore gravity. He understood that the Moon circles the Earth because a force is pulling the Moon toward Earth's center. Without that force, the Moon would continue moving in a straight line off into space. Newton also came to understand that the same force that keeps the Moon in its orbit is the same force that causes objects on Earth to fall to the ground.

Newton defined the **Universal Law of Gravitation**, which states that a force of attraction, called **gravity**, exists between all objects in the universe. The strength of the gravitational force depends on how much mass the objects have and how far apart they are from each other. The greater the objects' mass, the higher the force of attraction; also, the greater the distance between the objects, the smaller the force of attraction.

The distance between the Sun and each of its planets is substantial, but the Sun and each of the planets are also gigantic. Gravity keeps each planet orbiting the Sun because the star and its planets are enormous objects. The force of gravity also holds moons in orbit around planets. There are two additional key features of the solar system that helps us understand how it formed: 1) All the planets lie in nearly the same plane, or flat disk-like region, 2) All the planets orbit in the same direction around the Sun.

Formation of the Solar System

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The most widely accepted explanation of how the solar system formed is called the **nebular hypothesis**. According to this hypothesis, the Sun and the planets of our solar system formed about 4.6 billion years ago from the collapse of a giant cloud of gas and dust, called a **nebula**.

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The nebula was drawn together by gravity, which released gravitational potential energy. As small particles of dust and gas smashed together to create larger ones, they released kinetic energy. As the nebula collapsed, the gravity at the center increased, and the cloud started to spin because of its angular momentum. As it collapsed further, the spinning got faster, much as an ice skater spins faster when he pulls his arms to his sides during a spin.

Much of the cloud's mass migrated to its center, but the rest of the material flattened out in an enormous disk. The disk contained hydrogen and helium, along with heavier elements and even simple organic molecules.

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Formation of the Sun and Planets

As gravity pulled matter into the center of the disk, the density and pressure at the center became intense. When the pressure in the center of the disk was high enough, nuclear fusion within our star began, and the blazing star stopped the disk from collapsing further.

Meanwhile, the outer parts of the disk were cooling off. Matter condensed from the cloud, and small pieces of dust started clumping together to create ever bigger clumps of matter. Larger clumps, called **planetesimals**, attracted smaller clumps with their gravity. Gravity at the center of the disk attracted more massive particles, such as rock and metal, and lighter particles remained further out in the disk. Eventually, the planetesimals formed **protoplanets**, which grew to become the planets and moons that we find in our solar system today.

The gravitational sorting of material with the inner planets, Mercury, Venus, Earth, and Mars, dense rock and metal formed. The outer planets, Jupiter, Saturn, Uranus, and Neptune, condensed farther from the Sun from lighter materials such as hydrogen, helium, water, ammonia, and methane. Out by Jupiter and beyond, where it is frigid, these materials formed solid particles.

The nebular hypothesis was designed to explain some of the essential features of the solar system:

- Orbits of the planets lie in nearly the same plane with the Sun at the center

- Planets revolve in the same direction
- Planets mostly rotate in the same direction
- Axes of rotation of the planets are mostly nearly perpendicular to the orbital plane
- Oldest moon rocks are 4.5 billion years

The two videos below, from the European Space Agency (ESA), discusses the Sun, planets, and other bodies in the Solar System and how they formed. The first part of the video explores the evolution of our view of the solar system, starting with the early Greeks, who reasoned that since some points of light, which they called planets, moved faster than the stars, they must be closer.

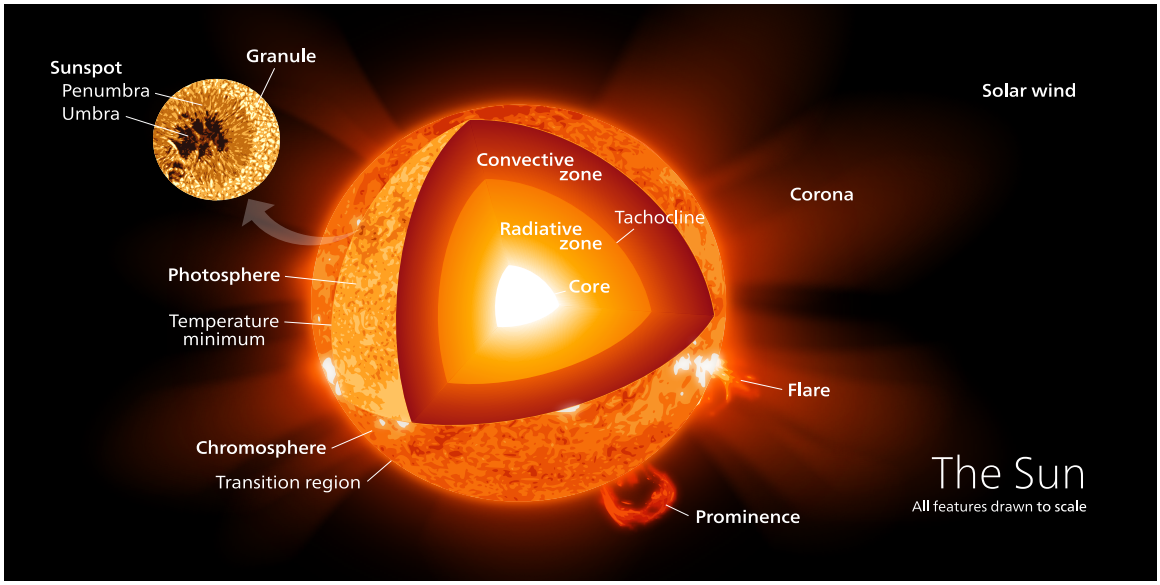
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7.5: The Sun

Consider Earth, the Moon, and all the other planets and satellites in the solar system. The mass of all of those objects together accounts for only 0.2 percent of the total mass of the solar system. The remaining 99.8 percent of the solar system's mass is within the Sun. The **Sun** is the center of the solar system and provides the light and heat that sustains almost all life on Earth.



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The Sun is a sphere, composed almost entirely of the elements hydrogen and helium. The Sun is not solid or typical gas. Most atoms in the Sun exist as plasma, the fourth state of matter made up of superheated gas with a positive electrical charge. (The Sun | Earth Science, n.d.)

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Internal Structure

Because the Sun is not solid, it does not have a defined outer boundary. It does, however, have a definite internal structure with identifiable layers.

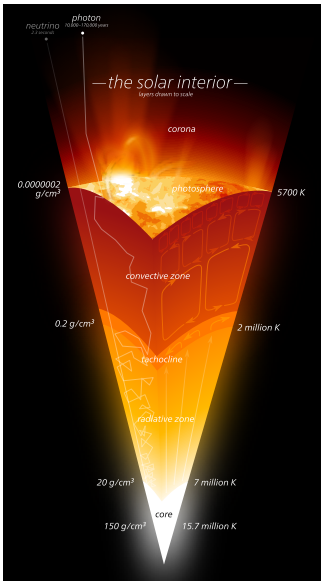
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The Sun's **central core** is plasma with a temperature of around 27 million degrees Celsius. At such high temperatures, hydrogen combines to form helium by nuclear fusion, a process that releases vast amounts of energy. This energy moves outward towards the outer layers of the Sun.

The **radiative zone**, just outside the core, has a temperature of about 7 million degrees Celsius. The energy released in the core travels exceptionally slow through the radiative zone. A particle of light, called a photon, travels only a few millimeters before it hits another particle. The photon is absorbed and then released again. A photon may take as long as 50 million years to travel through the radiative zone.

In the **convection zone**, hot material from near the radiative zone rises, cools at the Sun's surface, and then plunges back downward to the radiative zone. Convective movement helps to create solar flares and sunspots.



"Cross-section Diagram of the Solar Interior" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

The Outer Layers

The next three layers make up the Sun's atmosphere. Since there are no solid layers to any part of the Sun, these boundaries are fuzzy and indistinct.

The **photosphere** is the visible surface of the Sun, the region that emits sunlight. The photosphere is relatively cool, only about 6,700 degrees Celsius. The photosphere has several different colors; oranges, yellows, and reds, giving it a grainy appearance.

The **chromosphere** is a thin zone, about 2,000 km thick, that glows red as energy heats it from the photosphere. Temperatures in the chromosphere range from about 4,000-10,000 degrees Celsius. Jets of gas fire up through the chromosphere at speeds up to 72,000 km per hour, reaching heights as high as 10,000 km.

The **corona** is the outermost plasma layer and is called the Sun's halo or crown. The corona's temperature of 2 to 5 million degrees Celsius is much hotter than the photosphere.

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Surface Features

The Sun's surface features are quite visible for humans to observe, but only with specialized equipment. The most noticeable surface feature of the Sun are cooler, darker areas known as sunspots. **Sunspots** are located where loops of the Sun's magnetic field break through the surface and disrupt the smooth transfer of heat from lower layers of the Sun, making them cooler and darker and marked by intense magnetic activity. Sunspots usually occur in pairs. When a loop of the Sun's magnetic field breaks through the surface, a sunspot is created where the loop comes out and where it goes back in again.

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There are other types of interruptions of the Sun's magnetic energy. If a loop of the sun's magnetic field snaps and breaks, it creates solar flares, which are explosions that release vast amounts of energy. A strong solar flare can turn into a **coronal mass ejection**.

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A solar flare or coronal mass ejection release streams of highly energetic particles that make up the **solar wind**. The solar wind can be dangerous to spacecraft and astronauts because it sends massive amounts of radiation that can harm the human body. Solar flares have knocked out entire power grids and disturbing radio, satellite, and cell phone communications.

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Another highly visible feature on the Sun is **solar prominences**. If plasma flows along a loop of the Sun's magnetic field from sunspot to sunspot, it forms a glowing arch that reaches thousands of kilometers into the Sun's atmosphere. Prominences can last for a day to several months. Prominences are also visible during a total **solar eclipse**.

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7.6: Terrestrial Planets

On Earth, scientists can collect and analyze the chemistry of samples, do radiometric dating to determine their ages, and look at satellite images to see large-scale features. Rovers have landed on Mars and sent back enormous amounts of information, but much of the rest of what is known about the inner planets are from satellite images.

The inner planets, or **terrestrial planets**, are the four planets closest to the Sun: Mercury, Venus, Earth, and Mars. Unlike the outer planets, which have many satellites, Mercury and Venus do not have moons, Earth has one, and Mars has two. The inner planets have shorter orbits around the Sun and spin more slowly than the outer gas giants. Geologically, the inner planets are all made of cooled igneous rock with iron cores, and all have been geologically active, at least early in their history. None of the inner planets has rings. (Inner Planets | Earth Science, n.d.)

Terrestrial planets are substantially different from gas giants. The latter may not have solid surfaces and are composed mostly of hydrogen, helium, and water existing in various physical states. Terrestrial planets all have roughly the same structure: a central metallic core, mostly iron, with a surrounding silicate mantle. Terrestrial planets have canyons, craters, mountains, volcanoes, and secondary atmospheres.

Mercury

The smallest planet, **Mercury**, is the planet closest to the Sun. Because of Mercury's proximity to the Sun, it is difficult to observe from Earth, even with a telescope. However, the Mariner 10 spacecraft visited Mercury from 1974 to 1975. The MESSENGER spacecraft, which stands for Mercury Surface, Space Environment, Geochemistry, and Ranging, has been studying Mercury in detail since 2005. The craft is currently in orbit around the planet, where it is creating detailed maps. MESSENGER stands for Mercury Surface, Space Environment, Geochemistry, and Ranging.

The surface of Mercury is covered with craters. Ancient impact craters mean that for billions of years, Mercury has not changed much geologically. Also, with minimal atmosphere, the processes of weathering and erosion do not wear down structures on the planet. Mercury is one of the solar system's densest planets. It has a relatively large, liquid core, made mostly of melted iron, takes up about 42 percent of the planet's volume.

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Mercury is named for the Roman messenger god, who could run extremely quickly, just as the planet moves very quickly in its orbit around the Sun. A year on Mercury, the length of time it takes to orbit the Sun is just 88 Earth days.

Despite its short years, Mercury has very long days. A day is defined as the time it takes a planet to turn on its axis. Mercury rotates slowly on its axis, turning precisely three times for every two times it orbits the Sun. Therefore, each day on Mercury is 57 Earth days long. In other words, on Mercury, a year is only a Mercury day and a half long!

Mercury is close to the Sun so that it can get scorching. However, Mercury has virtually no atmosphere, no water to insulate the surface, and rotates very slowly. For these reasons, temperatures on the surface of Mercury vary widely. Indirect sunlight, the surface can be as hot as 427 degrees Celsius (801 degrees Fahrenheit). On the dark side, or in the shadows inside craters, the surface can be as cold as -183 degrees Celsius (-297 degrees Fahrenheit). Although most of Mercury is extremely dry, scientists think there may be a small amount of water in the form of ice at the poles of Mercury, in areas that never receive direct sunlight.

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Venus

Named after the Roman goddess of love, **Venus** is the only planet named after a female. Venus' thick clouds reflect sunlight well, so Venus is very bright, making it the brightest object in the sky beside the Sun and the Moon. Because the orbit of Venus is inside Earth's orbit, Venus always appears close to the Sun. When Venus rises just before the Sun rises, the bright object is called the morning star. When it sets just after the Sun sets, it is the evening star.

Of the planets, Venus is most similar to Earth in size and density. Venus is also our nearest neighbor. The planet's interior structure is similar to Earth's with a large iron core and a silicate mantle. However, the resemblance between the two inner planets ends there.

Venus rotates in a direction opposite the other planets and opposite to the direction it orbits the Sun. This rotation is extremely slow, only one turn every 243 days. This is longer than a year on Venus, where it only takes Venus 224 days to orbit the Sun.

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A thick layer of clouds covers Venus. Venus' clouds are not made of water vapor like Earth's clouds. Clouds on Venus are made mostly of carbon dioxide with a bit of sulfur dioxide and corrosive sulfuric acid. Because carbon dioxide is a greenhouse gas, the atmosphere traps heat from the Sun and creates a powerful greenhouse effect. Even though Venus is further from the Sun than Mercury, the greenhouse effect makes Venus the hottest planet. Temperatures at the surface reach 465 degrees Celsius (860 degrees Fahrenheit), which is hot enough to melt lead.

The atmosphere of Venus is so thick that the atmospheric pressure on the planet's surface is 90 times greater than the atmospheric pressure on Earth's surface. The dense atmosphere obscures the surface of Venus, even from spacecraft orbiting the planet.

Since spacecraft cannot see through the thick atmosphere, radar is used to map Venus' surface. Many features found on the surface are similar to Earth and yet are very different. Orbiting spacecraft have used radar to reveal mountains, valleys, and canyons. Most of the surface has large areas of volcanoes surrounded by plains of lava. Venus has many more volcanoes than any other planet in the solar system, and some of those volcanoes are very large. Most of the volcanoes are no longer active, but scientists have found that there is some active volcanism.

It is difficult for scientists to figure out the geological history of Venus. The environment is too harsh for a rover to go there. It is even more difficult for students to figure out the geological history of a distant planet based on the information given here. Scientists can still piece information together to begin t understand Venus's past.

On Earth, volcanism is generated because the planet's interior is hot. Much of the volcanic activity is caused by plate tectonic activity. However, on Venus, there is no evidence of plate boundaries, and volcanic features do not line up the way they do at plate boundaries.

Because the density of impact craters can be used to determine how old a planet's surface is, the small number of impact craters means that Venus' surface is still relatively young. Scientists think that there is frequent, planet-wide resurfacing of Venus with volcanism taking place in many locations. The cause is the heat that builds up below the surface that has no es-cape until finally it destroys the crust and results in volcanoes.

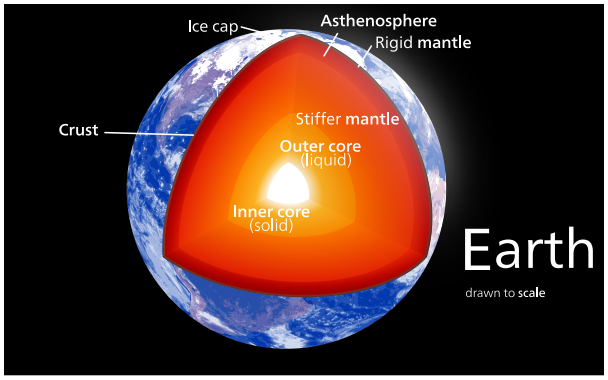
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Earth

Earth has vast oceans of liquid water, large masses of exposed land, and a dynamic atmosphere with clouds of water vapor.

Earth also has ice covering its polar regions. Earth's average surface temperature is 14 degrees Celsius (57 degrees Fahrenheit). Water is a liquid at this temperature, but the planet also has water in its other two states, solid and gas. The oceans and the atmosphere help keep Earth's surface temperatures reasonably steady.



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Earth is the only planet known to have known life. The presence of liquid water, the atmosphere's ability to filter out harmful radiation, and many other features make the planet uniquely suited to harbor life. Life and Earth now affect each other; for example, the evolution of plants allowed oxygen to enter the atmosphere in large enough quantities for animals to evolve. Although life has not been found elsewhere in the solar system, other planets or satellites may harbor primitive life forms. Life may also be found elsewhere in the universe.

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The heat that remained from the planet's accretion, gravitational compression, and radioactive decay allowed the Earth to melt, probably more than once. As it subsequently cooled, gravity pulled metal into the center to create the core. Heavier rocks formed the mantle, and lighter rocks formed the crust.

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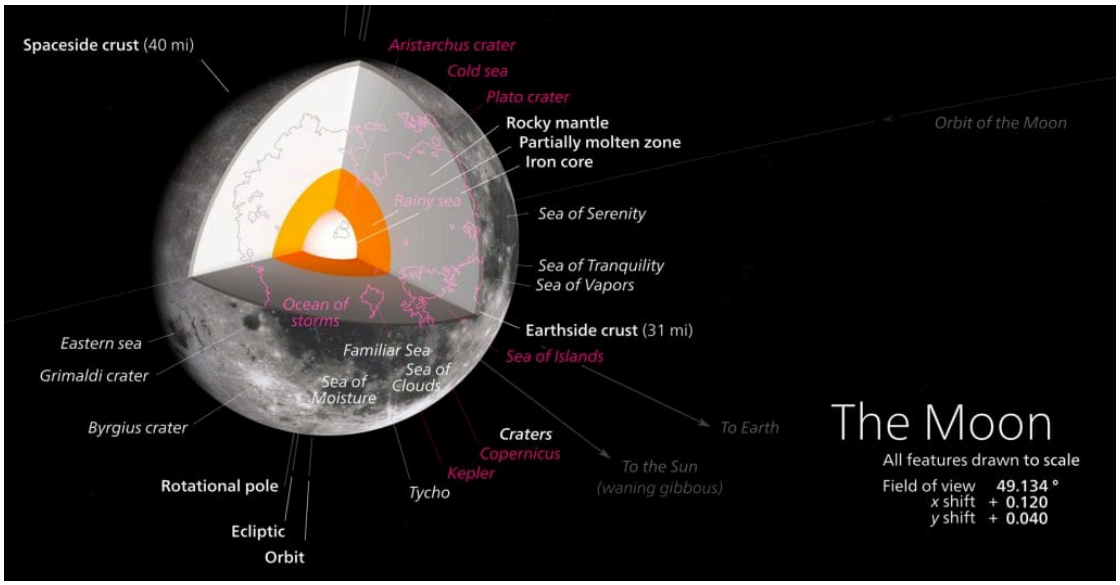
Earth's crust is divided into tectonic plates, which move around on the surface because of the convecting mantle below. The plates' movement causes other geological activity, such as earthquakes, volcanoes, and mountains. The locations of these features are mostly related to current or former plate boundaries. Earth is the only planet known to have plate tectonics.

Earth rotates on its axis once per day, by definition. Earth orbits the Sun once every 365.24 days, which is defined as a year. Earth has one large moon, which orbits Earth once every 29.5 days, a period known as a month.

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The Moon

Earth's moon is the only large moon orbiting a terrestrial planet in the solar system. The moon is covered with craters; it also has vast plains of lava. The considerable number of craters suggests that the moon's surface is ancient. There is evidence that the moon formed when a large object, perhaps as large as the planet Mars, struck Earth in the distant past.



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Mars

Mars is the fourth planet from the Sun and the first planet beyond Earth's orbit. Mars is quite different from Earth and yet more similar than any other planet. Mars is smaller, colder, drier, and appears to have no life, but volcanoes are common to both planets, and Mars has many.

Mars is easy to observe, so the planet has been studied more thoroughly than any other extraterrestrial planet in our solar system. Space probes, rovers, and orbiting satellites have all yielded information to planetary geologists. Although no humans have ever set foot on Mars, both NASA and the European Space Agency have set goals of sending people to Mars sometime between 2030 and 2040.

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Viewed from Earth, Mars is reddish. The ancient Greeks and Romans named the planet after the god of war. However, the surface is not red from blood but significant amounts of iron oxide in the soil. The Martian atmosphere is very thin relative to Earth's and has much lower atmospheric pressure. Although the atmosphere is made up mostly of carbon dioxide, the planet has only a weak greenhouse effect, so temperatures are only slightly higher than if the planet had no atmosphere.

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Mars has mountains, canyons, and other features similar to Earth, and some of these surface features are exceptional for their

size. Olympus Mons is a shield volcano, similar to the volcanoes that make up the Hawaiian Islands. However, Olympus Mons is also the largest mountain in the solar system. Mars also has the largest canyon in the solar system, Valles Marineris.

Mars has more impact craters than Earth, though fewer than the moon. Water cannot stay in liquid form on Mars because the atmospheric pressure is too low. However, there is much water in the form of ice and even prominent ice caps. Scientists also think that there is a lot of water ice present just under the Martian surface. This ice can melt when volcanoes erupt, and water can flow across the surface temporarily.

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Scientists think that water once flowed over the Martian surface because surface features look like water-eroded canyons. The presence of water on Mars, even though it is now frozen as ice, suggests that it might have been possible for life to exist on Mars in the past.

Mars has two tiny moons that are irregular rocky bodies. **Phobos** and **Deimos** are named after characters in Greek mythology; the two sons of Ares followed their father into war. Ares is equivalent to the Roman god Mars.

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7.7: Gas Giants

The Outer Planets

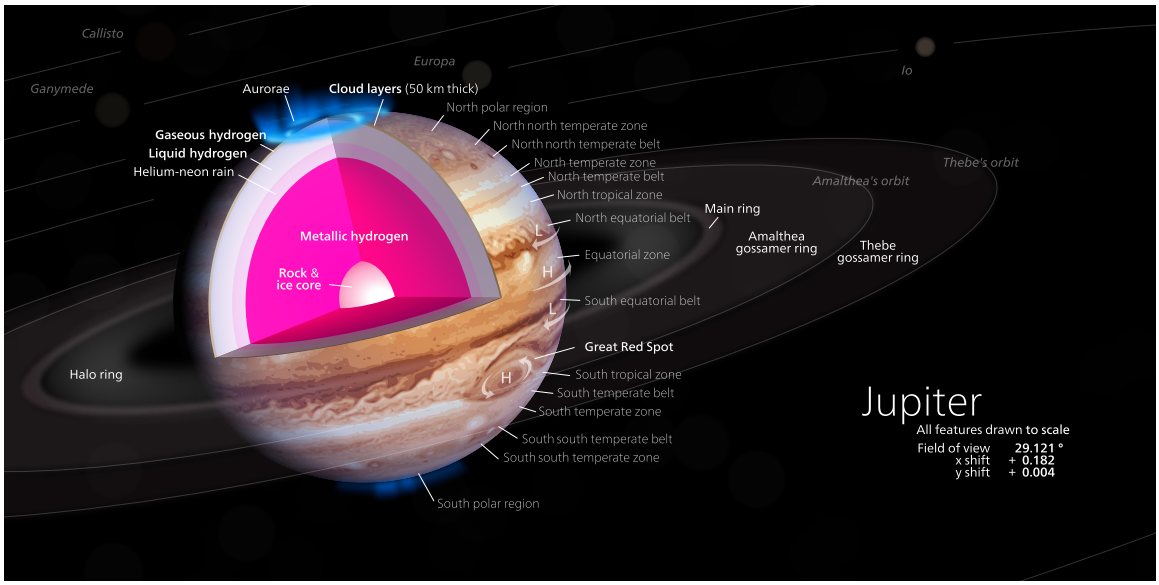
The four planets farthest from the Sun are the **outer planets**. These planets are much larger than the inner planets and are made primarily of gases and liquids, so they are also called gas giants or Jovian planets.

The **gas giants** are made up primarily of hydrogen and helium, the same elements that make up most of the Sun. Astronomers think that hydrogen and helium gases comprised much of the solar system when it first formed. Since the inner planets did not have enough mass to hold on to these light gases, their hydrogen and helium floated away into space. The Sun and the massive outer planets had enough gravity to keep hydrogen and helium from drifting away. (Outer Planets | Earth Science, n.d.)

All of the outer planets have numerous moons. They all also have planetary rings, composed of dust and other small particles that encircle the planet in a thin plane.

Jupiter

Because **Jupiter** is so massive, it reflects much sunlight and appears bright in the night sky; only the Moon and Venus are brighter. This brightness is all the more impressive because Jupiter is quite far from the Earth, 5.20 AUs away. It takes Jupiter about 12 Earth years to orbit once around the Sun.



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Jupiter is named for the king of the gods in Roman mythology. The planet is enormous, the most massive object in the solar system besides the Sun. Although Jupiter is over 1,300 times Earth's volume, it has only 318 times the mass of Earth. Like the other gas giants, it is less dense than Earth. Hypothetically, astronauts trying to land a spaceship on the surface of Jupiter would find that there is no solid surface. Jupiter is made mostly of hydrogen, with some helium, and small amounts of other elements.

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The upper layer of Jupiter's atmosphere contains clouds of ammonia (NH_3) in bands of different colors. These bands rotate

around the planet, but also swirl around in violent storms. The **Great Red Spot** is an enormous, oval-shaped storm found south of Jupiter's equator. This storm is more than three times as wide as the entire Earth. Clouds in the storm rotate in a counterclockwise direction, making one complete turn every six days. The Great Red Spot has been on Jupiter for at least 300 years since astronomers could first see the storm through telescopes.

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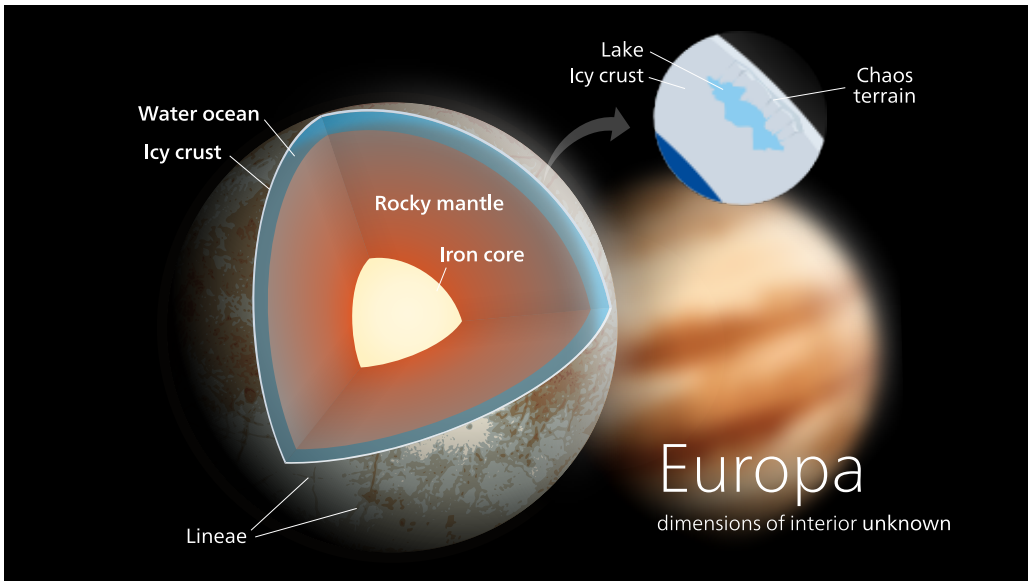
Jupiter's Moons

Jupiter has 63 moons orbiting it that we are aware of so far. Four are big enough and bright enough to be seen from Earth, using no more than a pair of binoculars. These four moons, **Io**, **Europa**, **Ganymede**, and **Callisto**, were first discovered by Galileo in 1610 and are referred to as the Galilean moons. The Galilean moons are more significant than the dwarf planets Pluto, Ceres, and Eris. Ganymede is not only the biggest moon in the solar system, but it is also even larger than the planet Mercury.

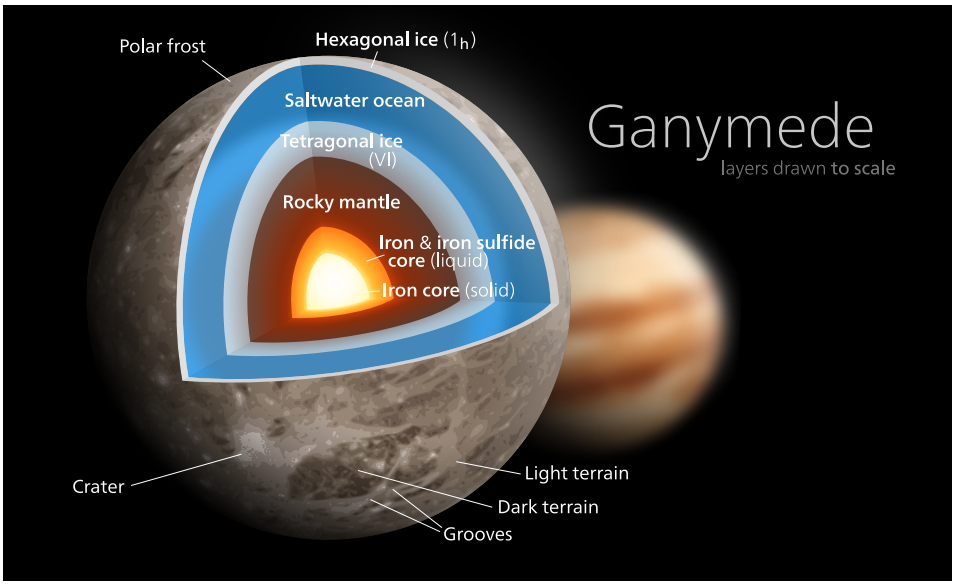
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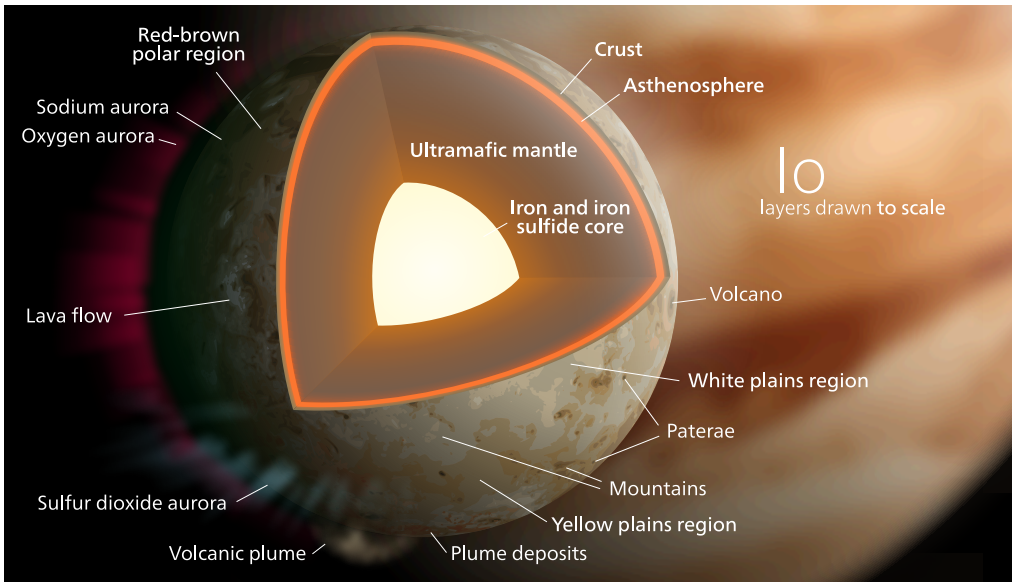
Scientists are particularly interested in Europa because it may be a place to find extraterrestrial life. Although the surface of Europa is a smooth layer of ice, there is evidence that there is an ocean of liquid water underneath. Europa also has a continual source of energy; it is heated as it is stretched and squashed by tidal forces from Jupiter. Numerous missions have been planned to explore Europa, including plans to drill through the ice and send a probe into the ocean. However, no such mission has yet been attempted.



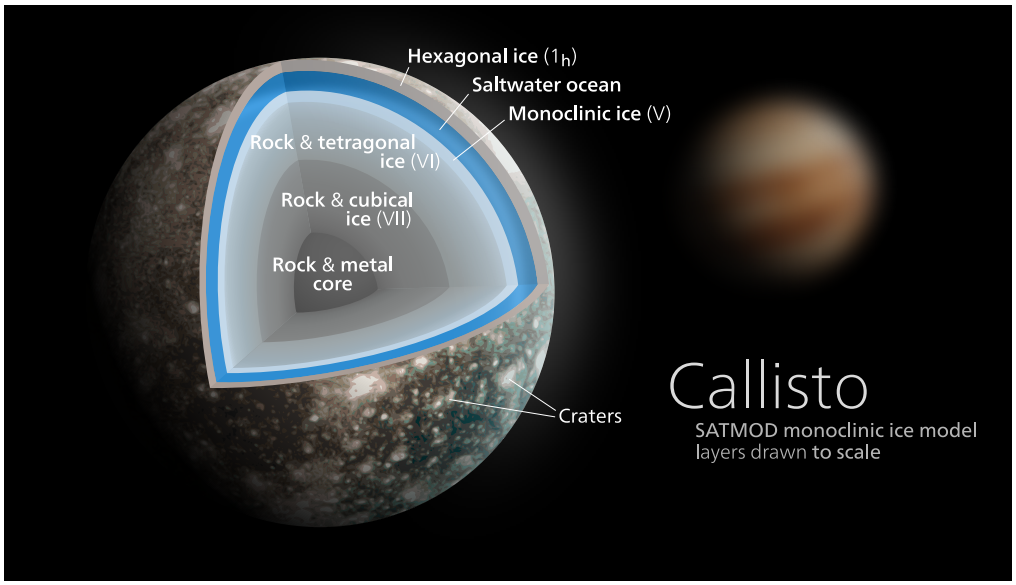
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"Io" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.



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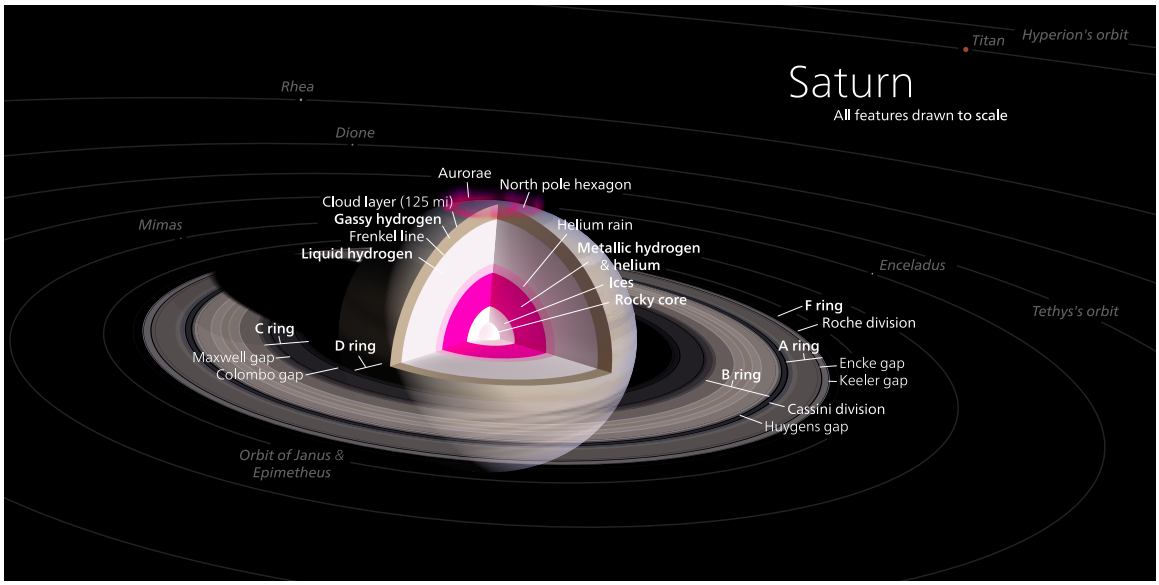
In 1979, two spacecraft, Voyager 1 and Voyager 2 visited Jupiter and its moons. Photos from the Voyager missions showed that Jupiter has a faint ring system. This ring system is very faint, so it is difficult to observe from Earth. Recently, NASA launched the Juno satellite to study Jupiter.

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Saturn

Saturn is famous for its beautiful rings. Although all the gas giants have rings, only Saturn's can be easily seen from Earth. In Roman mythology, Saturn was the father of Jupiter. Saturn's mass is about 95 times the mass of Earth, and its volume is 755 times Earth's volume, making it the second-largest planet in the solar system. Saturn is also the least dense planet in the solar system. It is less dense than water, meaning that Saturn would float on water. Saturn orbits the Sun once about every 30 Earth years.



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Like Jupiter, Saturn is made mostly of hydrogen and helium gases in the outer layers and liquids at greater depths. The upper atmosphere has clouds in bands of different colors. These rotate rapidly around the planet, but there seems to be less turbulence and fewer storms on Saturn than on Jupiter. One interesting phenomenon that has been observed in the storms on Saturn is the presence of thunder and lightning. The planet likely has a small rocky and metallic core.

In 1610 Galileo first observed Saturn's rings with his telescope, but he thought they might be two large moons, one on either side of the planet. In 1659, the Dutch astronomer Christian Huygens realized that the features were rings. Saturn's rings circle the planet's equator and appear tilted because Saturn itself is tilted about 27 degrees. The rings do not touch the planet.

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The Voyager 1 and 2 spacecraft in 1980 and 1981 sent back detailed pictures of Saturn, its rings, and some of its moons. Saturn's rings are made of particles of water and ice, with some dust and rocks. There are several gaps in the rings that scientists think have originated because 1) the material was cleared out by the gravitational pull within the rings or, 2) by the gravitational forces of Saturn and of moons outside the rings. The rings were likely formed by the breakup of Saturn's moons or a material that never accreted into the planet when Saturn formed initially.

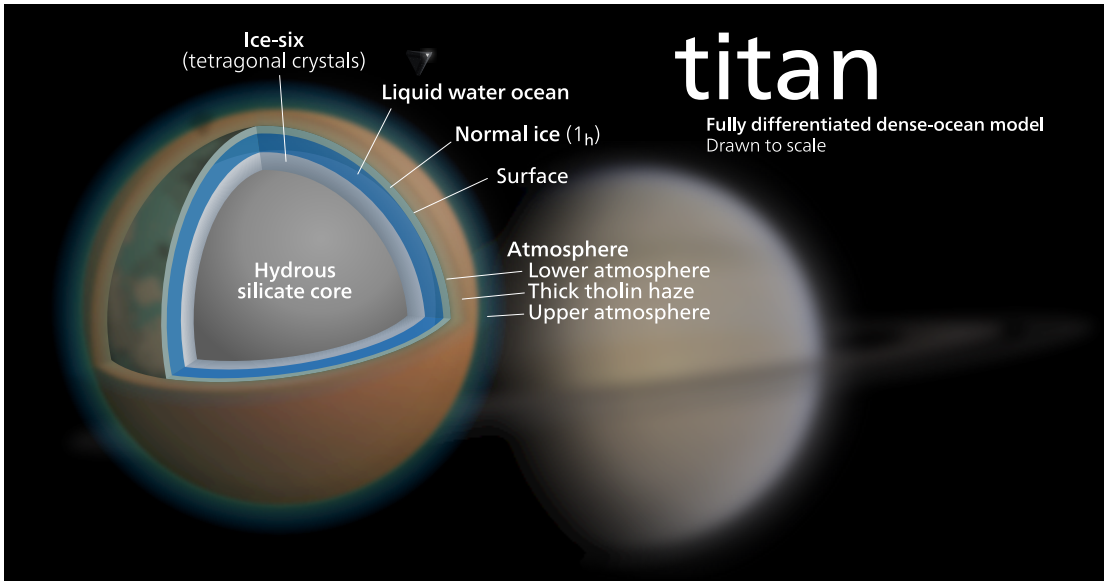
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Saturn's Moons

Most of Saturn's moons are very small, and only seven are large enough for gravity to have made them spherical. Only Titan is more massive than Earth's Moon at about 1.5 times its size. Titan is even more massive than the planet Mercury. Scientists are interested in Titan because its atmosphere is similar to what Earth's was like before life developed. Nitrogen is dominant, and

methane is the second most abundant gas. **Titan** may have a layer of liquid water and ammonia under a layer of surface ice. Lakes of liquid methane (CH4) and ethane (C2H6) are found on Titan's surface. Although conditions are similar enough to those of early Earth for scientists to speculate that extremely primitive life may exist on Titan, the extreme cold and lack of carbon dioxide make it unlikely.



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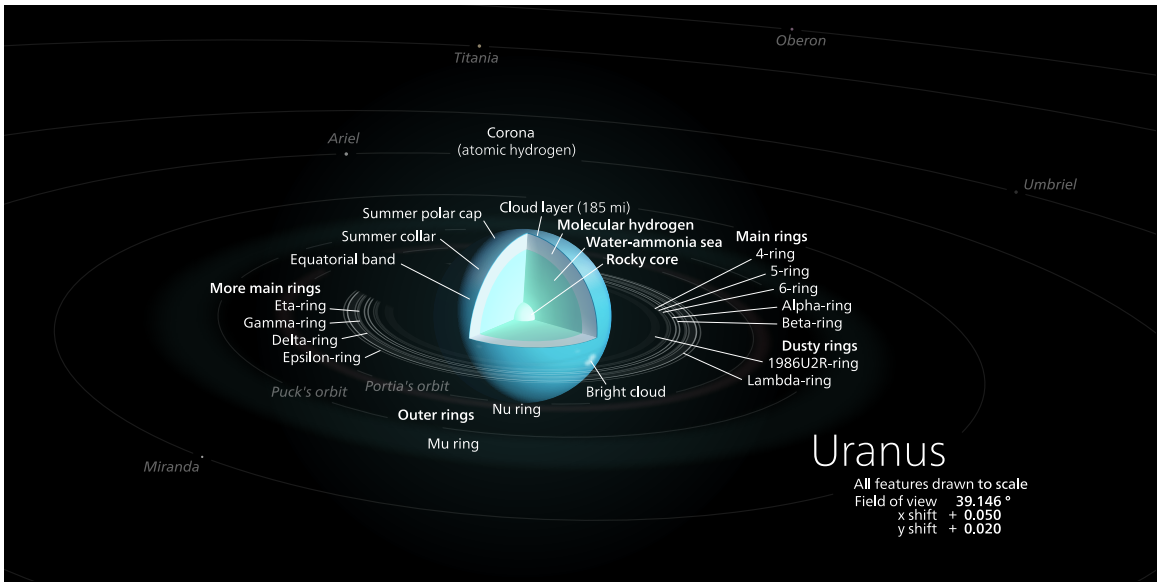
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Uranus

Uranus (YOOR-uh-nuhs) is named after the Greek god of the sky. From Earth, Uranus is so faint that it was unnoticed by ancient observers. William Herschel first discovered the planet in 1781. Although Uranus is enormous, it is incredibly far away, about 2.8 billion km (1.8 billion mi) from the Sun. Light from the Sun takes about 2 hours and 40 minutes to reach Uranus, and the planet orbits the Sun once about every 84 Earth years. Uranus has a mass of about 14 times the mass of Earth, but it is much less dense than Earth. Gravity at the surface of Uranus is weaker than on Earth's surface, so if a human were at the top of the clouds on Uranus, they would weigh about 10 percent less than what they would weigh on Earth.



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Like Jupiter and Saturn, Uranus is composed mainly of hydrogen and helium, with an outer gas layer that gives way to liquid on the inside. Uranus has a higher percentage of icy materials, including water, ammonia (NH_3), and methane (CH_4) than Jupiter and Saturn. When sunlight reflects off Uranus, clouds of methane filter out red light, giving the planet a blue-green color. There are bands of clouds in Uranus' atmosphere, but they are hard to see in normal light, so the planet looks like a plain blue ball.

Most of the solar system planets rotate on their axes in the same direction as they move around the Sun. Uranus is tilted on its side, so its axis is almost identical to its orbit. It rotates like a top that was turned so that it was spinning parallel to the floor. Scientists think that Uranus was probably knocked over by a collision with another planet-sized object billions of years ago.

Uranus's Moons

Uranus has a faint system of rings. The rings circle the planet's equator, but because Uranus is tilted on its side, the rings are almost perpendicular to the planet's orbit. Uranus has 27 known moons, and all but a few of them are named after characters from the plays of William Shakespeare. The five biggest moons are Miranda, Ariel, Umbriel, Titania, and Ober-on.

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Neptune

Neptune is the only major planet that cannot be seen from Earth without a telescope. Scientists predicted Neptune's existence before it was discovered because Uranus did not always appear exactly where it should appear. They knew that the gravitational pull of another planet beyond Uranus must be affecting Uranus' orbit.

image

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Neptune was discovered in 1846, in the position that had been predicted, and it was named Neptune for the Roman god of the sea because of its bluish color. In many respects, Neptune is similar to Uranus. Neptune has slightly more mass than Uranus, but it is somewhat smaller in size. Neptune is much farther from the Sun at nearly 4.5 billion km (2.8 billion mi) than Uranus. The planet's slow orbit means that it takes 165 Earth years to go once around the Sun.

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Neptune's blue color is mostly because of frozen methane. When Voyager 2 visited Neptune in 1986, there was a sizeable dark-blue spot that scientists named the Great Dark Spot, south of the equator. When the Hubble Space Telescope took pictures of Neptune in 1994, the Great Dark Spot had disappeared, but another dark spot had appeared north of the equator. Astronomers think that both of these spots represent gaps in the methane clouds on Neptune.

The changing appearance of Neptune is caused by its turbulent atmosphere. The winds on Neptune are more substantial than on any other planet in the solar system, reaching speeds of 1,100 km/h (700 mi/h) close to the sound speed. This extreme weather surprised astronomers since the planet receives little energy from the Sun to power weather systems. Neptune is also one of the coldest places in the solar system. Temperatures at the top of the clouds are about -218 degrees Celsius (-360 degrees Fahrenheit). Neptune has faint rings of ice and dust that may change or disappear in reasonably short time frames.

Neptune's Moons

Neptune has 13 known moons. Triton is the only one of them that has enough mass to be spherical. Triton orbits in the direction opposite to the orbit of Neptune. Scientists think Triton did not form around Neptune, but instead was captured by Neptune's gravity as it passed by.

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7.8: Other Objects in the Solar System

When the solar system formed, most of the matter ended up in the Sun. Material spinning in a disk around the Sun clumped together into larger pieces to form the eight planets. However, some of the smaller pieces of matter never joined one of these larger bodies and are still out there in space. (Other Objects in the Solar System | Earth Science, n.d.)

Asteroids

Asteroids are tiny, rocky bodies that orbit the Sun. “Asteroid” means “star-like,” and in a telescope, asteroids look like points of light, just like stars. Asteroids are irregularly shaped because they do not have enough gravity to become round. They are also too small to maintain an atmosphere, and without internal heat, they are not geologically active. Collisions with other bodies may break up the asteroid or create craters on its surface.

Asteroid impacts have dramatically influenced the shape of the planets, including Earth. Early impacts caused the planets to grow as they cleared their portions of space. An impact with an asteroid about the size of Mars caused Earth’s fragments to fly into space and ultimately create the moon. Asteroid impacts are linked to mass extinctions throughout Earth history.

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The Asteroid Belt

Hundreds of thousands of asteroids have been discovered in our solar system. They are still being discovered at a rate of about 5,000 new asteroids per month. The majority of the asteroids are found in between the orbits of Mars and Jupiter in a region called the **asteroid belt**. Although there are many thousands of asteroids in the asteroid belt, their total mass adds up to only about 4 percent of Earth’s moon.

Scientists think that the bodies in the asteroid belt formed during the formation of the solar system. The asteroids might have come together to make a single planet, but they were pulled apart by Jupiter’s intense gravity.

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Near-Earth Asteroids

More than 4,500 asteroids cross Earth’s orbit; they are near-Earth asteroids. Between 500 and 1,000 of these are over 1 km in diameter. Any object whose orbit crosses Earth’s can collide with Earth, and many asteroids do. On average, each year, a rock about 5–10 m in diameter hits Earth. Since past asteroid impacts have been implicated in mass extinctions, astronomers are always on the lookout for new asteroids and follow the known near-Earth asteroids closely to predict a possible collision as early as possible.

Scientists are interested in asteroids because they are representatives of the earliest solar system. Eventually, asteroids could be mined for rare minerals or construction projects in space. A few missions have studied asteroids directly. NASA’s DAWN mission orbited asteroid Vesta from July 2011 to September 2012 and is on its way to meet dwarf planet Ceres in 2015.

Thousands of objects, including comets and asteroids, are zooming around our solar system; some could be on a collision course with Earth. A meteor is a streak of light across the sky. People call them shooting stars, but small pieces of matter are burning up as they enter Earth’s atmosphere from space.

Meteors are called meteoroids before they reach Earth's atmosphere. Meteoroids are smaller than asteroids and range from the size of boulders down to the size of tiny sand grains. Still, smaller objects are called interplanetary dust. When Earth passes through a cluster of meteoroids, there is a meteor shower. These clusters are often remnants left behind by comet tails.

Meteorites

Although most meteors burn up in the atmosphere, larger **meteoroids** may strike the Earth's surface to create a meteorite. Meteorites are valuable to scientists because they provide clues about our solar system. Many meteorites are from asteroids that formed when the solar system formed. A few meteorites are made of rocky material that is thought to have come from Mars when an asteroid impact shot material off the Martian surface and into space.

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Comets

Comets are small, icy objects that have very elliptical orbits around the Sun. Their orbits carry them from the outer solar system to the inner solar system, close to the Sun. Early in Earth's history, comets may have brought water and other substances to Earth during collisions.

Comet tails form the outer layers of ice melt and evaporate as the comet flies close to the Sun. The ice from the comet vaporizes and forms a glowing coma, which reflects light from the Sun. Radiation and particles streaming from the Sun push this gas and dust into a long tail that always points away from the Sun. Comets appear for only a short time when they are near the Sun; they seem to disappear again as they move back to the outer solar system.

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The time between one appearance of a comet and the next is called the comet's period. Halley's comet, with a period of 75 years, will next be seen in 2061. The first mention of the comet in historical records may go back as much as two millennia. Short-period comets, with periods of about 200 years or less, come from a region beyond Neptune's orbit. The Kui-per belt (pronounced "KI-per") contains not only comets, but asteroids, and at least two dwarf planets.

Comets, with periods as long as thousands or even millions of years, come from a distant region of the solar system called the **Oort cloud**, about 50,000–100,000 AU from the Sun (50,000–100,000 times the distance from the Sun to Earth).

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Dwarf Planets

The dwarf planets of our solar system are exciting proof of how much we are learning about our solar system. With the discovery of many new objects in our solar system, in 2006, astronomers refined the definition of a planet. Their subsequent reclassification of Pluto to the new category dwarf planet stirred up a great deal of controversy. How the classification of Pluto has evolved is an interesting story in science.

Pluto

From the time it was discovered in 1930 until the early 2000s, **Pluto** was considered the ninth planet. When astronomers first located Pluto, the telescopes were not as good as they are today. Back then, astronomers believe Pluto and its moon, **Charon**, were one large object. With better telescopes, astronomers realized that Pluto was much smaller than they had initially been thought. Better technology also allowed astronomers to discover many smaller objects like Pluto that orbit the Sun. One of them, Eris, discovered in 2005, is even larger than Pluto.

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Even when it was considered a planet, Pluto was an oddball. Unlike the other outer planets in the solar system, which are all gas giants, it is small, icy, and rocky. With a diameter of about 2,400 km, it is only about one-fifth the mass of Earth's Moon. Pluto's orbit is tilted relative to the other planets and is shaped like a long, narrow ellipse. Pluto's orbit sometimes even passes inside Neptune's orbit.

In 1992 Pluto's orbit was recognized to be part of the **Kuiper Belt**. With more than 200 million Kuiper belt objects, Pluto has failed the test of clearing other bodies out its orbit. In 2006, the International Astronomical Union decided that there were too many questions surrounding what could be called a planet and so refined its definition.

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According to the new definition, a planet must:

- Orbit a star
- Be big enough that its gravity causes it to be shaped like a sphere.
- Be small enough that it is not a star itself.
- Have cleared the area of its orbit of smaller objects.
- A dwarf planet is an object that meets items the first three items in the list above, but not the fourth. Pluto is now called a dwarf planet, along with the objects Ceres, Make-make, and Eris.

According to the IAU, a dwarf planet must:

- Orbit a star
- Have enough mass to be nearly spherical
- Not have cleared the area around its orbit of smaller objects.
- Not be a moon

Pluto has three moons of its own. The largest, Charon, is big enough that the Pluto-Charon system is sometimes considered to be a double dwarf planet. Two smaller moons, Nix and Hydra, were discovered in 2005. However, having moons is not enough to make an object a planet.

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Ceres

Ceres is the most massive object in the asteroid belt. Before 2006, Ceres was considered the largest of the asteroids, with only about 1.3 percent of the mass of the Earth's Moon. However, unlike the asteroids, Ceres has enough mass that its gravity causes it to be shaped like a sphere. Like Pluto, Ceres is rocky. Ceres orbits the Sun, is round, and is not a moon. As part of the asteroid belt, its orbit is full of other smaller bodies, so Ceres fails the fourth criterion for being a planet.

Makemake

Makemake is the third largest and second brightest dwarf planet we have discovered so far. With a diameter estimated to be between 1,300 and 1,900 km, it is about three-quarters the size of Pluto. Makemake orbits the Sun in 310 years at a distance between 38.5 to 53 AU. It is thought to be made of methane, ethane, and nitrogen ices.

Eris

Eris is the most widely-known dwarf planet in the solar system, which is roughly 27 percent more massive than Pluto. The object was not discovered until 2003 because it is about three times farther from the Sun than Pluto, and almost 100 times farther from the Sun than Earth is. For a short time, Eris was considered the "tenth planet" in the solar system, but its discovery helped to prompt astronomers to better define planets and dwarf planets in 2006. Eris also has a small moon, Dysnomia, that orbits it once about every 16 days.

Astronomers know there may be other dwarf planets in the outer reaches of the solar system. Haumea was made a dwarf planet in 2008, and so now the total is five. Quaoar, Varuna, and Orcus may be added to the list of dwarf planets in the future. We still have a lot to discover and explore.

Extent of the Solar System

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8: RESOURCES AND ENERGY

8.1: Energy and Resources- Why It Matters- Geological Resources
8.2: Energy and Resources- Ecosystems and Humans
8.3: Energy and Resources- Metal Deposits
8.4: Energy and Resources- Mining and Ore Processing
8.5: Energy and Resources- Industrial Minerals
8.6: Energy and Resources- Reading- Effects of Mining
8.7: Energy and Resources- The Implications of Resource Extraction for the Climate and Earth Systems
8.8: Energy and Resources- Fossil Fuels
8.9: Energy and Resources- Nuclear Energy
8.10: Energy and Resources- Solar and Wind
8.11: Energy and Resources- Hydro
8.12: Energy and Resources- Wave and Tidal Energy
8.13: Energy and Resources- Geothermal and Geo-Exchange
8.14: Energy and Resources- Our Energy Future

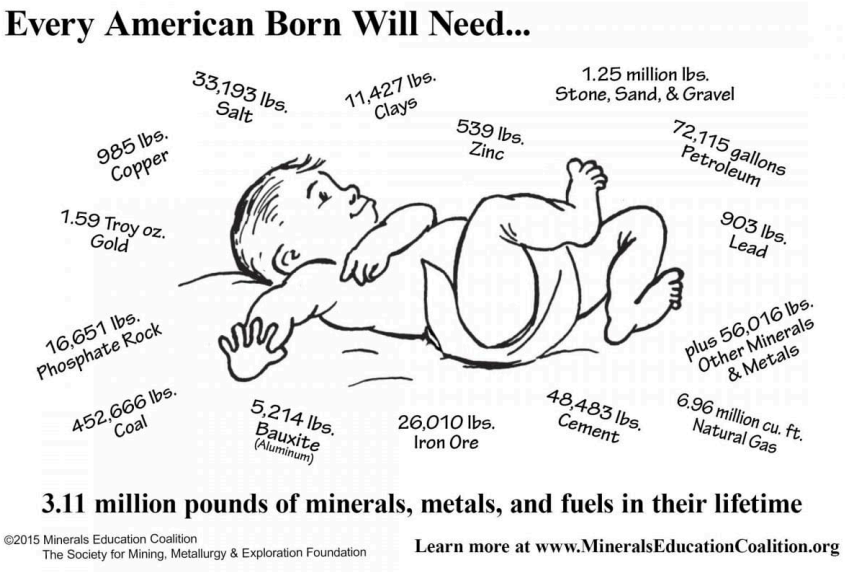
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8.1: Energy and Resources- Why It Matters- Geological Resources

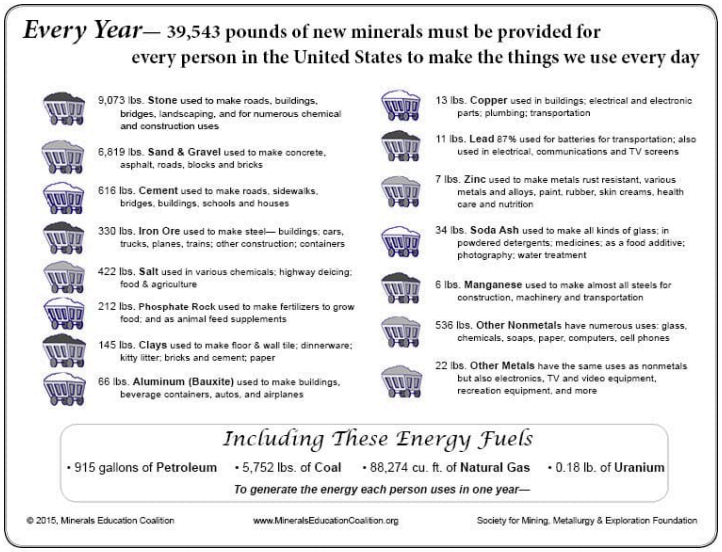
Identify common geological resources and discuss how people use them.

Introduction

This section takes into consideration everything we have studied thus far. We will take review the formation of rocks and minerals, concentrating on mineral and energy resources. These resources focus mainly on fossil fuels—oil, natural gas, and coal. However, we use a variety of other materials as well. Most of the resources we use are considered as indirect consumption of resources. For example, on average, each person in the US used approximately 2500 pounds of coal in 2022. While you may not go to the store and purchase coal to use like you would gasoline for your car, you do it in other indirect ways—for instance, 26% of the electricity in the US is generated by coal burning. The following graphic illustrates the type and amount of resources each American will need and use throughout their lives (note that the amount of coal used is overestimated, as these are data from 2014. Per capita coal consumption has since dropped).



This chart provides us with some staggering statistics on the amount of resources we use:



Were you surprised to see some of the items listed? How about the quantities—3.11 million pounds of resources per person?!

One item not shown on the figure is tantalum. If you have a cell phone, tablet, computer, camera or gaming system you own some tantalum. This resource is used because it has many desirable properties including high heat capacity, ductile and the ability to conduct electricity (Tantalum, 2015). However, tantalum is considered to be a "conflict resource." This means that it is mined in an area where a dispute or conflict is occurring. It could also mean that the resource is used to perpetuate the conflict. In the case of tantalum, it is mined in an area of the Congo where it is believed to have played a role in helping finance war in the area. This conflict is believed to have caused the death of 5,400,000 since 1998 (Tantalum, 2015)!

These resources are collected in a variety of ways from drilling to mining. Depending on the resource and its location, different mining methods may be used. And these resources are mined on every continent (except Antarctica).

Unfortunately not all of our resources will be around forever. Our nonrenewable resources are in jeopardy of depletion. Alternative or renewable resources will play a bigger role in meeting our energy needs in the future.

Learning Outcomes

- Learn common processes of geologic formation of rock and mineral resources.
- Describe some of the extraction methods and identify different types of mining.
- Describe geologic materials as current or potential energy resources and categorize sources as renewable or nonrenewable.

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8.2: Energy and Resources- Ecosystems and Humans

Learning Objectives

After completing this chapter, you will be able to:

1. Define environmental science and distinguish it from related fields such as environmental studies, ecology, and geography.
2. Identify key principles of the ecosystem approach to conserving natural resources.
3. Describe how environmental stressors and disturbances can affect species and ecosystems.
4. List at least three ways in which humans directly influence environmental conditions.
5. Identify four broad classes of environmental values.
6. Describe five important world views.
7. Understand the diverse issues of the environmental crisis by classifying them into three categories, and give several examples within each of them.
8. Discuss the environmental effects of humans as a function of two major influences: increases of population and intensification of lifestyle (per-capita effects).
9. Explain the differences between economic growth and ecologically sustainable development.

Environmental Science and Its Context

Every one of us is sustained by various kinds of **natural resources** – such as food, materials, and energy that are harvested or otherwise extracted from the environment. Our need for those resources is absolute – we cannot survive without them.

Collectively, the needs and activities of people comprise a human economy. That economy operates at various scales, ranging from an individual person, to a family, to communities such as towns and cities, countries, and ultimately the global human enterprise. While an enormous (and rapidly growing) number of people are supported by the global economy, a lot of environmental damage is also being caused. The most important of the damages are the depletion of vital natural resources, various kinds of pollution (including climate change), and widespread destruction of natural habitats to the extent that the survival of many of the natural ecosystems and species of Earth are at grave risk.

These issues are of vital importance to all people, and to all life on the planet. Their subject matter provides the context for a wide-ranging field of knowledge called **environmental studies**, an extremely broad discipline that examines the scientific, social, and cultural aspects of environmental issues. As such, the subject matter of environmental studies engages all forms of inquiry that are relevant to identifying, understanding, and resolving environmental problems. Within that context, **environmental science** examines the science-related implications of environmental issues (this is explained in more detail in the following section). The subject matter of environmental science is the focus of this book.

Issues related to environmental problems are extremely diverse and they interact in myriad ways. Despite this complexity, environmental issues can be studied by aggregating them into three broad categories:

1. the causes and consequences of the rapidly increasing human population
2. the use and depletion of natural resources
3. damage caused by pollution and disturbances, including the endangerment of biodiversity

These are extremely big issues – their sustainable resolution poses great challenges to people and their economy at all scales. Nevertheless, it is important to understand that the study of environmental issues should not be regarded as being a gloomy task of understanding awful problems – rather, the major goal is to identify problems and find practical ways to repair them and prevent others from occurring. These are worthwhile and necessary actions that represent real progress towards an ecologically sustainable economy. As such, people who understand and work towards the resolution of environmental problems can achieve high levels of satisfaction with their contribution. **Environmental literacy,** which can be defined as an understanding and appreciation of the natural world and the relationship that humans have with it, is a matter of empowerment because it enables people to take control of the condition of the environment.



Figure 8.2.1:Planet Earth. Earth is the third closest planet to the Sun, and it is the only place in the universe that is definitely known to sustain life and ecosystems. Other than sunlight, the natural resources needed to sustain the human economy are restricted to the limited amounts that can be extracted on Earth. This image of the Western Hemisphere was taken from a distance of 35-thousand km from the surface of Earth. Source: R. Stöckli, N. El Saleous, and M. Jentoft-Nilsen, NASA GSFC; http://earthobservatory.nasa.gov/IOTD/view.php?id=885

Specialists examining issues related to the environment may come from many different areas of study, each of which is referred to as a **discipline**. The various contributions each field makes are integrated into a comprehensive understanding of environmental issues – this is why environmental studies is referred to as an **interdisciplinary field**. For environmental science, the most relevant of the disciplinary subjects are atmospheric science, biology, chemistry, computer science, ecology, geography, geology, mathematics, medical science, oceanography, physics, and statistics. This is illustrated in Figure 8.2.2, which suggests that all fields of scientific knowledge are relevant to understanding the causes, consequences, and resolution of environmental problems.

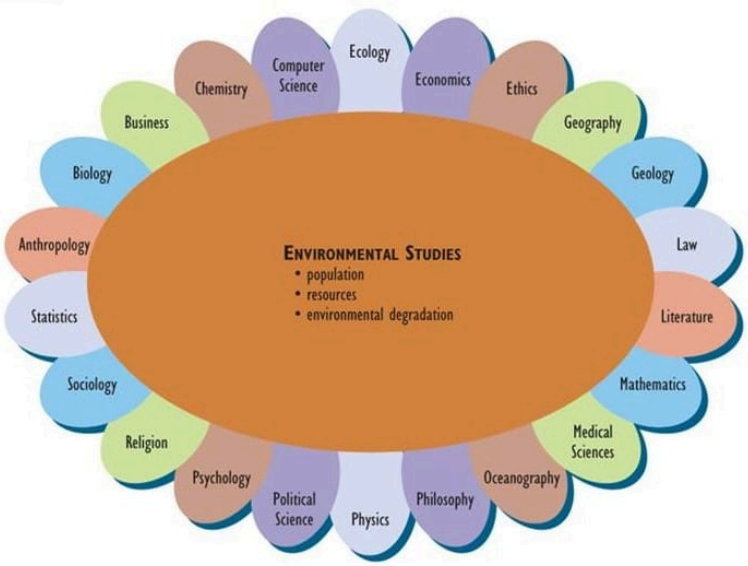


Figure 8.2.2: Environmental science has an interdisciplinary character. All scientific disciplines are relevant to the identification and resolution of environmental issues. However, the work requires an interdisciplinary approach that engages many disciplines in a coordinated manner. This integration is suggested by the overlaps among the disciplinary fields.

This book deals with the key subject areas of environmental science. To some degree, however, certain non-science topics are also examined because they are vital to understanding and resolving environmental issues. These non-science fields include ethics, philosophy, political science, and economics.

An environmental scientist is a **generalist** who uses science-related knowledge relevant to environmental quality, such as air or

water chemistry, climate modelling, or the ecological effects of pollution.

It is important to differentiate environmental science from **environmentalism**, which is advocacy for the environment. The interests of environmentalists may be informed by the work of environmental scientists, but the two groups are not necessarily the same because science is undertaken to gain an understanding of the world and does not include advocacy. Any person can be called an **environmentalist** if they care about the quality of the environment and work towards changes that would help to resolve the issue. Environmentalists may work as individuals, and they often pursue their advocacy through non-governmental organizations, such as the Sierra Club or The Nature Conservancy.



Figure 8.2.3: Modern consumerism results in huge demands for material and energy resources to build and run homes and to manufacture and operate machines and other goods. Source: B. Freedman

Human Activities are Environmental Stressors

These days, ecosystems are impacted by **anthropogenic** (human-caused) influences that have substantially altered the natural environment. Humans affect ecosystems and species in three direct ways: (a) by harvesting valuable biomass, such as trees and hunted animals; (b) by causing damage through pollution; and (c) by converting natural ecosystems to into land-uses for the purposes of agriculture, industry, or urbanization.

These actions also cause many indirect effects. For example, the harvesting of trees alters the habitat conditions for the diversity of plants, animals, and microorganisms that require forested habitat, thereby affecting their populations. At the same time, timber harvesting indirectly changes functional properties of the landscape, such as erosion, productivity, and the quantity of water flowing in streams. Both the **direct** and **indirect** effects of humans on ecosystems are important.

Humans have always left “footprints” in nature – to some degree, they have always influenced the ecosystems of which they were a component. Throughout most of human history, that ecological footprint was relatively shallow. This was because the capability of humans for exploiting their environment was not much different from that of other similarly abundant, large animals. However, during the cultural evolution of humans, the ecological changes associated with our activities progressively intensified. This process of cultural evolution has been characterized by the discovery and use of increasingly more sophisticated methods, tools, and social organizations to secure resources by exploiting the environment and other species.

Certain innovations occurring during the cultural evolution of humans represented particularly large increases in capability. Because of their great influence on human success, these advances are referred to as “revolutions.” The following are the most significant technological revolutions that have enabled humans to have a greater impact on their environment:

- methods of using machines and fossil fuels such as coal and oil (Industrial Revolution)
- discoveries in medicine and sanitation
- advances in agricultural efficiency

These and other revolutionary innovations all led to substantial increases in the ability of humans to exploit the resources of their environment and to achieve population growth. Unfortunately, enhanced exploitation has rarely been accompanied by the development of a compensating ethic that encourages conservation of the resources needed for survival. Even early hunting societies of more than about 10,000 years ago appear to have caused the extinction of species that were hunted too effectively.

The diverse effects of human activities on environmental quality are vital issues, and they will be examined in detail in later chapters. For now, we emphasize the message that intense environmental stress associated with diverse human activities has become the major factor causing ecological changes on Earth. Many of the changes are degrading the ability of the environment and ecosystems to sustain humans and their economies. Anthropogenic activities are also causing enormous damage to natural ecosystems, including to habitats needed to support most other species.

But not all this damage is inevitable. There is sincere hope and expectation that human societies will yet make appropriate adjustments and will choose to pursue options that are more sustainable than many of those now being followed. Environmental science broadens our understanding of our impacts and provides the basis for long-term solutions. Environmental literacy empowers non-scientists with this knowledge.

Ethics and World Views

The choice that people make can influence environmental quality in many ways – by affecting the availability of resources, causing pollution, and causing species and natural ecosystems to become endangered. Decisions influencing environmental quality are influenced by two types of considerations: knowledge and ethics.

In the present context, **knowledge** refers to information and understanding about the natural world, and **ethics** refers to the perception of right and wrong and the appropriate behavior of people toward each other, other species, and nature. Of course, people may choose to interact with the environment and ecosystems in various ways. On the one hand, knowledge provides guidance about the consequences of alternative choices, including damage that might be caused and actions that could be taken to avoid that effect. On the other hand, ethics provides guidance about which alternative actions should be favored or even allowed to occur.

Because modern humans have enormous power to utilize and damage the environment, the influence of knowledge and ethics on choices is a vital consideration. And we can choose among various alternatives. For example, individual people can decide whether to have children, purchase an automobile, or eat meat, while society can choose whether to allow the hunting of whales, clear-cutting of forests, or construction of nuclear power plants. All of these options have implications for environmental quality.

Perceptions of value (of merit or importance) also profoundly influence how the consequences of human actions are interpreted. **Environmental values** can be divided into two broad classes: **utilitarian** and **intrinsic**.

1. **Utilitarian value** (also known as instrumental value) is based on the known importance of something to the welfare of people. Accordingly, components of the environment and ecosystems are considered important only if they are resources necessary to sustain humans—that is, if they bestow economic benefits, provide livelihoods, and contribute to the life-support system. In effect, people harvest materials from nature because they have utilitarian value. These necessities include water, timber, fish and animals hunted in wild places, and agricultural crops grown in managed ecosystems.

   Ecological values are somewhat broader utilitarian values—they are based on the needs of humans, but also on those of other species and natural ecosystems. Ecological values often take a longer-term view, valuing ecosystems regardless of their usefulness to humans. **Aesthetic values** are also utilitarian but are based on an appreciation of beauty. They are subjective and influenced by cultural perspectives. For instance, environmental aesthetics might value natural wilderness over human-dominated ecosystems, free-living whales over whale meat, and large standing trees over toilet paper.

2. **Intrinsic value** is based on the belief that components of the natural environment (such as species and natural ecosystems) have inherent value and a right to exist, regardless of any positive, negative, or neutral relationships with humans. Under this system, it would be wrong for people to treat other creatures cruelly, to take actions that cause natural entities to become endangered or extinct, or to fail to prevent such occurrences. In effect, by this perception, all species have a right to exist.

As was noted previously, ethics concerns the perception of right and wrong and the values and rules that should govern human conduct. Clearly, ethics of all kinds depend upon the values that people believe are important. **Environmental ethics** deal with the responsibilities of present humans to both future generations and other species to ensure that the world will continue to function in an ecologically healthy way, and to provide adequate resources and livelihoods. The environmental values described

above underlie this system of ethics. Applying environmental ethics often means analyzing and balancing standards that may conflict, because aesthetic, ecological, intrinsic, and utilitarian values rarely all coincide.

There is also tension between ethical considerations that are individualistic and those that are holistic. For example, animal-rights activists are highly concerned with issues involving the treatment of individual organisms. Ecologists, however, are typically more concerned with holistic values, such as a population, species, or ecosystem. As such, an ecologist might advocate a cull of overabundant deer in a park in order to favour the survival of populations of endangered plants, whereas that action might be resisted by an animal-rights activist.

Values and ethics, in turn, support larger systems known as world views. A **worldview** is a comprehensive philosophy of human life and the universe, and of the relationship between people and the natural world. World views include traditional religions, philosophies, and science, as well as other belief systems. In an environmental context, generally important world views are known as **anthropocentric**, **biocentric**, and **ecocentric**, while the **frontier** and **sustainability** world views are more related to the use of resources.

The **anthropocentric** worldview considers humans as being at the center of moral consideration. People are viewed as being more worthy than any other species and as uniquely disconnected from the rest of nature. Therefore, the anthropocentric worldview judges the importance and worthiness of everything, including other species and ecosystems, in terms of the implications for human welfare.

The **biocentric** worldview focuses on living entities and considers all species (and individuals) as having intrinsic value. Humans are considered a unique and special species, but not as being more worthy than other species. As such, the biocentric worldview rejects discrimination against other species, or **speciesism** (a term similar to racism or sexism).

The **ecocentric** worldview considers the direct and indirect connections among species within ecosystems to be invaluable. It also includes consideration for non-living entities, such as rocks, soil, and water. It incorporates the biocentric worldview but goes well beyond it by stressing the importance of interdependent ecological functions, such as productivity and nutrient cycling.

The **frontier** worldview asserts that humans have a right to exploit nature by consuming natural resources in boundless quantities. This world view claims that people are superior and have a right to exploit nature. Moreover, the supply of resources to sustain humans is considered to be limitless, because new stocks can always be found, or substitutes discovered. The consumption of resources is considered to be good because it enables economies to grow. Nations and individuals should be allowed to consume resources aggressively, as long as no people are hurt in the process.

The **sustainability** worldview acknowledges that humans must have access to vital resources, but the exploitation of those necessities should be governed by appropriate ecological, intrinsic, and aesthetic values. The sustainability world view can assume various forms. The **spaceship worldview** is quite anthropocentric. It focuses only on sustaining resources needed by people, and it assumes that humans can exert a great degree of control over natural processes and can safely pilot “spaceship Earth.” In contrast, **ecological sustainability** is more ecocentric. It considers people within an ecological context and focuses on sustaining all components of Earth’s life-support system by preventing human actions that would degrade them. In an ecologically sustainable economy, natural goods and services should be utilized only in ways that do not compromise their future availability and do not endanger the survival of species or natural ecosystems.

The attitudes of people and their societies toward other species, natural ecosystems, and resources have enormous implications for environmental quality. Extraordinary damages have been legitimized by attitudes based on a belief in the inalienable right of humans to harvest whatever they desire from nature, without consideration of pollution, threats to species, or the availability of resources for future generations. Clearly, one of the keys to resolving the environmental crisis is to achieve a widespread adoption of ecocentric and ecological sustainability worldviews.

The Environmental Crisis

The modern environmental crisis encompasses many issues. In large part, however, we can classify the issues into three categories: population, resources, and environmental quality. In essence, these topics are what this book is about. However, the core of their subject areas is the following:

- Two kinds of **natural resources** can be distinguished. A n**on-renewable resource** is present in a finite quantity. As these resources are extracted from the environment, in a process referred to as mining, their stocks are inexorably diminished and so are available in increasingly smaller quantities for future generations. Non-renewable resources include metals and

fossil fuels such as petroleum and coal. In contrast, a **renewable resource** can regenerate after harvesting, and if managed suitably, can provide a supply that is sustainable forever. However, to be renewable, the ability of the resource to regenerate cannot be compromised by excessive harvesting or inappropriate management practices. Examples of renewable resources include fresh water, the biomass of trees and agricultural plants and livestock, and hunted animals such as fish and deer. Ultimately, a sustainable economy must be supported by renewable resources. Too often, however, potentially renewable resources are not used responsibly, which impairs their renewal and represents a type of mining.

Environmental Quality

This subject area deals with **anthropogenic pollution** and **disturbances** and their effects on people, their economies, other species, and natural ecosystems. Pollution may be caused by gases emitted by power plants and vehicles, pesticides, or heated water discharged into lakes. Examples of **disturbance** include clear-cutting, overfishing, and forest fires.

Environmental Impacts of Humans

In a general sense, the cumulative impact of humans on the biosphere is a function of two major factors: (1) the size of the population and (2) the per-capita (per-person) environmental impact. The human population varies greatly among and within countries, as does the per-capita impact, which depends on the kind and degree of economic development that has occurred.

One powerful tool for expressing environmental impact is the **ecological footprint**. This is essentially the amount of land that is required to provide the resources and dispose of the wastes associated with a particular lifestyle. It is estimated based upon various categories of consumption and is useful in comparing the impact that different people have on the planet. Recent calculations using this model suggest that humans are using more than the amount of resources that the earth can sustainably regenerate. When this happens, it is said that we are in an **ecological deficit**. This means that while we may still be able to extract the resources necessary to support our lifestyles, we are no longer doing so sustainably and as a result, we will not be able to continue indefinitely.

In general, the size of an ecological footprint tends to increase with wealth or **affluence**. People in wealthy nations tend to have much larger footprints than those in developing countries. As such, lifestyle decisions have a large impact on our overall footprint. The **per capita ecological footprint** (footprint per person) is one of the highest in the world. But that is only part of the story of overall impact.

Paul Ehrlich, an American ecologist, has expressed this simple relationship using an “impact formula,” as follows: $I = P \times A \times T$, where

- I is the total environmental impact of a human population
- P is the population size
- A is an estimate of the per-capita affluence in terms of resource use
- T is the degree of technological development of the economy, on a per-capita basis

As the size of a population increases, so does the overall environmental impact. Similarly, as affluence increases, the impact goes up as well. Technology does not have as direct a relationship because some technologies can be damaging to the environment (widespread use of cars), while others can have a positive impact (wind turnbines).

Calculations based on this simple IPAT formula show that affluent, technological societies have a much larger per-capita environmental impact than do poorer ones.

How does the United States’ impact on the environment compare with that of more populous countries, such as China and India? We can examine this question by looking at two simple indicators of the environmental impact of both individual people and national economies: (a) the size of the human population, (b) the use of energy and (c) gross domestic product (**GDP**, or the annual value of all goods and services produced by a country). The use of energy is a helpful environmental indicator because power is needed to carry out virtually all activities in a modern society, including driving vehicles, heating or cooling buildings, manufacturing industrial products, and running computers. GDP represents all of the economic activities in a country, each of which results in some degree of environmental impact.

One of the major influences on the environmental impact of any human population is the number of people (the population size). In this respect, the US has a much smaller population compared to China, India (Figure 1.3a).

However, on a per-person basis, people living in US or Canada have much larger environmental impacts than do those living in China or India, as indicated by both per-capita energy use (Figure 1.3c) and per-capita GDP (Figure 1.3e). This difference is an inevitable consequence of the prosperous nature of the lifestyle of North Americans and other wealthier people, which on a per-capita basis is achieved by consuming relatively large amounts of natural resources and energy while generating a great deal of waste materials.

However, the per-capita environmental impact is only part of the environmental influence of a country, or of any human population. To determine the national effect, the per-capita value must be multiplied by the size of the population. When this is done for energy, China and the U.S. have by far the largest values, while Canada and India are much less (Figure 1.3b). Still, it is remarkable that the national energy use of Canada, with its relatively small population, is close to that of India and within an order of magnitude of China, which have enormously larger populations. The same pattern is true of national the GDPs of those countries.

These observations drive home the fact that the environmental impact of any human population is a function of both (a) the number of people and (b) the per-person environmental impact. Because of this context, wealthy countries like the US have much larger environmental impacts than might be predicted based only on the size of their population. On the other hand, the environmental impacts of poorer countries are smaller than might be predicted based on their population. We can conclude that the environmental crisis is due to both overpopulation and excessive resource consumption.

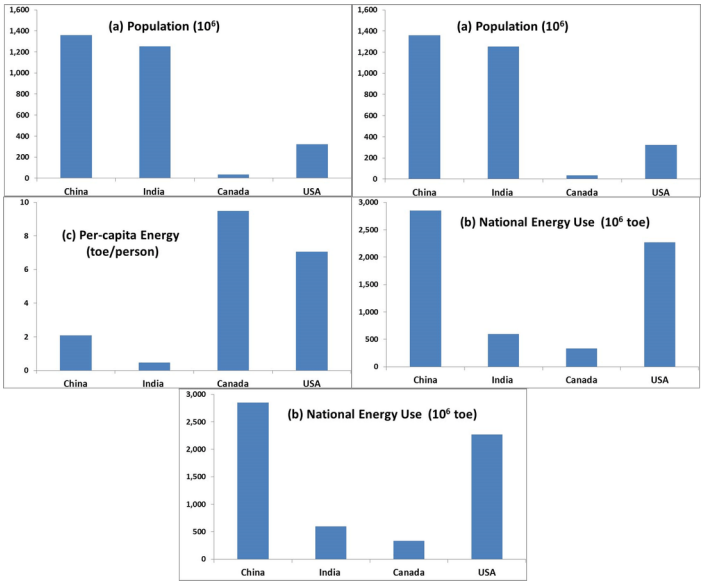


Figure 8.2.4: The relative environmental impacts of China, India, Canada, and the United States. The environmental impacts of countries, and of their individual citizens, can be compared using simple indicators, such as the use of energy and the gross domestic product. Canada's relatively small population, compared with China and India, is somewhat offset by its higher per-capita GDP and use of energy. However, because the per-capita data for the U.S. and Canada are similar, relative population sizes are the key influence on the environmental impacts of these two countries. Sources of data: population data are for 2015 (U.S. Census Bureau, 2015); energy use (all commercial fuels) for 2013 (BP, 2013); GDP for 2013 (CIA, 2014).



Figure 8.2.5: Places where people live, work, grow food, and harvest natural resources are affected by many kinds of anthropogenic stressors. These result in ecosystems that are not very natural in character, such as the pavement and grassy edges of this major highway in Toronto. Source: B. Freedman.

Ecologically Sustainable Development

Sustainable development refers to the development of an economic system that uses natural resources in ways that do not deplete them or otherwise compromise their availability to future generations. In this sense, the present human economy is clearly non-sustainable. The reason for this bold assertion is that the present economy achieves rapid economic growth through vigorous depletion of both non-renewable and renewable resources. **Economic growth** and development are different phenomena. Economic growth refers to increases in the size of an economy because of expansions of both population and per-capita resource use. This growth is typically achieved by increasing the consumption of natural resources, particularly non-renewable ones such as fossil fuels and metals. The rapid use results in an aggressive depletion of vital non-renewable resources, and even renewable ones.

> Almost all national economies have been growing rapidly in recent times. Moreover, most politicians, economic planners, and business people hope for additional growth of economic activity, in order to generate more wealth and to provide a better life for citizens. At the same time, however, most leaders of society have publicly affirmed their support of sustainable development. However, they are confusing sustainable development with "sustainable economic growth." Unfortunately, continuous economic growth is not sustainable because there are well-known limits due to finite stocks of natural resources, as well as a limited ability of the biosphere to absorb wastes and ecological damage without suffering irreversible degradation. This limit is a fundamental principle of ecological economics (covered later in the text).

Economic development is quite different from economic growth. Development implies a progressively improving efficiency in the use of materials and energy, a process that reflects socio-economic evolution toward a more sustainable economy. Within that context, so-called developed countries have a relatively well-organized economic infrastructure and a high average per-capita income (because of their latter characteristic, they may also be referred to as high-income countries). Examples include the United States, Japan, countries of western Europe, and Australia. In contrast, less-developed or low-income countries have much less economic infrastructure and low per-capita earnings. Examples include Afghanistan, Bolivia, Myanmar, and Zimbabwe. A third group is comprised of rapidly developing or middle-income countries, such as Brazil, Chile, China, India, Malaysia, Russia, and Thailand

A sustainable economy must be fundamentally supported by the wise use of renewable resources, meaning they are not used more quickly than their rate of regeneration. For these reasons, the term **sustainable development** should refer only to progress being made toward a sustainable economic system. Progress in sustainable development involves the following sorts of desirable changes:

- increasing efficiency of use of non-renewable resources, for example, by careful recycling of metals and by optimizing the use of energy

- increasing use of renewable sources of energy and materials in the economy (to replace non-renewable sources)
- improving social equity, with the ultimate goal of helping all people (and not just a privileged minority) to have reasonable access to the basic necessities and amenities of life

Despite abundant public rhetoric, our society has not yet made much progress toward true sustainability. This has happened because most actions undertaken by governments and businesses have supported economic growth, rather than sustainable development.

Sustainable development is a lofty and necessary goal for society to pursue. But if a sustainable human economy is not attained, then the non-sustainable one will run short of resources and could collapse. This would cause terrible misery for huge numbers of people and colossal damage to the biosphere.

The notion of sustainability can be further extended to that of **ecologically sustainable development**. This idea includes the usual aspect of sustainable development in which countries develop without depleting their essential base of natural resources, essentially by basing their economy on the wise use of renewable sources of energy and materials. Beyond that, however, an ecologically sustainable economy runs without causing an irretrievable loss of natural ecosystems or extinctions of species, while also maintaining important **environmental services**, such as the provision of clean air and water. Ecological sustainability is a reasonable extension of sustainability, which only focuses on the human economy. By expanding to embrace the interests of other species and natural ecosystems, ecological sustainability provides an inclusive vision for a truly harmonious enterprise of humans on planet Earth. Identifying and resolving the barriers to ecological sustainability are the fundamental objectives and subject matter of environmental studies. It provides a framework for all that we do.

Conclusions

Environmental science is a highly interdisciplinary field that is concerned with issues associated with the rapidly increasing human population, the use and diminishing stocks of natural resources, damage caused by pollution and disturbance, and effects on biodiversity and the biosphere. These are extremely important issues, but they involve complex and poorly understood systems. They also engage conflicts between direct human interests and those of other species and the natural world.

Ultimately, the design and implementation of an ecologically sustainable human economy will require a widespread adoption of new world views and cultural attitudes that are based on environmental and ecological ethics, which include consideration for the needs of future generations of people as well as other species and natural ecosystems. This will be the best way of dealing with the so-called “environmental crisis,” a modern phenomenon that is associated with rapid population growth, resource depletion, and environmental damage. This crisis is caused by the combined effects of population increase and an intensification of per-capita environmental damage.

Finally, it must be understood that that the study of environmental issues is not just about the dismal task of understanding awful problems. Rather, a major part of the subject is to find ways to repair many of the damages that have been caused, and to prevent others that might yet occur. These are helpful and hopeful actions, and they represent necessary progress toward an ecologically sustainable economy.

Questions for Review

1. Define environmental science, environmental studies, and ecology. List the key disciplinary fields of knowledge that each includes.
2. What is the difference between morals and knowledge, and how are these conditioned by personal and societal values?
3. Explain how cultural attributes and expressions can affect the ways that people view the natural world and interact with environmental issues.

Questions for Discussion

1. Describe how you are connected with ecosystems, both through the resources that you consume (food, energy, and materials) and through your recreational activities. Which of these connections could you do without?
2. How are your personal ethical standards related to utilitarian, ecological, aesthetic, and intrinsic values? Think about your world view and discuss how it relates to the anthropocentric, biocentric, and ecocentric world views.
3. Make a list of the most important cultural influences that have affected your own attitudes about the natural world and environmental issues.

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8.3: Energy and Resources- Metal Deposits

The earliest known metal mines, in Bulgaria and Serbia and some neighbouring areas of southeastern Europe, date back about 7000 years, with the main metal of interest being copper. Copper was also mined and used in the Great Lakes region of North America at around the same time.

Today there are mines, for virtually every metal in the periodic table, on every continent except Antarctica (where mining is banned by treaty), and the value of the mined products are enormous—both to the companies that do the mining and the nations where the mining takes place, and to the people everywhere that use the metals in their lives every day. Iron represents, by far, the largest amount of metal mined. It is used mostly in construction (buildings, bridges, etc.), for railways, and for vehicles, although most manufactured products have some iron in them. Each year we mine and process 2.5 billion tonnes of iron, which is approximately the weight of all of the cars, trucks and buses currently in the entre world. Aluminum, which is used in electrical transmission lines, construction and aircraft, is second. Chromium is third because it is an important component of steel, while copper, fourth, is used widely for electrical components.

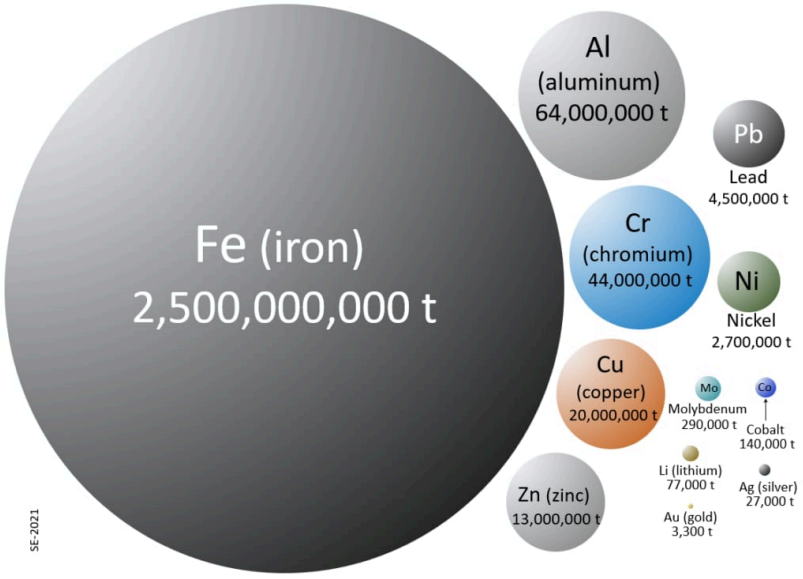


Figure 8.1.1 The Amounts of Some of the Important Metals Mined Each Year on Earth. Each sphere is proportional in volume to the weight of that metal mined. There is 39 times as much iron mined as aluminum, and 760,000 times as much iron as gold.

A metal deposit is a body of rock in which one or more metals has been concentrated to the point of being economically viable for recovery. Not all metal-bearing rock is useful as ore. The granitic rock of the crust has an aluminum (Al) content of about 8%, but most of that is within the mineral feldspar, and it is very difficult to separate that Al from the other elements. The main ore of Al is bauxite, in which the Al is present as Al-hydroxides. Bauxite is much more readily processed into aluminum metal than is granite.

Some background levels of important metals in average rocks are shown on Table 8.1, along with the typical grades necessary to make a viable deposit, and the corresponding concentration factors. Looking at copper, for example, we can see that while average rock has around 40 ppm (parts per million) of copper, a grade of around 10,000 ppm or 1% is necessary to make a viable copper deposit. In other words, copper ore has about 250 times as much copper as typical rock. For all of the other elements in the list the concentration factors are much higher. For gold it's 2000 times and for silver it's around 10,000 times.

Table 8.1.1 Typical Background and Ore Levels of Some Important Metals (ppm = parts per million)

Metal	Typical Background Level	Typical Economic Grade	Concentration Factor
Copper	40 ppm	10,000 ppm (1%)	250 times
Gold	0.003 ppm	6 ppm	2000 times

Lead	10 ppm	50,000 ppm (5%)	5000 times
Molybdenum	1 ppm	1,000 (0.1%)	1000 times
Nickel	25 ppm	20,000 (2%)	800 times
Silver	0.1 ppm	1,000 (0.1%)	10,000 times
Uranium	2 ppm	10,000 (1%)	5000 times
Zinc	50 ppm	50,000 (5%)	1000 times

The economic viability of any metal deposit depends on a wide range of factors including its grade, size, shape and depth below surface, proximity to infrastructure, the current price of the metal, ease of processing, the labour and environmental regulations in the area, and many others. One of the most important of these factors is the grade (the concentration of metal in the ore) and whether it is high enough to make it mineable at a profit. For example, a typical economic grade for copper is 1%, but that will vary widely depending on the status of the various factors listed above, including size, shape and depth of the deposit, ease of processing the ore, proximity to infrastructure, and the labour and environmental rules in the country where the orebody is located.[1]

From Table 8.1 we can see that some significant concentration must take place to form a mineable deposit. This concentration may occur during the formation of the host rock, or after the rock is formed, through a number of different types of processes. There is a very wide variety of ore-forming processes, and there are hundreds of types of mineral deposits. The origins and characteristics of a few of them are described below.

Magmatic Deposits

A magmatic deposit is one in which the metal concentration takes place primarily at the same time as the formation and emplacement of the magma. Most of the nickel mined in the world, and much of the copper, comes from magmatic deposits such as those in Indonesia, Canada, southern Africa, Australia and Siberia (Figure 8.1.2). The magmas from which these deposits are formed are of mafic or ultra-mafic composition (they are derived from the mantle), and therefore they have relatively high nickel and copper contents to begin with (as much as 100 times that of normal rocks in the case of nickel). These elements can be further concentrated within the magma as a result of addition of sulphur from partial melting of the surrounding rocks. The heavy nickel and copper sulphide minerals are then concentrated further still by gravity segregation (i.e., crystal settling towards the bottom of the magma chamber). In some cases, there are significant concentrations of platinum-bearing minerals in deposits of this type.

Most of magmatic deposits around the world are Precambrian in age—probably because the mantle was significantly hotter at that time, and the necessary ultramafic magmas were more likely to exist close to the surface.



Figure 8.1.2 The Nickel Mine and Smelter at Thompson, Manitoba.

Volcanogenic Massive Sulphide Deposits

Much of the world's copper, zinc, lead, silver and gold is mined from volcanogenic massive sulphide (VMS) deposits associated with submarine volcanism. There are similar deposits in many countries, with some of the larger ones in Spain and Portugal, in southern Africa, Canada, and Russia.[2]

VMS deposits are formed from the water discharged at high-temperature (250 to 300° C) at ocean-floor vents, primarily in areas of subduction-zone volcanism. Although most VMS deposits are tens to hundreds of millions of years old, the environment of their formation is comparable to that of a modern-day black smoker (Figure 8.1.3) which form where hot metal- and sulphide-rich water issues from the sea floor. They are called massive-sulphide deposits because the sulphide minerals (including pyrite (FeS_2) , sphalerite (ZnS), chalcopyrite ($CuFeS_2$) and galena (PbS)) are generally present at very high concentrations (making up the majority of the rock in some cases). The metals and the sulphur are leached out of the sea-floor rocks by convecting groundwater driven by the volcanic heat, and then quickly precipitated where that hot water cools suddenly and changes chemically on entering the cold sea water, so the process of concentration of the metal is a sudden change in metal solubility where the hot water cools quickly at the sea-floor rock-water interface. The volcanic rock that hosts VMS deposits is formed in the same area and at the same general time as the accumulation of the ore minerals.

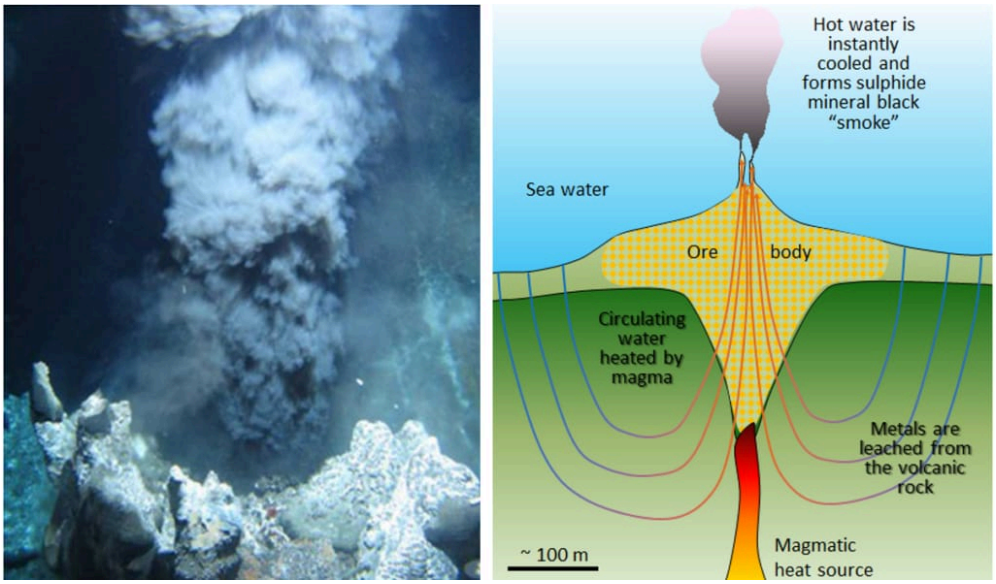


Figure 8.1.3 (Left) A Black Smoker on the Juan de Fuca Ridge Off the West Coast of Vancouver Island . (Right) A Model of the Formation of a Volcanogenic Massive Sulphide Deposit on the Sea Floor.

Porphyry Deposits

Porphyry deposits are the most important ores of copper and molybdenum in western North and South America, and in other areas of the Pacific Rim. Most porphyry deposits also include some gold, and in a few cases gold is the primary commodity.

A porphyry deposit forms around a cooling felsic stock (magma chamber) in the upper part of the crust. They are called "porphyry" because upper crustal stocks are typically porphyritic in texture, the result of a two-stage cooling process. Metal enrichment results from convection of groundwater related to the heat of the stock, and also from hot water expelled by the cooling magma (Figure 8.1.4). The host rocks, which commonly include the stock itself and the surrounding country rocks, are normally highly fractured and brecciated. During the ore-forming process some of the original minerals in these rocks get altered to potassium feldspar, biotite, epidote and various clay minerals. The important ore minerals include chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4) and pyrite in copper porphyry deposits, or molybdenite (MoS_2) and pyrite in molybdenum porphyry deposits. Gold is present as minute flakes of native gold.

This type of environment (i.e., around and above an intrusive body) is also favourable for the formation of other types of deposits—particularly vein-type gold deposits (a.k.a. epithermal deposits). Many of the other gold deposits situated all along the western edge of both South and North America are of the vein type shown in Figure 8.1.4, and are related to nearby magma bodies.

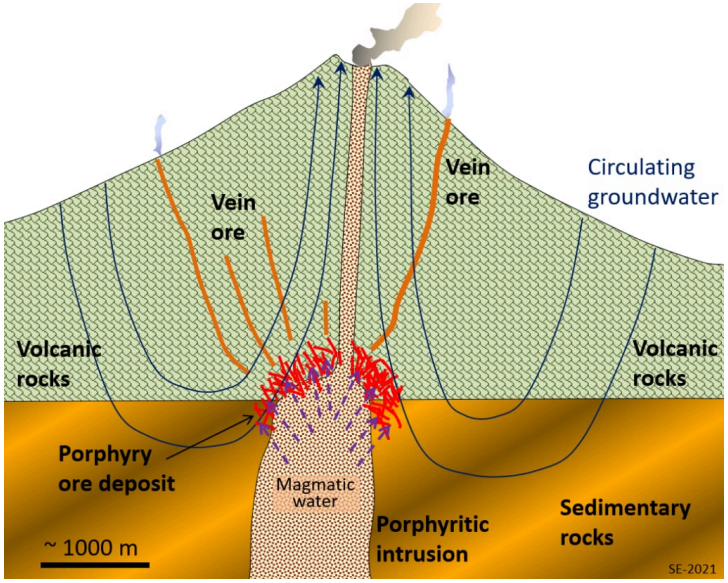


Figure 8.1.4 A Model for the Formation of a Porphyry Deposit Around an Upper-Crustal Porphyritic Stock, and of Associated Vein Deposits.

Some porphyry deposits are huge, and if the ore is near to the surface they are most economically mined by open-pit methods (more on that below). The largest porphyry copper deposit in the world is at Chuquicamata in northern Chile (Figure 8.1.5). It has been in operation for over 100 years, has produced over 29 million tonnes of copper metal, and is expected to continue operation for at least another 50 years. The mine is owned by the government of Chile and supports a nearby city with a population of 160,000.



Figure 8.1.5 The Chuquicamata Open Pit Copper Mine in Northern Chile. The pit is 4.3 km long, 2.7 km wide and 1.1 km deep. Mining currently takes place underground, below the bottom of the pit.

Banded Iron Formation

Most of the world's important iron deposits are of the banded iron formation type, and most of them formed during the initial oxygenation of the Earth's atmosphere between 2400 and 1800 Ma. At that time abundant iron in dissolved form in the ocean (as Fe^{2+}) became oxidized to its insoluble form (Fe^{3+}) as the Earth's atmosphere gradually became more oxygen-rich. The iron minerals accumulated on the sea floor, mostly as hematite and magnetite interbedded with chert (Figure 8.1.6). Unlike many other metals, which are economically viable at grades of around 1% or even much less, iron deposits are only viable if the grades are in the order of 50% iron.



Figure 8.1.6 Banded iron formation from an unknown location in North America on display at a museum in Germany . The rock is about 2 m across. The reddish bands are mostly hematite (Fe2O3) and the darker bands a mostly magnetite (Fe3O4). (by André Karwath , at Museum of Mineralogy and Geology, Dresden, Germany, Creative Commons Attribution-Share Alike 2.5 Generic, from https://commons.wikimedia.org/wiki/F...tone_(aka).jpg)

Unconformity-Type Uranium Deposits

There are several different types of uranium deposits, but some of the largest and richest are those within the Athabasca Basin of northern Saskatchewan. They are called unconformity-type because they are all situated very close to the unconformity between the Proterozoic Athabasca Group sandstone and the much older Archean sedimentary, volcanic and intrusive igneous rock (Figure 8.1.7). The origin of unconformity-type U deposits is not perfectly understood, but it is thought that two particular features are important: the relative permeability of the Athabasca Group sandstone, and the presence of graphitic schist within the underlying Archean rocks. The permeability of the sandstone allowed groundwater to flow through it and leach out small amounts of U which stayed in solution in the oxidized form U^{6+}. The graphite (C) created a reducing environment (non-oxidizing) that converted the U from U^{6+} to insoluble U^{4+}, at which point it was precipitated as the mineral uraninite (UO_2).

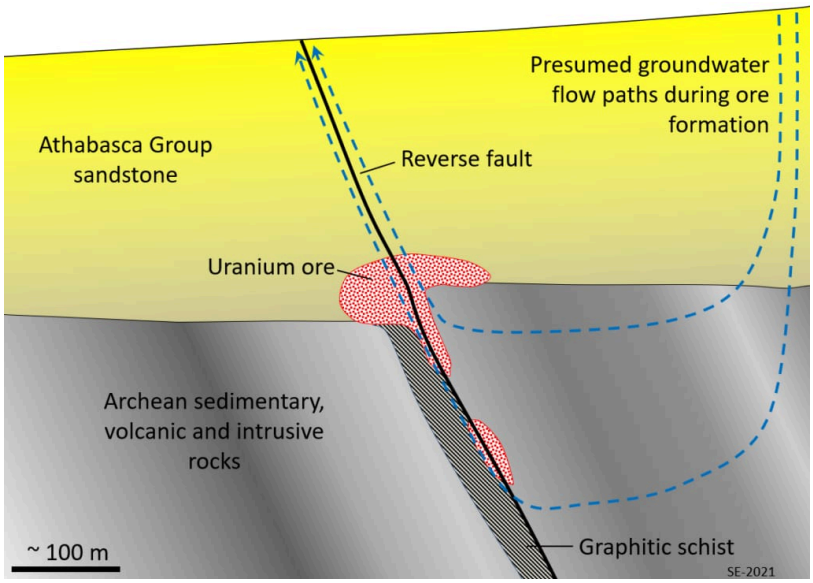


Figure 8.1.7 Model of the Formation of Unconformity-Type Uranium Deposits of the Athabasca Basin, Saskatchewan

Exercise 8.2 The Importance of Heat and Heat Engines

Thermal energy (heat) from within the Earth is critical in the formation of many types of ore deposits, for a variety of reasons. Look back through the deposit-type descriptions above and complete the following table describing which of those deposits types depend on a source of heat for their formation, and why.

Table 8.1.2 Which Deposit Types Depend on a Source of Heat? And for What?

Deposit Type	Is heat a factor?	If so, what is the role of the heat?
Magmatic		
Volanogenic massive sulphide		
Unconformity-type uranium		
Banded iron formation		
Porphyry		

Exercise answers are provided Appendix 2.

Cobalt Deposits

Cobalt is an important component of lithium-based batteries, and the recent surge in the demand for batteries for electric vehicles and other purposes has resulted in increased demand for cobalt. Most of the world's cobalt currently comes from sedimentary-rock hosted deposits in Zambia and Congo, Africa, although there is a significant amount that is mined along with nickel in magmatic and other deposits, especially those in Australia and Canada.

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1. There is no doubt that mining companies will be attracted to jurisdictions where relaxed labour and environmental rules make it easier for them to make a profit. This is the nature of capitalism, and the onus falls upon the jurisdiction to make laws that will protect their environment and their workers, and on the mining companies to avoid exploiting workers and damaging the environment. ↩
2. Galley, A., Hannington, M., & Jonasson, I. (2007). Volcanogenic massive sulphide deposits. In Goodfellow, W. (Ed.), *Mineral deposits of Canada: A synthesis of major deposit-types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods*. Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, 141-161. https://www.researchgate.net/publica..._deposit_types ↩

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8.4: Energy and Resources- Mining and Ore Processing

Metal deposits are mined in a variety of different ways depending on their depth, shape, size and grade. Relatively large deposits that are quite close to surface and somewhat regular in shape are mined using open-pit mine methods (Figure 8.1.5 in Section 8.1). Creating a giant hole in the ground is generally cheaper than making an underground mine, but it is also less precise, so it is necessary to mine a lot of waste rock along with the ore, and that waste rock becomes an environmental liability. Relatively deep deposits, or those with elongated or irregular shapes are typically mined from underground with deep vertical shafts, declines (sloped tunnels) and levels (horizontal tunnels) (Figures 8.2.1 and 8.2.2). In this way it is possible to focus the mining on the orebody itself. In some cases, the near-surface part of an orebody is mined with an open pit, while the deeper parts are mined underground.

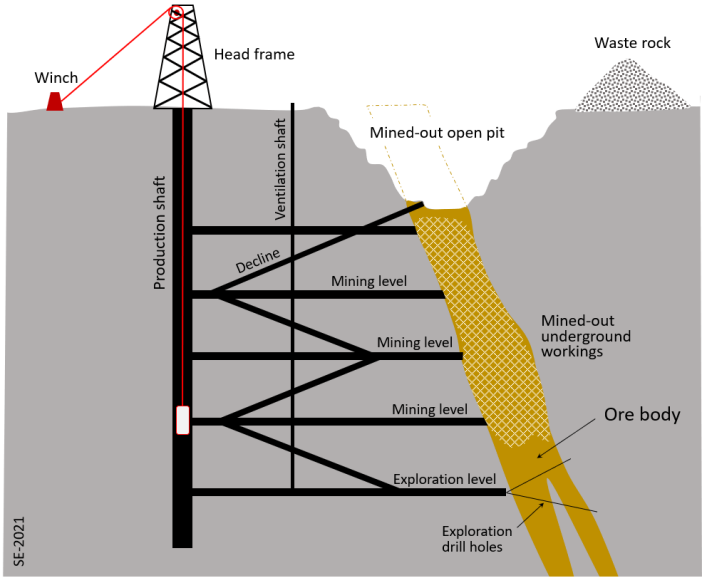


Figure 8.2.1 Simplified Schematic of an Underground Mine. A shaft is a vertical mine opening, a level is horizontal and a decline is sloped so as to allow passage by wheeled vehicles.



Figure 8.2.2 Underground at the Myra Falls Mine, Vancouver Island

A typical ore body will contain a few percent of ore minerals—typically sulphide minerals like chalcopyrite or sphalerite—along with the minerals of the original rock (e.g., quartz, feldspar, amphibole etc.). Most ores also contain some other non-ore minerals (e.g., hematite) and some other sulphide minerals, especially pyrite (FeS_2).

When ore is first processed (typically close to the mine) it is crushed to gravel-sized chunks and then ground to a fine powder and the ore minerals are physically separated from the rest of the rock to make a concentrate. At a molybdenum mine, for example, this concentrate may be almost pure molybdenite (MoS_2). The rest of the rock is known as tailings. It comes out of the concentrator as a wet slurry and is typically stored near to the mine, in most cases within a tailings pond.

The tailings pond at the Volcanogenic Massive Sulphide copper-zinc-silver-gold Myra Falls Mine on Vancouver Island is shown on Figure 8.2.3. The tailings are contained by an embankment. Also visible in the foreground of Figure 8.2.3 is a pile of waste rock, which is non-ore rock that was mined in order to access the ore. Although this waste rock has low levels of ore minerals, at many mines it contains up to a few percent pyrite. The tailings and the waste rock at most mines are an environmental liability because they both contain pyrite plus small amounts of ore minerals. When pyrite is exposed to oxygen and water it generates sulphuric acid—also known as acid rock drainage (ARD). Acidity itself is a problem to the environment, but because the ore elements, for example copper or lead, are more soluble in acidic water than in neutral water the ARD is also typically quite rich in metals, many of which are toxic. The causes and consequences of ARD are summarized below in Box 8.1.



Figure 8.2.3 The Tailings Pond at the Myra Falls Mine on Vancouver Island. The dry rock in the foreground is waste rock. The structure in the background on the right is the head-frame for the mine shaft. Myra Creek flows between the tailings pond and the head frame, and the tailings embankment has been constructed to keep the tailings out of the creek.

Tailings ponds and waste-rock storage piles must be carefully designed, built and maintained to ensure their integrity, and also to ensure that acidic and metal-rich water is not leaking out. In August 2014 the tailings pond (retention basin) at the Mt. Polley Mine in central BC failed, releasing 10 million cubic metres of waste-water along with 4.5 million cubic metres of tailings slurry into Polley Lake, Hazeltine Creek and Quesnel Lake (Figure 8.2.4).



Figure 8.2.4 The Mt. Polley Mine Area Before (left) and After (right) to the Dam Breach of August 2014. The tailings were stored in the area labelled “retention basin”.

At the time of the failure of the retention dam work was underway to raise the level of the dam so that more tailings could be stored. Because of changes to the mining regulations the structure had not been inspected by government officials for at least two years. The released water and metal-rich tailings flowed first into Polley Lake, and then down Hazeltine Creek into Quesnel Lake. Surface water samples collected in the affected water bodies showed elevated levels of suspended solids, chromium, copper, iron and phosphorous during 2014, but the levels had returned to “normal” by 2016.[1] The remediation project has cost the mining company $70 million, and the mine was out of operation for 3 years (2014 to 2017). Three engineers that were involved in the design, construction and maintenance of the dam are facing disciplinary hearings by Engineers and Geoscientists B.C.

Most mines have concentrators on site because it is relatively simple to separate ore minerals from non-ore minerals, and thus significantly reduce the costs and other implications of transportation. But separation of ore minerals is only the preliminary stage of metal refinement, for most metals the second stage involves separating the actual elements within the ore minerals. For example, the most common ore of copper is chalcopyrite ($CuFeS_2$). The copper must be separated from the iron and sulphur to make copper metal and that involves complicated and very energy-intensive processes that are done at smelters or other types of refineries. Because of their cost and the economies of scale, there are far fewer refineries than there are mines.

Some of the potential environmental effects of metal mines are summarized on Table 8.2. All mining activities result in a loss of natural environment because land has to be cleared and is no longer available for or useful to the plants and animals that once lived there. Mining involves blasting, breaking and crushing rock, and so dust is created. Some of this material is metal-rich, and is fine enough to be wind-borne, and so can be dispersed widely. Some gets into water courses. Because sulphide minerals—especially pyrite—lead to acidification of water acid rock drainage is a common problem around mine sites (see Box 8.1). Materials, such as waste rock that is piled up around a mine, are subject to slope failure and such failures represent risks to people, infrastructure and to the environment. Tailings represent a special class of such materials because they are typically saturated with water, and are also rich in metals and so are potential sources of ARD. Tailings are a problem if their containment structure is breached (as at Mt. Polley), but can also be an ongoing issue of the water they contain is able to slowly leak from the storage facility. Finally, smelting processes involve application of enough heat to melt ore concentrates and that produces gases and ash that become airborne and hence are widely dispersed. In most cases the heat comes from fossil fuels.

The Sudbury region of Ontario is an example of the environmental risk of smelter stacks. Sudbury is home to the largest nickel smelting operation in the world. By the middle part of the 20th century a region of several hundred square km around mine district had either been completely de-vegetated or damaged by the contaminants released or the acidity they produced. In 1970 a 385 m tall superstack was built in Sudbury to allow smelter contamination to be dispersed further. This allowed for eventual revegetation of the region around the city but resulted in the spread of the contamination over a much wider area, even into other provinces and states.[2]

Table 8.2.1 A Summary of Some Environmental Risks Associated with Metal Mining

Activity	Potential Environmental Risks
Mining	Loss of natural environment, wind-blown contaminated dust from open excavations, acid rock drainage (ARD)
Waste rock storage	Loss of natural environment, slope failure, wind-blown contaminated dust, ARD
Tailings storage	Loss of natural environment, potential slope failure, potential slurry spills, potential leakage of contaminated water, wind-blown contaminated dust, ARD
Smelting	Loss of natural environment, toxic particulates and gases from chimneys, leaching of metals from smelter waste material (slag), release of greenhouse gases

Box 8.1 Acid Rock Drainage at Mt Washington, BC

Any material that contains the mineral pyrite (FeS_2), or some other iron sulphide mineral, has the potential to produce acidity in the surrounding surface environment. That's because pyrite oxidizes quite readily at surface, and its oxidation leads to the release of hydrogen ions (H^+) into the surface water and groundwater. A simplified equation for this process is as follows:

$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4\ H^+$
pyrite + oxygen + water -> dissolved iron + sulphate + hydrogen ions

Materials around a mine site that might contain pyrite include rock outcrops exposed by mining, road-building or construction, waste rock or any rock that was mined but doesn't have enough metal to be considered ore, and tailings from a processing plant. The important point is that these materials may have been underground and so not susceptible to weathering, but, because of construction and mining activities they are now exposed to water and oxygen at surface.



Figure 8.2.5 Waste Rock and Acid-Rock Drainage at the Mt. Washington Mine, BC

Figure 8.2.5 shows part of the Mt. Washington porphyry copper mine on Vancouver Island.[3] Waste rock piles are present in the background, and rock that has been exposed by mining is visible in the foreground. Both are producing acid rock drainage, and the pH of the water in this area is as low as 4.

Acid water alone has a negative effect on aquatic and terrestrial organisms, but in most cases the acid drainage from a mine also includes elevated levels of metals. This is because the rocks that are weathering tend to be metal-rich, and also because most metals are more soluble in acidic water than in neutral water.

Water draining from the Mt. Washington Mine flows into the Tsolum River an important salmon stream in the Comox Valley. In the 1930s and 1940s this stream had runs of up to 200,000 pink salmon, 15,000 coho, 11,000 chum and 3,500 steelhead.[4] The mine operated for only 3 years from 1964 to 1966, but by 1987 only 14 coho could be found in the river and other fish stocks were also significantly depleted. In 1982 a fish hatchery released 2.5 million pink salmon fry into the Tsolum River; none returned.

Very low copper concentrations, in the order of 10 µg/L, can be toxic to Pacific salmon.[5] In the 1980s and 1990s copper concentrations in the Tsolum River ranged from 20 to 400 µg/L, while copper concentrations in one of the tributaries leading from the Mt. Washington Mine were in the range 5,000 to 15,000 µg/L.[6]

A remediation plan for the Tsolum River was established in 2003. The plan included steps to reduce the level of acid drainage at source, and also to naturally treat some of the water flowing into the river. The main stream draining the mine site was diverted into an existing wetland, and the flow out of this wetland was controlled so that most flow coincided with peak discharge periods of the Tsolum River (to achieve dilution). Reduction in ARD at source was achieved by diverting some surface drainage around the old mine workings and covering a large part of the workings with a bituminous liner.[7]
By 2010 the copper level in the Tsolum River was consistently below 11 µg/L, and it has continued to drop since then. In 2018 over 220,00 Pink salmon, 32,000 Chum, 4,100 Coho and 600 Steelhead were counted in the river.[8]..

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8.5: Energy and Resources- Industrial Minerals

Metals are critical for our technological age, but there are a lot of other not-so-shiny materials that are needed to facilitate our way of life. For everything made out of concrete or asphalt we need sand and gravel. For concrete we also need limestone to make lime (CaO). For the glass in our computer screens, and for glass-sided buildings, we need silica sand plus sodium oxide (Na_2O), sodium carbonate (Na_2CO_3), and calcium oxide (CaO). Potassium is an essential nutrient for farming in many areas, and for a wide range of applications (e.g., ceramics and many industrial processes) we also need various types of clay.

Sand and gravel represent, the greatest volume of mined material on Earth, at around 50 billion tonnes/year, which is 20 times as much as iron . The best types of sand and gravel resources are those that have been sorted by streams, and in many regions of Canada and the northern USA (and elsewhere) the most abundant and accessible fluvial deposits are associated with glaciation. That doesn't include till of course, because it has too much silt and clay, but it does include glaciofluvial outwash, which is present in thick deposits in many glaciated regions, similar to the one shown on Figure 8.3.1. In a typical gravel pit these materials are graded on-site according to size and then used in a wide range of applications from constructing huge concrete dams to filling children's sandboxes. Sand is also used to make glass, but for most types of glass it has to be at least 95% quartz (which the sandy layers shown in Figure 8.3.1 are definitely not), and for high-purity glass and for the silicon wafers used for electronics the source sand has to be over 98% quartz.



Figure 8.3.1 Sand and Gravel in an Aggregate Pit Near to Nanaimo, BC

Approximately 4 billion tonnes of concrete are used globally each year—a little over one-half tonne per person. The cement used for concrete is made from approximately 80% calcite ($CaCO_3$) and 20% clay. This mixture is heated to 1450° C to produce the required calcium silicate compounds (e.g., Ca_2SiO_4) and during that process the carbonate is transformed into carbon dioxide which is released into the atmosphere. The calcite typically comes from limestone quarries like the one shown on Figure 8.3.2. Limestone is also used as the source material for many other products that require calcium compounds, including the manufacture of steel and glass, processing pulp and paper and in plaster products for construction.



Figure 8.3.2 Triassic Quatsino Fm. Limestone Being Quarried on Texada Island, BC

Sodium is required for a wide range of industrial processes, and the most convenient source is sodium chloride (rock salt), which is mined from evaporite beds in many parts of the world. Rock salt is also used as a source of sodium and chlorine in the chemical industry, to melt ice on roads, as part of the process of softening water, and as a seasoning. Under certain conditions the salt sylvite (KCl) accumulates in evaporite beds. The potassium is used as a fertilizer.

Another evaporite mineral, gypsum ($CaSO_4.2H_2O$) is the main component of plaster board ("drywall") that is widely used in the construction industry.

Rocks are quarried or mined for many different uses, such as building facades, countertops, stone floors and head-stones. In most of these cases the favoured rock types are granitic rocks and marble. Quarried rock is also used in some applications where rounded gravel isn't suitable, such as the ballast (road bed) for railways, where crushed angular rock is needed because it provides a more stable base.

Exercise 8.3 Sources of Important Lighter Metals

When we think of the manufacture of consumer products, plastics and the heavy metals (copper, iron, lead, zinc) easily come to mind, but we often forget about some of the lighter metals and non-metals that are important. Consider the following elements and determine their sources. Answers for all of these except magnesium can be found above. See if you can figure out a likely mineral source of magnesium.

Element:	Silicon	Calcium	Sodium	Potassium	Magnesium
Source(s):					

Exercise answers are provided Appendix 2.

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8.6: Energy and Resources- Reading- Effects of Mining

Environmental Effects

Environmental issues can include erosion, formation of sinkholes, loss of biodiversity, and contamination of soil, groundwater and surface water by chemicals from mining processes. In some cases, additional forest logging is done in the vicinity of mines to create space for the storage of the created debris and soil. Contamination resulting from leakage of chemicals can also affect the health of the local population if not properly controlled. Extreme examples of pollution from mining activities include coal fires, which can last for years or even decades, producing massive amounts of environmental damage.

Mining companies in most countries are required to follow stringent environmental and rehabilitation codes in order to minimize environmental impact and avoid impacting human health. These codes and regulations all require the common steps of environmental impact assessment, development of environmental management plans, mine closure planning (which must be done before the start of mining operations), and environmental monitoring during operation and after closure. However, in some areas, particularly in the developing world, government regulations may not be well enforced.

Waste

Ore mills generate large amounts of waste, called tailings. For example, 99 tons of waste are generated per ton of copper, with even higher ratios in gold mining. These tailings can be toxic. Tailings, which are usually produced as a slurry, are most commonly dumped into ponds made from naturally existing valleys. These ponds are secured by impoundments (dams or embankment dams). In 2000 it was estimated that 3,500 tailings impoundments existed, and that every year, 2 to 5 major failures and 35 minor failures occurred; for example, in the Marcopper mining disaster at least 2 million tons of tailings were released into a local river. Subaqueous tailings disposal is another option. The mining industry has argued that submarine tailings disposal (STD), which disposes of tailings in the sea, is ideal because it avoids the risks of tailings ponds; although the practice is illegal in the United States and Canada, it is used in the developing world.

The waste is classified as either sterile or mineralised, with acid generating potential, and the movement and storage of this material forms a major part of the mine planning process. When the mineralised package is determined by an economic cut-off, the near-grade mineralised waste is usually dumped separately with view to later treatment should market conditions change and it becomes economically viable. Civil engineering design parameters are used in the design of the waste dumps, and special conditions apply to high-rainfall areas and to seismically active areas. Waste dump designs must meet all regulatory requirements of the country in whose jurisdiction the mine is located. It is also common practice to rehabilitate dumps to an internationally acceptable standard, which in some cases means that higher standards than the local regulatory standard are applied.

Open-Pit Mining



Figure 1. Opencut coal mine loadout station and reclaimed land at the North Antelope Rochelle coal mine in Wyoming, United States.

After mining finishes, the mine area must undergo rehabilitation. Waste dumps are contoured to flatten them out, to further stabilise them. If the ore contains sulfides it is usually covered with a layer of clay to prevent access of rain and oxygen from the air, which can oxidise the sulfides to produce sulfuric acid, a phenomenon known as acid mine drainage. This is then generally covered with soil, and vegetation is planted to help consolidate the material. Eventually this layer will erode, but it is generally hoped that the rate of leaching or acid will be slowed by the cover such that the environment can handle the load of acid and associated heavy metals. There are no long term studies on the success of these covers due to the relatively short time in which large scale open pit mining has existed. It may take hundreds to thousands of years for some waste dumps to become “acid neutral” and stop leaching to the environment. The dumps are usually fenced off to prevent livestock denuding them of vegetation. The open pit is then surrounded with afence, to prevent access, and it generally eventually fills up with ground water. In arid areas it may not fill due to deep groundwater levels.



Figure 2. An open-pit sulfur mine at Tarnobrzeg, Poland undergoing land rehabilitation

Metal Reserves and Recycling

During the twentieth century, the variety of metals used in society grew rapidly. Today, the development of major nations such as China and India and advances in technologies are fueling an ever greater demand. The result is that metal mining activities are expanding and more and more of the world’s metal stocks are above ground in use rather than below ground as unused reserves. An example is the in-use stock of copper. Between 1932 and 1999, copper in use in the USA rose from 73 kilograms (161 lb) to 238 kilograms (525 lb) per person.

95% of the energy used to make aluminum from bauxite ore is saved by using recycled material. However, levels of metals recycling are generally low. In 2010, the International Resource Panel, hosted by the United Nations Environment Programme (UNEP), published reports on metal stocks that exist within society and their recycling rates.

The report’s authors observed that the metal stocks in society can serve as huge mines above ground. However, they warned that the recycling rates of some rare metals used in applications such as mobile phones, battery packs for hybrid cars, and fuel cells

are so low that unless future end-of-life recycling rates are dramatically stepped up these critical metals will become unavailable for use in modern technology.

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8.7: Energy and Resources- The Implications of Resource Extraction for the Climate and Earth Systems

Mining and ore-processing require a huge amount of energy for operating machinery, transportation, and, especially, for smelting and refining. That includes about 15% of total global electricity and 11% of total global energy overall,[1] and therefore acquiring the metals used to make all the things we buy has a huge climate impact. We need to think carefully about that every time we buy something that has metal in it. And, of course, we need to think about that every time we buy a manufactured product that has *anything* in it.

Recovering fossil fuels is also energy intensive and leads to emissions of greenhouse gases at every step in the process, but the really significant climate cost of fossil fuels is in their use, and that's why we can no longer consider fossil fuels as an energy source for the future, and we have to stop looking for and developing more fossil fuel resources right now.

Mining and ore-processing have implications for Earth systems in a number of ways:

- Mining results in exposure of rock to weathering, both within the mines (especially surface mines) and because ore-processing involves crushing and grinding rock into small pieces, producing waste materials that are highly susceptible to weathering.
- Weathering includes oxidation of sulphide minerals, releasing acid into the environment, leading to some of the outcomes summarized in Box 8.1, and might also include hydrolysis of silicates, in which case it could consume CO_2 from the atmosphere.
- Refining metals (especially smelting) introduces a wide range of toxic materials into the atmosphere, as well as acidity, that can have significant negative for plant life, and so for ecosystems in general.
- Production of cement by heating of calcium carbonate results in the release of carbon dioxide, and so contributes to climate change.
- Mining, and the related construction of roads and railways, contributes to slope failures and that can have a range of Earth systems implications, some of which are described in Chapter 1.

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8.8: Energy and Resources- Fossil Fuels

There are several types of fossil fuels, but all of them involve the storage of organic matter in sediments or sedimentary rocks. All fossil fuels are rich in carbon and almost all of that carbon ultimately originates from CO_2 taken out of the atmosphere millions of years ago during photosynthesis. That process, driven by solar energy, involves reduction (the opposite of oxidation) of the carbon, resulting in it being combined with hydrogen instead of oxygen. The resulting "organic matter" is made up of complex and varied carbohydrate molecules.

Most of the organic matter produced in this way is oxidized back to CO_2 relatively quickly once the organism dies (within weeks to decades in most cases), but any of it that gets isolated from the oxygen of the atmosphere, for example deep in the ocean or in a stagnant bog, may last long enough to be buried by sediments and, if so, may be preserved for tens to hundreds of millions of years. Under natural conditions, that means it will be stored until those rocks are eventually exposed at surface and weathered.

In this section we'll discuss the origins and extraction of the important fossils fuels, including coal, oil and gas. Coal, the first fossil fuel to be widely used, forms mostly on land in swampy areas adjacent to rivers and deltas in areas with humid tropical to temperate climates. The vigorous growth of vegetation leads to an abundance of organic matter that accumulates within the stagnant water of swamps, ponds and lakes with little circulation, and thus does not decay and oxidize. This situation, where the dead organic matter is submerged in oxygen-poor water, must be maintained for centuries to millennia in order for enough material to accumulate to form a thick layer (Figure 8.4.1a). At some point the swamp deposit is covered with more sediment—typically because a river changes its course or overtops its bank (Figure 8.4.1b). As more sediments are added the organic matter starts to become compressed and heated. Low grade lignite coal will form at depths between a few 100 m and 1500 m and temperatures up to about 50˚ C (Figure 8.4.1c). At between 1000 to 5000 m and temperatures up to 150˚ C m bituminous coal will form (Figure 8.4.1d). At depths beyond 5000 m and temperatures over 150˚ C anthracite coal will form.

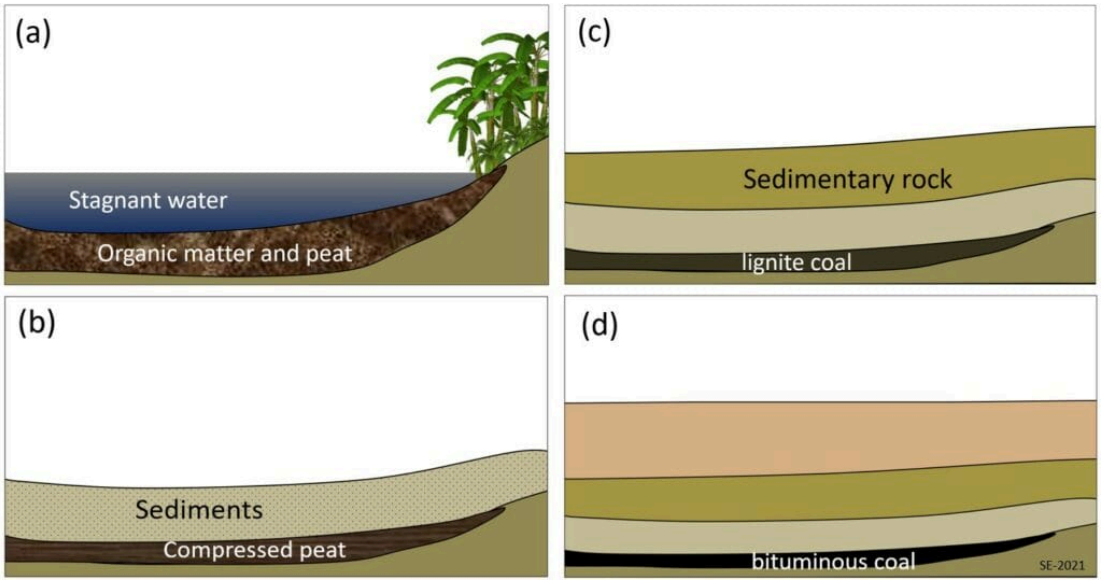


Figure 8.4.1 Formation of Coal. (a) Accumulation of organic matter within a swampy area, (b) the organic matter is covered and compressed by deposition of a new layer of clastic sediments, (c) with greater burial lignite coal is formed, and (d) at even greater depths bituminous (and eventually anthracite) coal are formed.

During the process of converting organic matter to coal some methane is produced and it is stored within the pores of the coal. When coal is mined methane is released into the mine where it can become a serious explosion hazard. Modern coal-mining machines have methane detectors on them and will actually stop operating if the methane levels are dangerous. It is possible to extract the methane from coal beds without mining the coal and the gas recovered in this way is known as coal bed methane.

While almost all coal is formed on land from terrestrial vegetation, most oil and gas is derived primarily from marine microorganisms that accumulate within sea-floor sediments. In areas where marine productivity is high dead organic matter is delivered to the seafloor fast enough that at least some of it escapes being oxidized. This material accumulates in the muddy sediments and then those get buried to significant depth beneath other sediments.

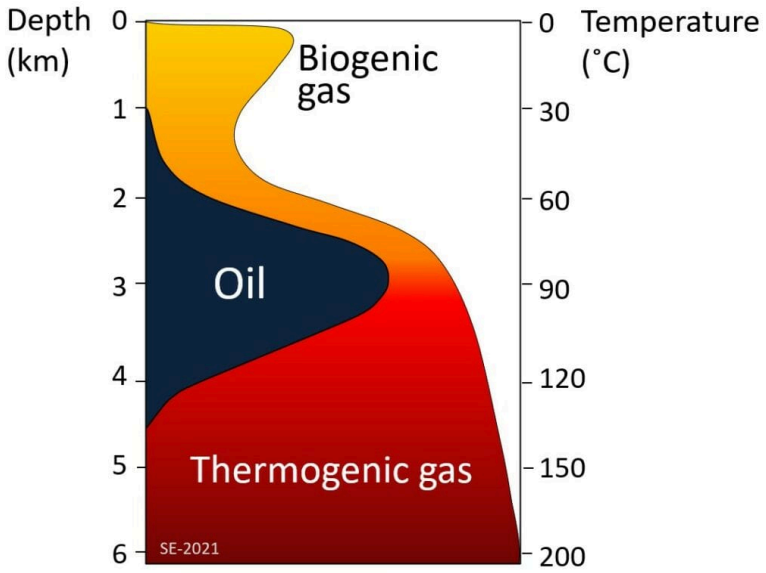


Figure 8.4.2 The Depth and Temperature Limits for Biogenic Gas, Oil, and Thermogenic Gas

As the depth of burial increases so does the temperature—due to the geothermal gradient—and gradually the organic matter within the sediments gets converted to hydrocarbons (Figure 8.4.2). The first stage is the biological production (involving anaerobic bacteria) of methane. Most of this escapes back to surface, but some is trapped in methane hydrates near to the sea floor. At depths beyond about 2 km, and at temperatures ranging from 60 to 120˚ C, the organic matter is converted by chemical processes to oil. This depth and temperature range is known as the oil window. Beyond 120˚ C most of the organic matter is chemically converted to methane (i.e., natural gas).

The rock within which the formation of gas and oil takes place is known to petroleum geologists as the source rock. This rock is typically rich in organic matter, and a good example would be a black shale. Both liquid oil and gaseous methane are lighter than water, so as liquids and gases are formed they tend to move slowly towards surface, out of the source rock and into reservoir rocks. Reservoir rocks are typically relatively porous and permeable rocks such as sandstone or fractured limestone, because that allows migration of the fluids from the source rocks, and also facilitates recovery of the oil or gas. In some cases, the liquids and gases make it all the way to surface, where they are oxidized and the carbon is returned naturally to the atmosphere, but in others they are contained by overlying impermeable rocks (a.k.a. “cap rock”, e.g., mudrock) in situations where anticlines, faults, stratigraphy changes and reefs or salt domes create traps (Figure 8.4.3).

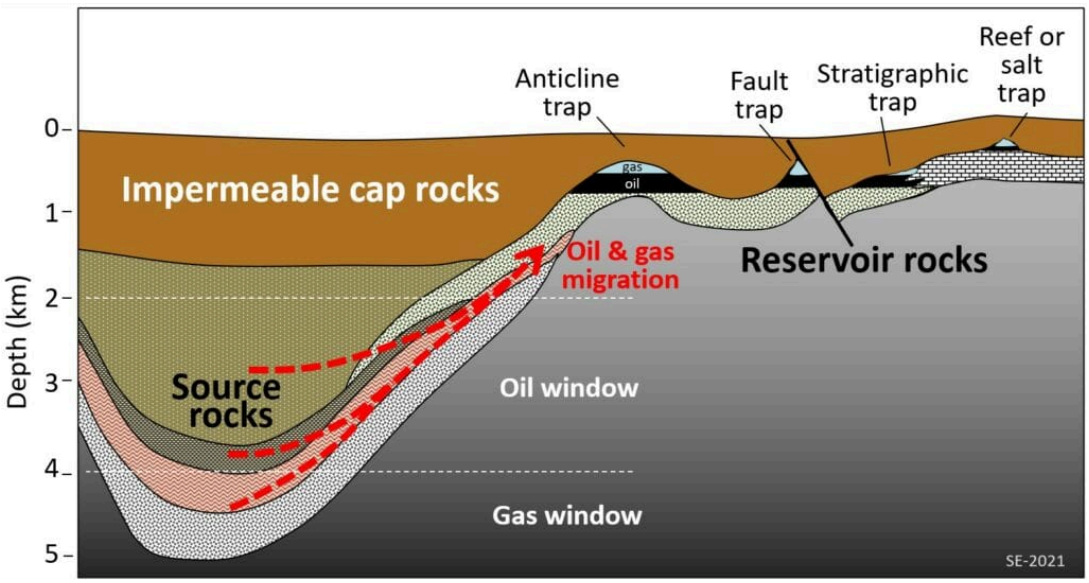


Figure 8.4.3 Migration of Oil and Gas from Source Rocks into Traps in Reservoir Rocks

The liquids and gases that are trapped within reservoirs will become separated into layers based on their density, with gas rising

to the top, then oil, and water underneath. The proportions of oil and gas will depend primarily on the temperature in the source rocks. Some petroleum fields, such as many of those in Alberta, are dominated by oil, while others, notably those in northeastern BC, are dominated by gas.

In general petroleum fields are not visible from surface, and their discovery involves the search for structures in the sub-surface that have the potential to form traps. Seismic surveys are the most commonly used tool for early-stage petroleum exploration, as they can reveal important information about the stratigraphy and structural geology of sub-surface sedimentary rocks. An example from the Gulf of Mexico south of Texas is shown on Figure 8.4.4. In this area a thick evaporite deposit ("salt") has formed domes because salt is lighter than other sediments and tends to rise slowly towards surface, and this has created traps. The sequence of deformed rocks is capped with a layer of undeformed rock.

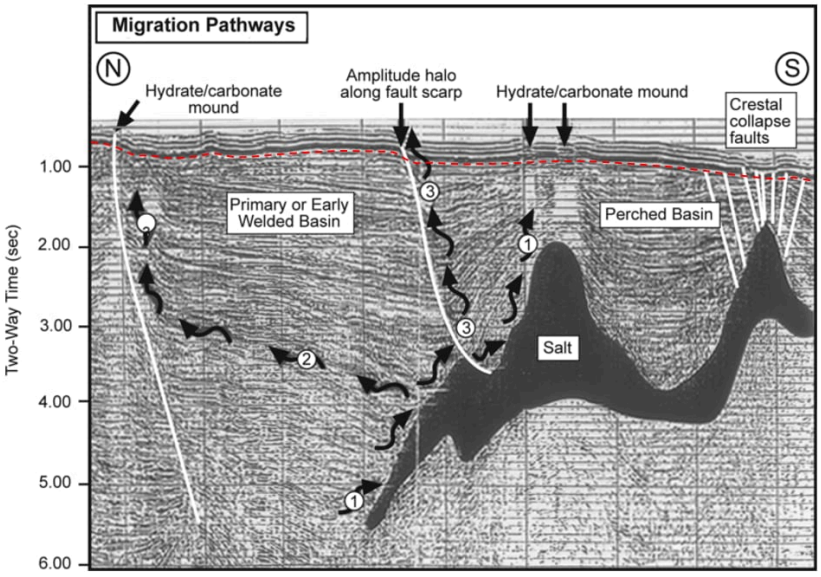


Figure 8.4.4 Seismic Section Through the East Breaks Field in the Gulf of Mexico. The dashed red line marks the approximate boundary between deformed rocks underneath and younger undeformed rocks lying horizontally on top. The wiggly arrows are interpreted migration paths.

The type of oil and gas reservoirs illustrated in Figures 8.4.3 and 8.4.4 are described as conventional reserves. Some unconventional types of oil and gas include oil sands, shale gas and coal-bed methane.

Oil sands are important because the reserves in Alberta are so large (the largest single reserve of oil in the world), but they are very controversial from an environmental and social perspective. They are "unconventional" because the oil is exposed at surface and is highly viscous because of microbial changes that have taken place at surface. The hydrocarbons that form this reserve originated in deeply buried Paleozoic rocks adjacent to the Rocky Mountains and migrated up and towards the east (Figure 8.4.5).

The oil sands are controversial primarily because of the environmental cost of their extraction. Since the oil is so viscous, it requires heat energy to make it sufficiently liquid to process. This energy comes from gas; approximately 25 m^3 of gas is used to produce 0.16 m^3 (~one barrel) of oil. (That's bad, but not quite as bad as it sounds, as the energy equivalent of the required gas is about 20% of the energy embodied in the produced oil.) The other environmental cost of oil sands production is the devastation of vast areas of land where strip-mining is taking place, and the unavoidable release of contaminants into the groundwater and rivers of the region.

At present most oil sand recovery is achieved by mining the sand and processing it on site. Exploitation of oil sand that is not exposed at surface depends on in situ processes, an example being the injection of steam into the oil-sand layer to reduce the viscosity of the oil so that it can be pumped to surface.

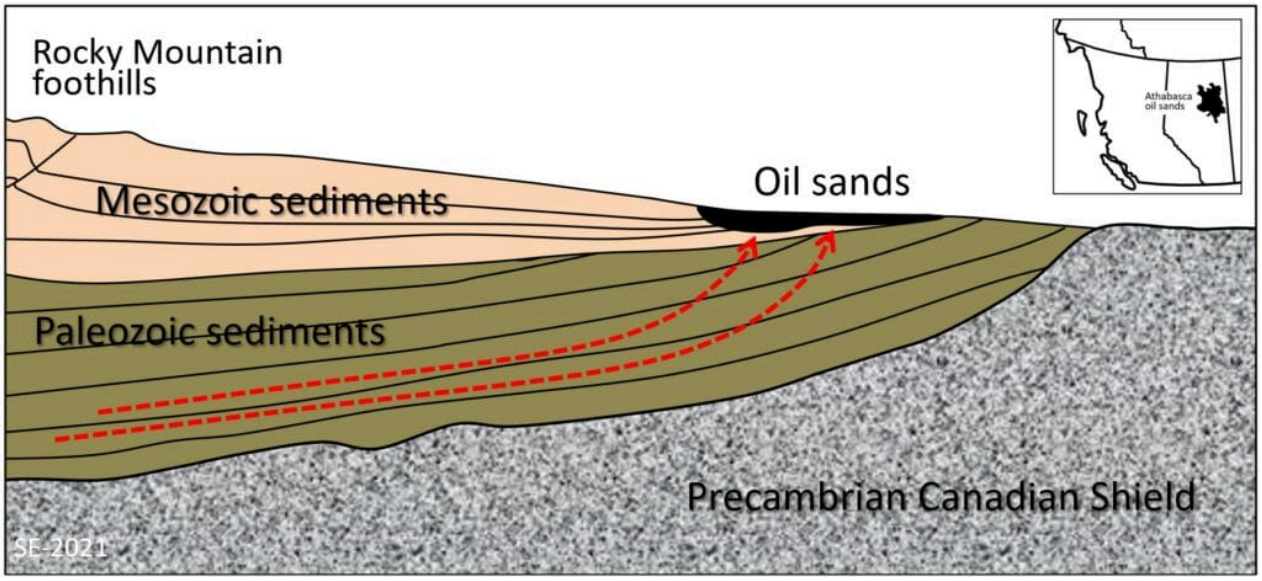


Figure 8.4.5 Schematic Cross-Section of Northern Alberta Showing the Source Rocks and Location of the Athabasca Oil Sands

Shale gas is gas that is trapped within rock that is too impermeable for the gas to escape under normal conditions and can only be extracted by fracturing the reservoir rock using water and chemicals under extremely high pressure. This procedure is known as hydraulic fracturing or fracking. Fracking is controversial because of the volume of water used, and because the fracking companies are not required to disclose the nature of the chemicals used. Although fracking is typically done at significant depths there is always the risk that overlying water-supply aquifers could be contaminated (Figure 8.4.6). Fracking also induces low-level earthquakes, which do have the potential to cause damage.

Directional Drilling and Fracking to recover

Figure 8.4.6 Depiction of the Process of Directional Drilling and Fracking to Recover Gas From Impermeable Rocks. The light blue arrows represent the potential for release of fracking chemicals to aquifers.

It is important for us to understand the origins and exploitation of fossil fuels, but it is equally important to recognize that the Earth can no longer sustain the current rate of fossil fuel use, or in fact any use at all. If we want to avoid catastrophic climate change we need to reduce the use and production of fossil fuels quickly—eventually to zero, and that means there is no point in searching for new fossil fuel resources, or in further developing known resources.

At the United Nations Framework Convention on Climate Change meeting in Paris in 2016 the countries of the world agreed to a goal of limiting anthropogenic (human-caused) warming to 1.5° C above pre-industrial levels.[1] In order to achieve that goal, the Intergovernmental Panel on Climate Change (IPCC) has stated that we must decrease anthropogenic CO_2 emissions (and therefore fossil fuel use) by 45% below 2010 levels by 2030, and that we must reach net-zero CO_2 emissions by 2050.[2] If we wish to limit warming to 2.0° C above pre-industrial levels, we must decrease anthropogenic CO_2 emissions by 25% below 2010 levels by 2030, and that we must reach net-zero CO_2 emissions by 2070.

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1. Every country in the world has signed the Paris Agreement, and so every person in the world needs to be on board with

reaching its goals. Seven countries: Eritrea, Iran, Iraq, Libya, South Sudan, Turkey and Yemen have signed, but have not ratified the agreement. In 2019 the United States announced its withdrawal from the Paris Agreement, but that decision was reversed in February 2021. ↵

2. IPCC. (2018). Summary for policymakers. In Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* World Meteorological Organization. https://www.ipcc.ch/site/assets/uplo..._report_LR.pdf ↵

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8.9: Energy and Resources- Nuclear Energy

Nuclear energy is the energy that is stored in the nuclei of atoms; it comes in two types. Fission energy is released when large atoms like uranium split apart into smaller atoms. This is constantly taking place within the Earth—and it is part of the source of geothermal energy—and all around us, but the rate is very slow. We can build devices that increase that rate enough to generate heat in a controlled way, but there are some downsides to the technology.

Fusion energy is released when small atoms like hydrogen are fused together to make larger atoms. This is what is happening inside the sun, so we use that energy all of the time. We can reproduce nuclear fusion here on Earth in in the form of a hydrogen bomb, but that technology doesn't allow for a controlled rate of energy release. Over the past several decades governments of several countries have spent tens of billions on research into controllable nuclear fusion. Fifty years ago, commercial nuclear fusion was considered to be less than fifty years away. During that time significant progress has been made in understanding what is needed to make that happen, but in 2021, it is still likely that a proof of the concept of fusion energy production is 5 to 10 years away, and that a fusion energy industry is likely another 25 years beyond that.

Nuclear Fission

Nuclear fission has been used for generating electricity since the late 1950s and there are currently around 440 fission reactors operating in 30 countries, producing about 10% of the world's electricity. In a few countries, including France, Slovakia and Ukraine nuclear fission makes up more than 50% of electricity generation[1].

While naturally occurring uranium in rock splits apart only very slowly, the rate of fission is accelerated many thousands of times in a fission reactor because the uranium is highly concentrated, and the fuel is packed close enough together so that the neutrons released by one fission event will almost immediately trigger another fission in a nuclear chain reaction. An important point is that the chain reaction process must be carefully controlled by substances called moderators and, in the event of some irregularity, the reaction can be slowed relatively quickly by inserting control rods that inhibit the chain reaction process. It is important to realize that although a fission reactor can be dramatically slowed by inserting the control rods, the massive reactor core will still remain very hot for several days. This residual heat has been the cause of several nuclear accidents. A diagram of a type of fission reactor is provided on Figure 9.5.1, and the important components are described.

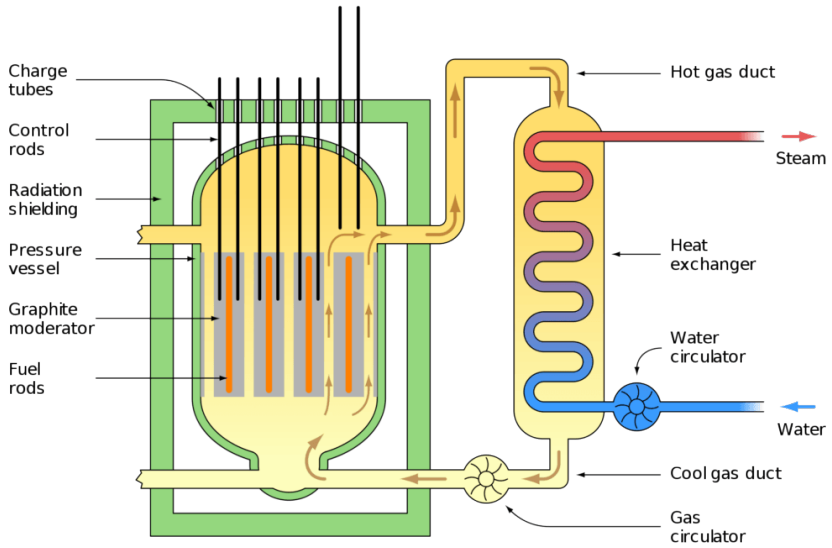


Figure 9.5.1 The Components of a Gas-Cooled Nuclear Fission Reactor . The uranium fuel elements are shown in orange. The graphite moderator, which keeps the reaction from getting out of control, is grey. The control rods that can be used to dramatically slow the chain reaction are black. Heat generated by the fission in the fuel is heats a gas which is circulated through a heat exchanger to boil water that is then used to run a steam turbine.

Modern nuclear reactors have many levels of protection against irregular operating conditions and against more significant failure

and out-of-control behaviour. While that might give us some comfort, it cannot be denied that there have been some major failures in the nuclear power industry, at least one of which has had significant human and environmental implications. Three such failures are described in Box 9.1. Each of these led to a loss of public confidence in the safety of nuclear power, and to reductions in the number of reactors ordered and constructed in subsequent years.

Box 9.2 Nuclear Fission Plant Failures

Three significant nuclear plant failures—Three Mile Island (Pennsylvania), Chernobyl (Ukraine) and Fukushima (Japan)—have shaped the public's perception of the safety of the nuclear industry, and have also informed the industry's efforts to make nuclear reactors as safe as possible.

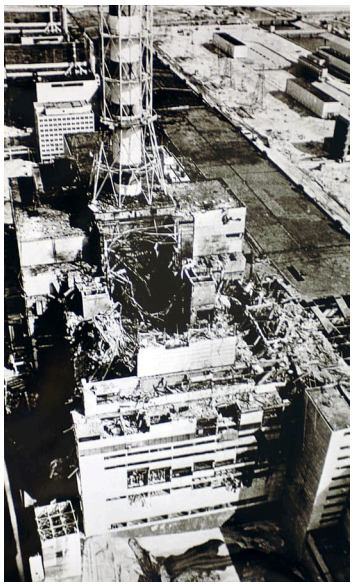


Figure 9.5.2 The Chernobyl Nuclear Fission Reactor Following the Accident in 1986

The Three Mile Island accident in March 1979 involved an operator error, the failure of a cooling system valve and the failure of the system that was meant to warn the operators of the valve's malfunction. This led to a loss of coolant within the reactor vessel and resulted in partial melting of the nuclear fuel. There were high levels of radioactivity within the plant, and some radioactive materials were released into the environment via steam. Health officials eventually concluded that there were no deaths or significant illnesses that could be attributed to the accident, however that conclusion was controversial at the time, and remains so in the minds of many people.

The Chernobyl accident of April 1986 also involved an operator error and a system failure that resulted in the reactor power level increasing when it should have been decreasing (Figure 9.5.2). This led to a steam explosion that ruptured the reactor core and triggered an open-air reactor fire that continued for 9 days, releasing airborne radioactive material into the environment. A total of 28 plant workers and firefighters died within several days of the accident.[2] A 2006 United Nations report concluded that as many as 4000 cancer deaths are likely to occur amongst 5 million residents in the contaminated region around the plant over the 80 years following the accident, and that this represents a 0.3% increase over expected cancer deaths for that region.[3]

The Fukushima accident of March 2011 was the direct result of a magnitude 9 earthquake and a subsequent tsunami. Although none of the reactors was damaged by the earthquake, they were automatically shut down when the earthquake struck and therefore could not provide power to the cooling systems. Six external power supply systems failed because of the earthquake and although an emergency diesel power plant continued to supply power to cooling pumps, this was destroyed 50 minutes later by the 15 metre-high tsunami that overtopped protective barriers and inundated the plant. The result was that there was no cooling available for the still-hot reactors, three of which suffered melting within the reactor cores. No deaths have been attributed to the Fukushima accident, and although it is estimated that approximately 130 deaths may eventually occur because of elevated cancer rates , that number is small compared with the number of expected cancer deaths from other causes.

In a typical reactor the fuel elements will last for 18 months to a few years. Some types of reactors can be refuelled while still operating, but most have to be shut down for periods of up to several weeks. The spent fuel is removed and replaced with fresh fuel. The highly radioactive spent fuel is stored in swimming-pool sized tanks at the reactor site for about 5 years, and then is

transferred to dry storage facilities, which are also on-site in most cases. On-surface storage of nuclear waste is not a viable option because the materials remain radioactive for thousands of years and represent both a health risk and security risk (from the perspective of nuclear proliferation). Several countries, including Canada and the United States, have conducted research into the deep underground storage of nuclear waste, but as of 2021, only Finland has an operating long-term storage facility.

Although the waste from nuclear fission is a serious problem, the volumes are not huge. The amount of radioactive waste produced for a person who used nuclear energy for their lifetime supply of electricity is about 3 kg. Nuclear fuel is quite heavy, so that amount would likely fit within a coffee cup.

Nuclear Fusion

Nuclear fusion can be achieved when hydrogen nuclei are forced close enough together to allow them to fuse together. The advantage of nuclear fusion for electricity generation is that it's fuel (hydrogen) is abundantly available and it doesn't produce significant amounts of toxic or radioactive waste. Nuclear fusion has the potential to produce energy from fuel that is virtually inexhaustible, without producing a significant amount of waste, but the process of achieving it is extremely complex, requires large amounts of energy to initiate the process, and extremely high temperatures (in the order of 100,000,000° C). These conditions, and the existence of lots of fast-moving neutrons, have possible implications for the mechanism that are still poorly understood.

The most advanced nuclear fusion project is ITER (International Thermonuclear Experimental Reactor) which has been under construction in southern France since 2008 and is expected to be complete by 2025 (Figure 9.5.3). This project is funded by the European Union, China, India, Japan, Russia, South Korea and the United States.

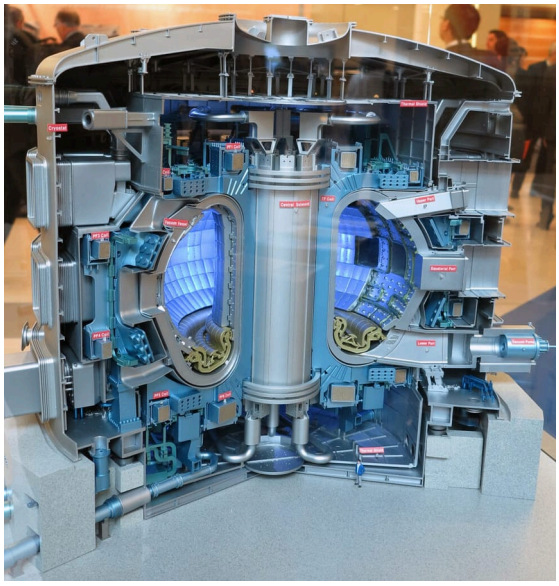


Figure 9.5.3 A Model of the ITER Fusion Reactor. There is a person for scale at the bottom.

ITER will not be used to produce any electricity, but it is expected to be able to generate about 10 times more energy than the amount needed for its operation. It is estimated that the total construction and operating cost of ITER will be in the region of $65 billion.

The follow-up to ITER is called DEMO (DEMOnstration Power Station). It is currently being planned by the EUROfusion consortium, but is unlikely to be ready to operate until 2050. Although DEMO is intended to produce electricity that will be fed into the grid, it will not be a commercially operating power station.

In summary, while nuclear fusion could provide abundant energy without significant waste products or climate implications, its development has been and will continue to be extremely expensive and its realization is still at least 30 years away, probably more than that.

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- **Figure 9.5.3** ITER Exhibit by IAEA Imagebank, 2013, CC BY-SA 2.0, via Wikimedia Commons, https://commons.wikimedia.org/wiki/F..._(cropped).jpg

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1. World Nuclear Association, https://www.world-nuclear.org/ ↵
2. Wikipedia contributors. (2021, November 14). Chernobyl disaster. *Wikipedia* (accessed November 15, 2021), https://en.Wikipedia.org/wiki/Cherno...iate_aftermath ↵
3. *The Chernobyl Forum: 2003–2005. (2006). Chernobyl's legacy, health, environmental and socio-economic impacts* (second revised version). World Health Organization. https://www.who.int/publications/m/i...on-and-ukraine ↵

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8.10: Energy and Resources- Solar and Wind

Solar Energy

We use solar energy to grow food of course, and for some industrial processes (like concentrating lithium brines), and to passively heat buildings, but early in the 21st century the most important and fastest growing use of solar energy is for generating electricity. Solar energy is abundant. The amount of sunlight energy received on Earth is approximately 10,000 times the amount of energy consumed by humans in 2005.[1] As shown on Figure 9.1.1, solar potential is greatest in sub-tropical regions, but it is also significantly affected by weather conditions, and is highest in drier climates. That is why the dry central region of southern Canada, for example, has much greater solar potential than the wetter and cloudier west coast, even at the same latitude.

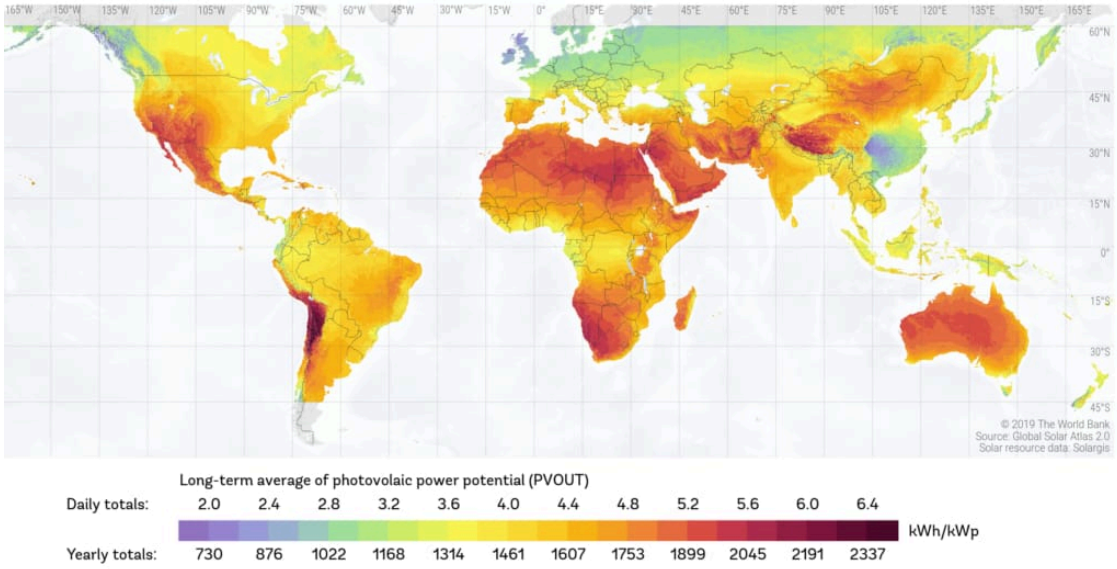


Figure 9.1.1 Global Solar Energy Potential

There are two main ways to generate electricity from the sun. One is through heat, the other through photovoltaic cells. The Crescent Dunes facility in Nevada is an example of solar heat electricity generation (Figure 9.1.2). This facility has 10,347 movable mirrors that reflect sunlight onto a tower in the centre of the complex. The highly concentrated sunlight is used to heat molten salt that powers a steam turbine to generate electricity. The hot molten salt retains enough heat to continue producing electricity for 9 hours after sundown, and therefore the plant can operate through the high electricity-demand period in the evenings. The Crescent Dunes station operated from 2016 to 2019 but is currently shut down because of technical issues with the molten salt container.[2] Solar thermal energy has the disadvantage of relatively high capital and operating costs, such that the electricity production cost at most existing plants is currently higher than for some other sources, including photo-voltaic solar. But it has the advantage of short-term energy storage, which allows for energy production into the evening when it's need most and that could outweigh higher production cost in areas where there are time-of-day premiums on the value of electricity.

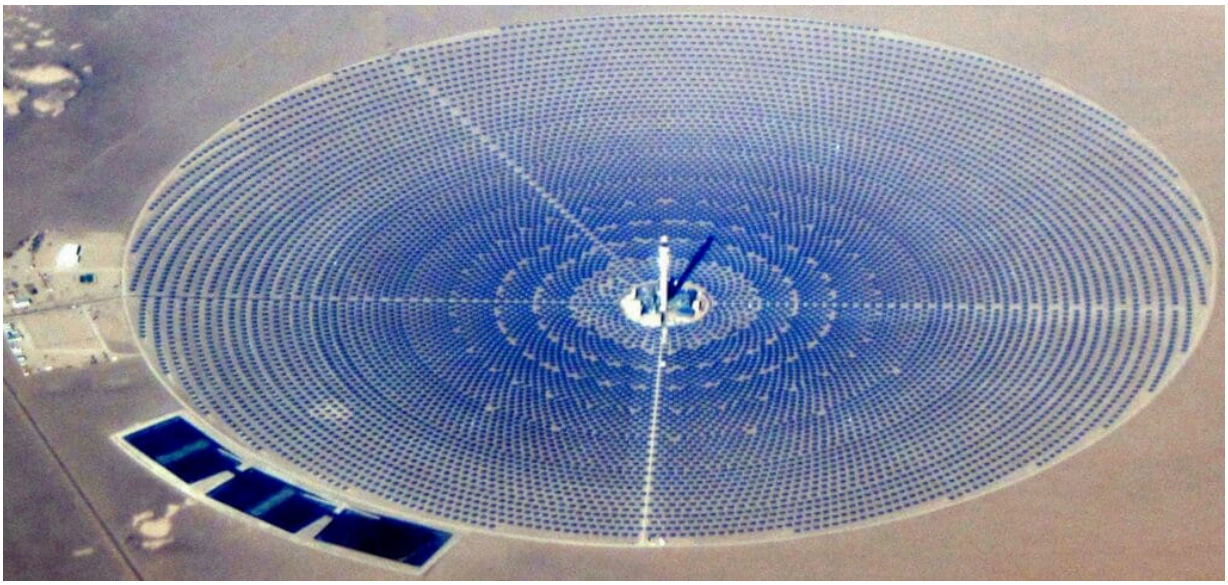


Figure 9.1.2 Crescent Dunes Thermal Solar Plant Near to Tonopah, Nevada

Photo voltaic solar (or PV) is based on the use of cells that convert sunlight directly to electricity. Solar PV is easily scalable, from several modules on a single roof (Figure 9.1.3) to thousands of modules at a utility-scale facility (Figure 9.1.4). The efficiency of solar PV technology has increased significantly over the past several decades. Commercially available modules have evolved from about 10% efficiency in the 1970s to about 20% efficiency in the early 2020s. Experimental solar cells are now operating at about 40% efficiency—meaning that 40% of the sun's energy that strikes them is converted into electricity. While efficiency has gone up over that period, costs have come down dramatically. According to the International Energy Agency the average cost of solar PV modules has dropped from over $100/watt in 1975, to $10/W in 1987, to $1/W in 2015, and to $0.2/W in 2020.[3]

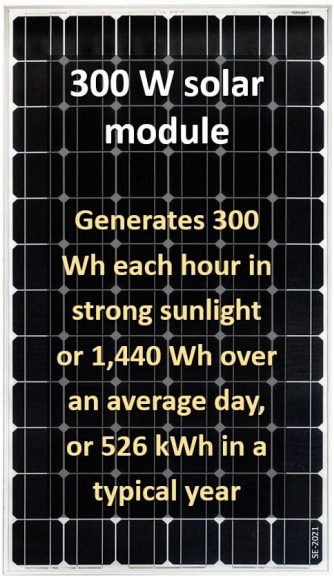


Figure 9.1.3 Installing Solar Modules on a Roof



Figure 9.1.4 A Commercial Solar PV Installation in Greece

Box 9.1 Watts and Watt Hours



(Steven Earle, CC BY 4.0)

In this chapter we are talking about power and energy using the terms Watts and Watt hours. A Watt is a measure of power, which is the rate that energy is produced or consumed by a device. A 10 W LED light bulb consumes electricity at a rate of 10 W. A Watt is already a rate, so we don't need to use something like "W/hour". A 300 W solar panel in full sunlight generates electricity at a rate of 300 W. Each hour at that rate it will produce 300 W hours of energy. A 300 W solar module could power thirty 10 W light bulbs for as long as the sunlight holds up.

During each hour of full sunlight, a 300 W solar module will generate 300 Wh (Watt hours) of energy. A solar installation like the one in Figure 9.1.3, has a capacity factor of about 20%, meaning it can only generate about 20% of its rated power over the course of a year (because of darkness and cloud cover). In one average day each module in that system will generate 24 x 300 x 0.2 = 1,440 Wh of energy (or 1.44 kWh). In one year, each module will generate 1.44 x 365 = 526 kWh.

In the context of large energy projects, we need bigger numbers to express the rate of power generation, such as MW (Mega-Watts or 1,000,000 W) or GW (Giga-Watts or 1,000,000,000 W), or energy production, such as MWh and GWh.

Solar PV modules (and thermal solar) do not generate electricity all of the time, certainly not when the sun is down, and not that

well under cloudy conditions. In areas with a reasonably good solar resource the capacity of solar modules is about 20% of the rated wattage. In other words, 100 modules rated at 250 watts (25 kW) should produce electricity at an average rate of 5 kW, or should generate 43,800 kWh of energy over the course of a year, which is about enough to power 4 houses in North America, more than that in Europe.

According to the International Renewable Energy Agency solar represented 23% of the world's renewable energy supply in 2019, and that proportion is growing. The increasing efficiency and decreasing cost of solar PV modules has made it a viable option for a large part of the energy supply in a world without fossil fuels. The US National Renewable Energy Lab has estimated that a national grid with 55% solar and wind sources—both of which are intermittent—could be viable if the remaining power sources can be ramped up and down to even out the supply. Energy storage (such as pumped hydro or batteries) could also help to make this a reality.

A typical solar PV module, like those shown on Figure 9.1.3, contains about 76% glass (by weight), 10% plastic, 8% aluminum (in the frame), 5% silicon and 1% other metals (as wires and connectors). It takes energy to make these components and assemble them, but the amount of embodied energy is small compared with the amount of energy that can be produced by the module. The energy output of a solar module depends significantly on the region and the setting in which it is installed, but a modern well situated solar module should recover its energy costs in approximately one year,[4] and the module should last for at least 25 years. Furthermore, many parts of a solar module are easily recyclable (or re-usable) including the glass and the metal frame. The silicon in the cells can also be melted for re-use. Even though the modules can be recycled, a significant increase in the use of solar-PV energy (which is what we need) will require more mining to supply the raw materials.

Exercise 9.1 Solar Potential

Using Figure 9.1.5 (or Figure 9.1.1 if you live outside of this area), determine the solar energy potential of your region. If you live in a reddish area, the potential is very high (score 3), orange: high (score 2) and yellow: moderately high (score 1).

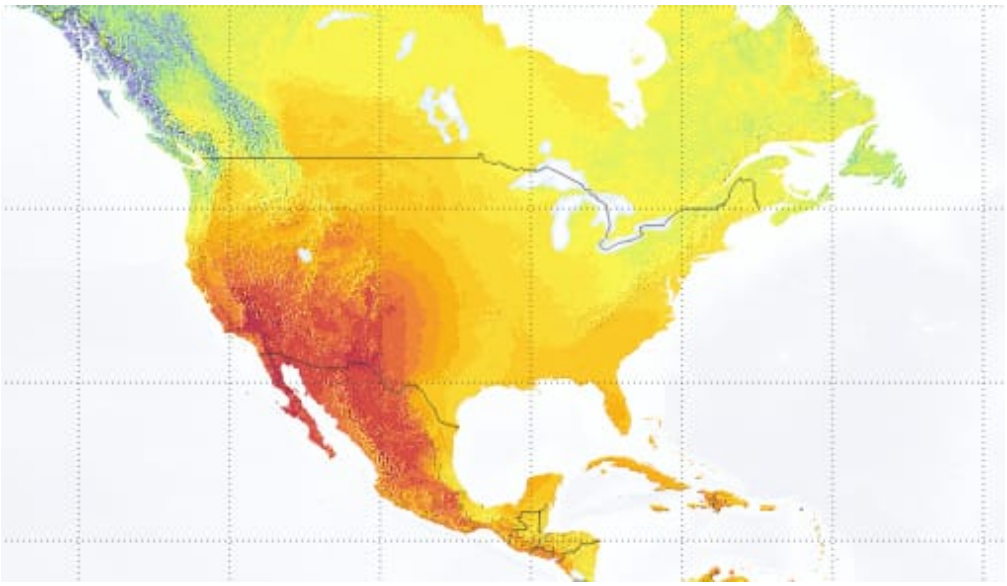


Figure 9.1.5 Global solar energy potential for North America (by The World Bank, 2017, CC BY 4.0, https://commons.wikimedia.org/wiki/F..._Potential.png)

Now think about the potential of the place in which you live (the building, or the piece of land around it). If there are places (on the roof, on the ground, or even on the walls) that get at least 4 hours of direct sun in a day (averaged year-round, and not counting bad weather), then your potential is moderate (score 1), if it's 6 hours/day then it's good (score 2), and if it is at least 8 hours/day then it is very good (score 3).

If the sum of your two scores is 4 or higher, then your place is likely to be viable for solar power, and that means that the cost of installation of solar panels would probably be recovered in about 10 years (or less). Of course, there are many other factors, such as the nature of your building, the cost of electricity, and the willingness of your electric utility to let you tie in to the grid.

Wind Energy

Wind is a product of solar energy and gravity because air masses move in response to differences in air density created by solar heating. Wind energy has been used for centuries to turn windmills and to power sailing vessels, but it's only in the past few decades that wind has been used to generate electricity. As shown on Figure 9.1.5, wind is geographically variable as an energy resource. Average wind speeds are higher on the oceans than on land, and consistently higher in flat areas compared with mountainous areas. In North America the best wind resources are in eastern coast offshore, especially north from Virginia, and in western coast offshore areas, from California north, within the Great Lakes and Hudson Bay, and within the plains in both the US and Canada. Mountain ridges also have consistently strong winds.

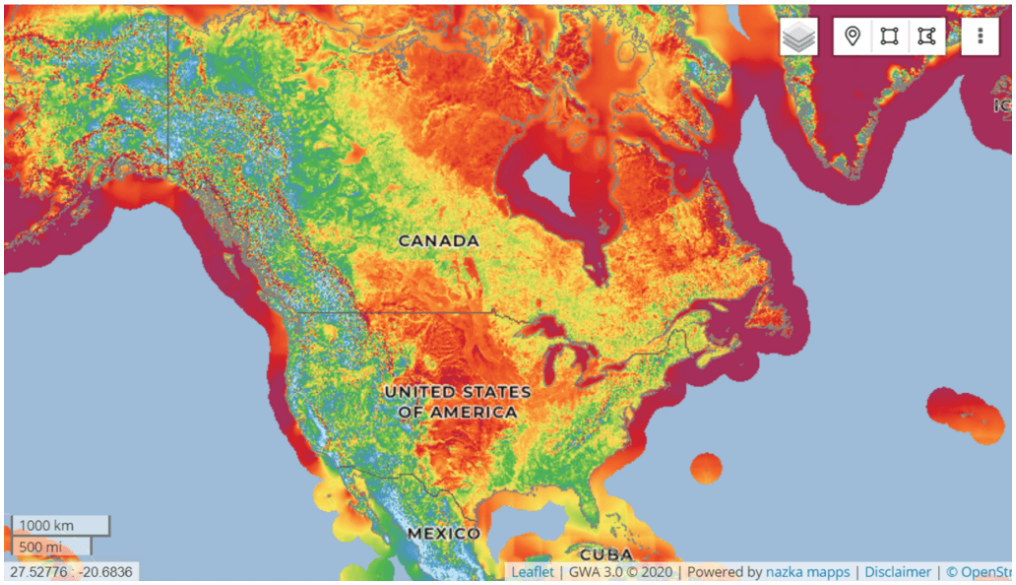


Figure 9.1.6 Typical Wind Speeds at 100 m Elevation Within and Around North America

Most utility-scale wind turbines are of the horizontal axis type, mounted on a tall tower. Over the past 30 years the power potential of wind turbines has increased by a factor of nearly 30 times (Figure 9.1.6) and the towers have become very tall. Of course, a 10 MW wind turbine doesn't generate power at 10 MW all of the time. The typical capacity factors for land-based turbines are in the order of 30%, while offshore turbines are higher, at around 40%. The tall 10 MW and higher turbines being installed in offshore locations in the mid 2020s are likely to have even higher capacity factors because wind consistency increases with elevation. Most existing offshore turbines are embedded in the sea floor in areas with water depths of less than 50 m. Floating turbines have been developed for use in areas with deeper water. A single 10 MW offshore turbine operating at 50% capacity can generate enough electricity to power about 4,000 homes in North America.

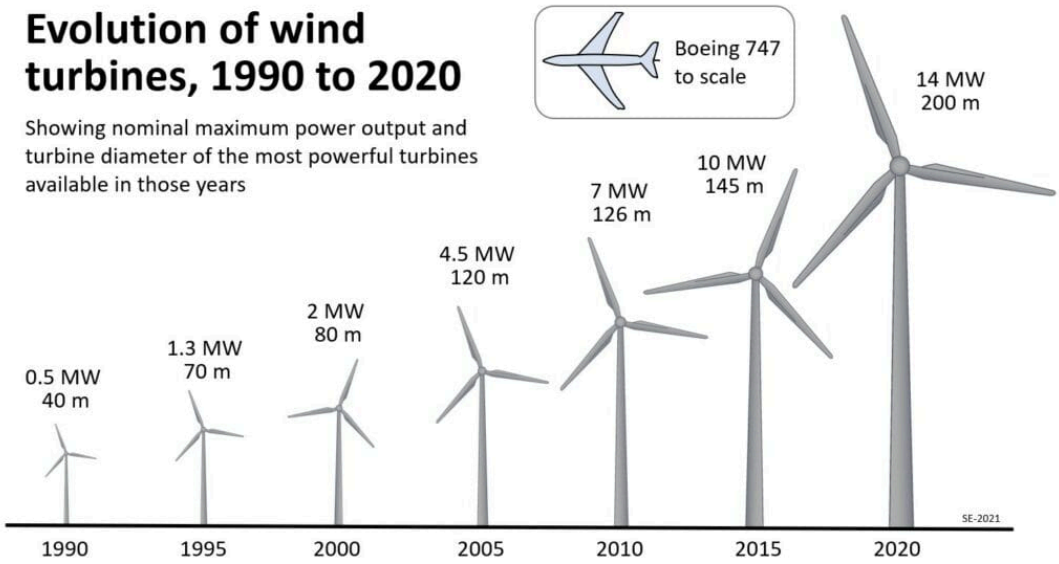


Figure 9.1.7 Highest Rated Wind Turbines Available at Various Times Between 1990 and 2020

According to the International Renewable Energy Agency wind energy makes up about 25% of installed renewable energy. Based on data from 2019, China and the US have the highest installed wind generation capacity, but Denmark has the highest proportion of wind-generated electricity, at 48%, followed by Ireland (33%), Portugal (27%), Germany (26%), the UK (22% – see Figure 9.1.7) and Spain (20%).[5]



Figure 9.1.8 An Offshore Wind Farm Under Construction in the UK in 2011. These turbines are rated at 3.5 MW.

Modern wind turbines are large and complex, and their manufacture and installation require a lot of materials and energy. For example, a typical 3 MW turbine, similar to the ones on Figure 9.1.7, includes about 1100 tonnes of concrete for the base on the sea floor (or on land), 276 tonnes of steel, for the base the tower and the nacelle (the housing that holds the generating mechanism, and to which the blades are attached), 2.6 tonnes of copper and 2.3 tonnes of aluminum, and 20 tonnes of fibreglass and epoxy resin for the blades.[6] As for solar modules, the energy payback of a turbine will depend on the features of the location selected, but it is typically less than one year, compared with an expected lifetime of at least 20 years. Much of this material can be recycled when the turbine is decommissioned.

Every year thousands of birds (and bats) are killed by wind turbines, although the rate of bird-kill is decreasing because the newer larger turbines spin slower than older models, and because a range of strategies are being developed to decrease the risk. To put this in perspective, millions of birds are killed each year by power lines, moving vehicles and tall buildings, and the total number

from all of these sources of mortality is dwarfed by the number killed by domestic cats.

Solar and wind power are currently the cheapest forms of electricity generation according to the US Energy Information Administration. The average levelized cost of solar is $0.30 per kWh, while that for onshore wind is $0.37 per kWh. All other forms of electricity generation are more expensive, including gas, coal, hydro and nuclear.[7] While most other energy forms are likely to become more expensive in coming years, solar and wind are likely to get cheaper because of technological improvements and economies of scale.

Exercise 9.2 Intermittent Wind and Solar Resources



Figure 9.1.9 A Combined Wind Turbine and Solar PV Energy Facility

A combined wind turbine and solar PV energy facility (like the one shown on Figure 9.1.9). has been established to serve an area with about 50,000 homes in southern Alberta It comprises 150,000 solar modules at 600 W each (total capacity 90 MW) and 20 wind turbines at 5 MW each (total capacity 100 MW). The region is often sunny and has good wind resources, but of course there are cloudy days and dark winter days, and there are calm days.

The following table, which is based on the weather conditions for a week in late spring, shows how many hours of strong sunlight equivalent* there are on each day to power the modules at their 600 W capacity, and how many hours of strong wind equivalent are available to power the turbines at their rated 5 MW capacity.

Complete the other rows of the table to work out the average amount of energy produced by each system on each of the 7 days, and the total amount of energy produced. For example, to estimate the daily energy production for the solar array, in MWh, multiple the number of hours of strong sun equivalent by the total capacity of the system (90 MW). For wind, multiply the hours of strong wind equivalent by the total capacity (100 MW). The first column (Monday) is done for you.

Day:	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.
Hours of strong sun	4	10	10	10	8	2	3
Hours of strong wind	17	19	6	2	1	3	14
Daily MWh solar	360						
Daily MWh wind	1700						
Daily total MWh	2060						
No. of homes supplied	76,296						

An average house in North America uses about 10 MWh of electricity per year, which is equivalent to 0.027 MWh per day, so if

you divide the “Daily total MWh” by 0.027 you can estimate the number of homes that can supplied with electricity by this system on each day.

As the facility operator, what do you plan to do with the extra electricity on days when you have a surplus, and to keep your customers supplied with electricity on days when you don’t have enough?

*For example, on a given day there might be 4 hours of strong sunlight, 3 hours of weak morning or evening sunlight, and 6 hours with conditions ranging from partial to complete cloud. These might all add up to 8 hours of “strong sunlight equivalent”.

Exercise answers are provided Appendix 2.

Media Attributions

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7. US Energy Information Administration. (2021). Levelized costs of new generation resources in the *Annual Energy Outlook 2021*. https://www.eia.gov/outlooks/aeo/pdf...generation.pdf ↩

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8.11: Energy and Resources- Hydro

Hydro power is a product of solar energy because water, evaporated by the sun, falls onto land at elevation, and then flows down to the ocean. If we interrupt that flow, we can use its potential energy to generate electricity. Hydro power is particularly effective in areas where there has been tectonic uplift to create mountains, and where there is abundant precipitation in the form or rain or snow.

There are two main types of hydro-electric facilities, those that involve construction of dams, and those that involve diversion of part of the water of a stream into a canal and/or a pipe. We'll refer to the first type as "dam and reservoir hydro", and to the second type as "run-of-river hydro".

Hydro electricity is a very mature industry that goes back to the late 19th century. It currently represents 47% of the installed global renewable energy capacity (and 6.5% of all energy capacity), but the rate of growth in hydro is now very close to 0%. Although there have been many enhancements to hydro energy technology in the past 100 years, it's not likely that we will see significant technological advances in the future, and while there are many rivers that have still hydro potential, the public appetite for changing how rivers flow, just to generate electricity, is waning.

Dam and Reservoir Hydro

Most large hydro projects involve construction of a dam across a river and the creation of a reservoir behind that dam. The difference in elevation between the surface of the reservoir and that of the river below the dam is the hydraulic head, and the amount of energy that can be generated is proportional to that difference and to the rate at which water can flow through the turbines. An example is the Revelstoke Dam on the Columbia River in British Columbia (Figure 9.2.1). The Revelstoke Dam is 175 m high. It has created a reservoir (Lake Revelstoke) that is 130 km long and has flooded just over 100 km^2 of land. The electricity production capacity at Revelstoke Dam is 2,480 MW.

The significant value of a dam and reservoir is that a lot of water is stored (except under long-term drought conditions), and that water can be used to generate electricity according to the demand. The rate of flow through the turbines can be slowed (or even stopped) during the night (or over the summer) when demand is low and increased in the daytime (or during the winter) when the demand is higher. This type of production flexibility is especially valuable in areas where there is a significant proportion of non-dispatchable electricity generation from sources like solar and wind.

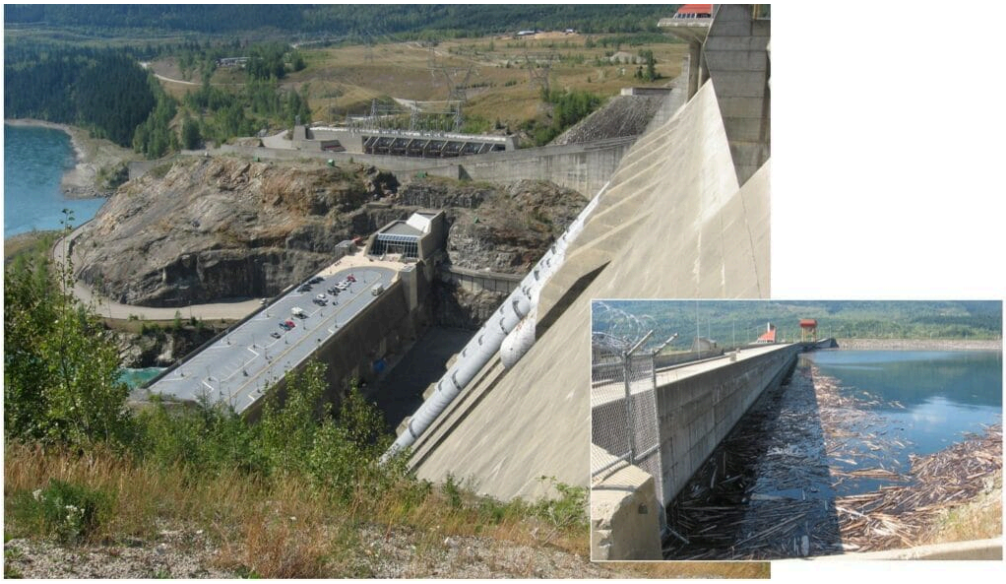


Figure 9.2.1 The Revelstoke Dam on the Columbia River, British Columbia. Water flows through the large pipes (penstocks) to turbines that are within the structure in the centre, and then out into the river below. The inset shows part of the reservoir (Lake Revelstoke) on the upper side of the dam.

Two significant disadvantages of dam and reservoir hydro are that they block passage of migratory fish, and that they result in the flooding of large areas of land that was useful for other purposes or for nature. It's true that fish ladders can be constructed, but they are not typically successful in the case of a high dam like the one at Revelstoke. Flooding of land is inevitable when dams are constructed, and the implications of that include:

- loss of human habitat (e.g., construction of the Three Gorges Dam in China, the world's single largest hydro project, resulted in relocation of 1.24 million residents from 13 cities, 140 towns and 1350 villages),
- loss of farmland (which is a big issue for the Site C dam under construction in British Columbia),
- loss of natural terrestrial and aquatic (river) habitat,
- increased risk of slope failure and bank erosion (see Section 5.2 in relation to the Revelstoke Dam and the Downie Slide),
- potential for release of mercury naturally present in soils[1], and
- potential for release of carbon dioxide from breakdown of organic matter (this is most likely to be an issue in tropical areas and where the reservoir is shallow).

Run-of-River Hydro

A run-of-river hydro installation is illustrated on Figure 9.2.2. Sechelt Creek flows into a coastal inlet about 60 km northwest of Vancouver. The three parts of the project are the head pond, at an elevation of 360 m, where a weir has been built to ensure that the upper end of the penstock is always submerged. Water flows from there through a 4-km long 1.2 m diameter steel pipe (penstock) to the powerhouse, where it is used to turn either one or both of two 8 MW turbine generators. This project did not involve flooding any land (the head pond is entirely within the river's normal channel) and it has not disrupted the passage or habitat of migratory fish. (A waterfall just upstream from the powerhouse has always prevented ocean fish from migrating to the middle and upper parts of Sechelt Creek.)



Figure 9.2.2 Components of a Run of River Hydro Project at Sechelt Creek, British Columbia. Left: the weir and head pond (at 360 m elevation); centre: part of the penstock; right: one of two 8 MW turbines at 10 m elevation.

Water is not stored in a reservoir in the case of run-of-river hydro, instead the generation of electricity is dependent on the discharge of water at any one time. Over the course of a year the discharge of a stream like Sechelt Creek can vary significantly from season to season and even from day to day.

Two examples of river discharge variations are provided on Figure 9.2.3. The Qualicum River is situated in a coastal area of Vancouver Island where although the surrounding mountains are frozen and snow-covered over the winter, the lowland areas tend to remain unfrozen and rain is common. The hydrograph is dominated by rainfall in the fall, winter and early spring months, and very little precipitation from June through later September. The Stikine River drains a region in northern BC in a mountainous area that remains frozen through the winter and there is almost no melting between December and April. The hydrograph is characterized by very low flows during the cold months, and very strong snow-melt and rain-driven flows in the spring, summer and early fall.

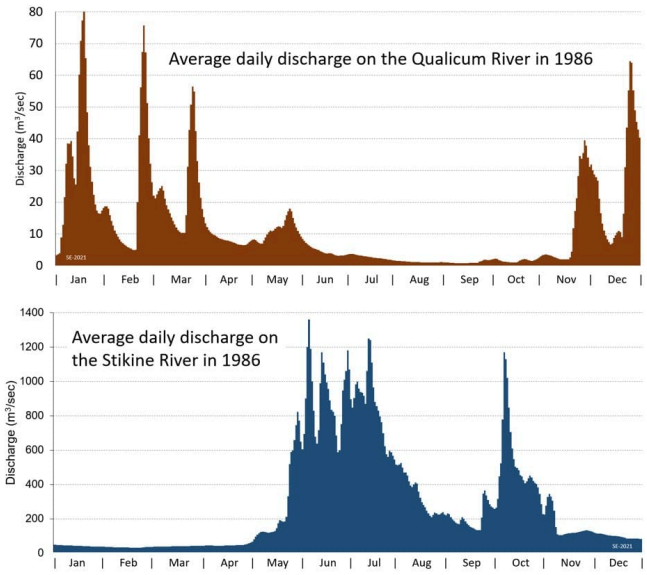


Figure 9.2.3 1986 Variations in Daily Discharge on the Qualicum River (Vancouver Island) and the Stikine River (Northern Interior, BC)

The significant differences in the flow patterns of the Qualicum and Stikine Rivers illustrates the importance of understanding supply and demand when it comes to run-of-river generation. Sechelt Creek has a hydrograph similar to that of the Qualicum River, and so it can typically generate electricity at peak power in the period from November through June, but produces little or no power over the summer months. This fits well with the electrical power demand in British Columbia, which is greatest in winter, but a river like the Stikine would not be very suitable for run-of-river generation in British Columbia because it has relatively little flow in the winter months.

Exercise 9.3 Power and Energy

When you turn on a tap or crank a pump handle the water flows out a certain rate (the flow rate) and if you let it flow for a while you'll have some water in a container (a volume). The electrical equivalents of flow rate and volume are power and energy, and as described in Box 9.1, we can express those as watts and watt hours. This is confusing because we are used to expressing rates using terms like litres/minute, or kilometres/hour, but a watt is already a rate (in fact it is 1 joule/second). To get the amount of energy used or produced we need to multiply the rate by time. A watt-hour (Wh) is a unit of energy, and it the amount used when a 1 W led bulb is on for 1 hour, or how much is produced when a 300 W solar panel is placed in direct sunlight for 12 seconds (1/300th of an hour).

Here are some practice questions to help you get this straight.

1. Which of these amounts might be appropriate to express the amount of energy stored in an electric car battery:
   a) 100 km/h, b) 50 kW, c) 5 kWh, or d) 600 km?
2. Which term might be appropriate to express the capacity of a hydro-electric project:
   a) 500 MW, b) 75 KWh, c) 5000 L/s, or d) 75 kW/h?
3. Which term might be used to describe an LED lightbulb:
   a) 10 Wh, b) 20 W/hour, c) 8 W, or d) 20 lumens/h
4. What would be an appropriate term to express the amount of energy used by an electric bike:
   a) 20 km/h, b) 10 Wh/km, c) 300 W, or d) 50 kWh

Exercise answers are provided Appendix 2.

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1. Small amounts of mercury are naturally present in an oxidized form in soil. When an area is flooded the resulting less-oxidizing conditions at the bottom of the reservoir promote the conversion of some of that mercury to a soluble form which then gets into the water and is dispersed downstream. This mercury has health implications for aquatic species, and also for those who depend on aquatic species (especially fish) as a food source. ↵

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8.12: Energy and Resources- Wave and Tidal Energy

Waves are generated by wind blowing over water, so this form of energy originates from the sun. On the other hand, tides are related to rotation in the sun-Moon-Earth system and from the resulting variations in the gravitational force on Earth. That energy comes from the original angular momentum (spin) of the solar-system and the galaxy, and can possibly be traced right back to the Big Bang.[1]

Wave Energy

The size of waves at any location is a function of the strength of the wind, and also the extent of the body of water over which that wind blows. This factor is known as the “fetch”. The longer the fetch the bigger the waves. Waves tend to be short and steep close to a storm, but longer and shallower far away. Typical large ocean waves have wavelengths in the order of 100 m and amplitudes in the order of a few metres. While waves are driven by the wind, they tend to be somewhat more reliable than the wind as a source of energy. At most exposed coastal locations there will be some wave action, even if there is little or no wind at that time. In general, wave energy is greatest in the areas of greatest wind energy, as shown on Figure 9.1.5.

Several different wave energy devices have been designed and tested over the past several decades. They include shore-based systems, sea-floor tethered systems, and anchored floating systems that bend as waves pass. Some of these are illustrated on Figure 9.3.1. All of them have cylinders that are compressed and then relaxed every time a wave goes by, and the pressure created by that is converted into electricity.

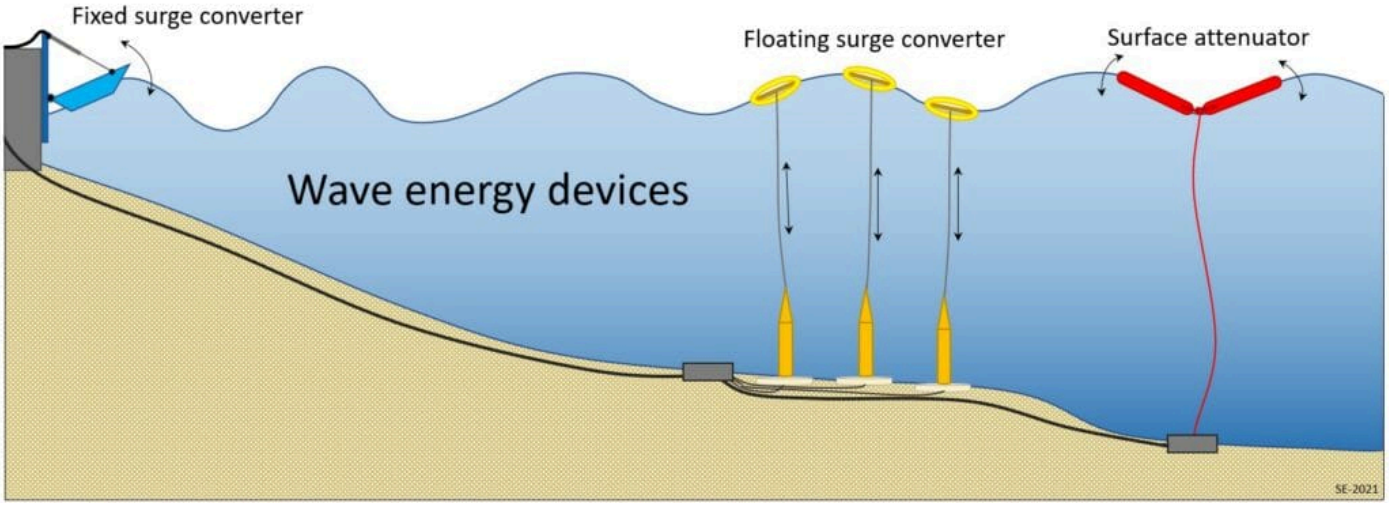


Figure 9.3.1 Three Different Wave Energy Systems

Although all three of these types of systems have been demonstrated in the past, at present (spring 2021) the only operating and grid-connected wave energy installations are of the fixed-surge type, and those are small, with power ratings in the kilowatts, not megawatts.

Tidal Energy

The tides are generated by variations in the geometry of the sun-Earth-Moon system and the effect that those have on the level of the surface of the ocean. In most areas there are two high tides and two low tides every day (known as semidiurnal tides), although a few regions have only one high and one low per day (diurnal tides). The range between high and low tides is highly variable from place to place. The world’s highest tide range are in the order of 16 m difference between low and high tides in the Bay of Fundy between Nova Scotia and New Brunswick. On the other hand, many regions have tidal ranges of less than 1 m. Some examples of differing tidal ranges are shown on Figure 9.3.2.

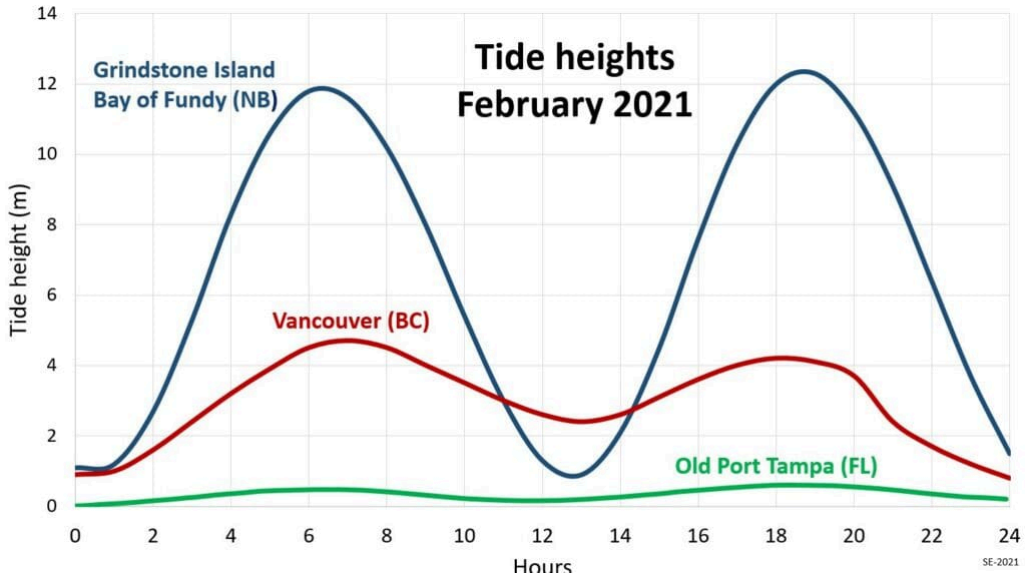


Figure 9.3.2 Typical Tidal Ranges at Three Stations, Old Port Tampa (Florida), Vancouver, British Columbia, and Grindstone Island, New Brunswick, February 2021

There are several ways to convert tidal energy into electrical energy, but the two most commonly explored methods include the construction of a barrage (a dam) across a tidal estuary, and the installation of underwater turbines within channels that have significant tidal flow. The barrage method has been proven to be effective, but it can have serious environmental implications because a barrage results in changes to water-level fluctuations, salinity and turbidity in tidal flat areas, most of which are of great ecological importance. A tidal barrage is shown on Figure 9.3.3. The barrage acts like a dam, and the flow of both incoming and outgoing tides can be converted to electricity using turbines installed within the structure. There are three significant operating barrage tidal installations at present, including Sihwa Lake (South Korea, 254 MW, operating since 2011), La Rance River (France, 240 MW, operating since 1966) and Annapolis Royal (Nova Scotia, 20 MW, operated from to 1984 to 2019). Others have been proposed, but as of 2021, none is under construction.

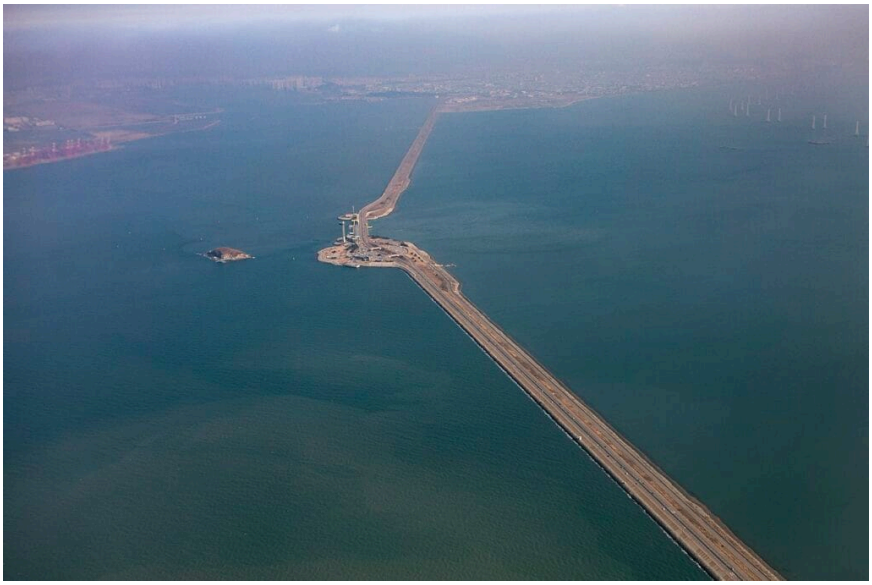


Figure 9.3.3 Part of the Sihwa Lake Tidal Barrage in South Korea, Completed in 2011 and Rated at 254 MW

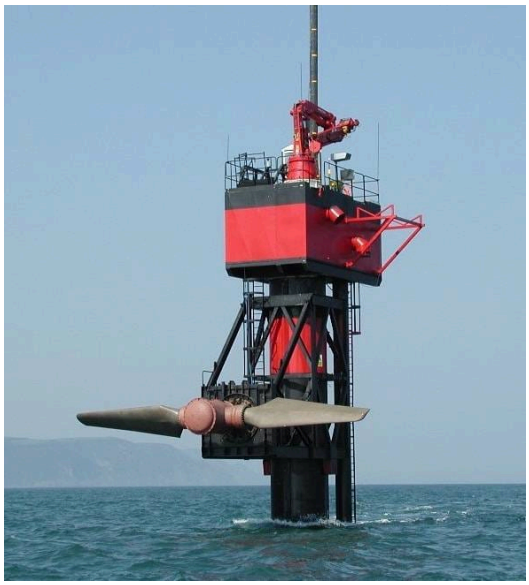


Figure 9.3.4 A Single-Rotor Seaflow Tidal Stream Generator, With the Turbine in the Raised Position

The other main type of tidal system is a tidal stream turbine that is typically installed in a location with strong tidal currents. An example is shown on Figure 9.3.4. Most such devices are either embedded in, or resting on, the sea floor, although some are buoyant and are anchored to the sea floor. Based on information available in 2021, only one tidal stream is currently in operation, and that is the MeyGen project on the north coast of Scotland, which has four 1.5 MW sea-floor turbines connected to the grid, with more turbines reportedly to be under construction.

The potential for tidal energy is huge, but the engineering and environmental challenges are significant, and the high capital cost has been a barrier to implementation of many planned projects.

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1. Commissariat, T. (2011). Was the universe born spinning? Cosmology Research Update. *Physics World*. https://physicsworld.com/a/was-the-u...born-spinning/ ↩

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8.13: Energy and Resources- Geothermal and Geo-Exchange

Geothermal energy is heat that originates within the Earth—which includes heat left over from the original formation of the Earth and heat produced by radioactive decay—and is either naturally present at surface or is accessed at depth by drilling. We can harness this energy where there is higher than average heat flow from depth, and this is most common in areas near to active volcanoes. About 50% of all geothermal energy use is for heating buildings and other infrastructure, about 33% for hot pools and spas (Figure 9.4.1), while only about 17% is used to generate electricity. In many cases the left-over heat from electrical generation facilities is used for district heating or for swimming and bathing facilities.



Figure 9.4.1 The Geothermal Pool at Fludir, Iceland

A geo-exchange system (a.k.a. geothermal heat pump, or ground-source heat pump) is not based on geothermal energy at all. Instead, geo-exchange relies on the relatively constant temperature of the ground at depths between about 1 and 5 m, and that temperature is maintained by energy from the sun. Geo-exchange is used for either heating or cooling, or both.

Geothermal

In the context of generating electricity, geothermal heat is used to boil water or some other fluid to power a turbine. In the case of very hot sources, water piped to surface from depth will spontaneously convert to steam because of the reduction in pressure. If the water from depth is less than about 180° C it won't spontaneously boil but can be used in a binary cycle system to heat a working fluid, such as pentene or toluene, that will boil at a lower temperature than water.

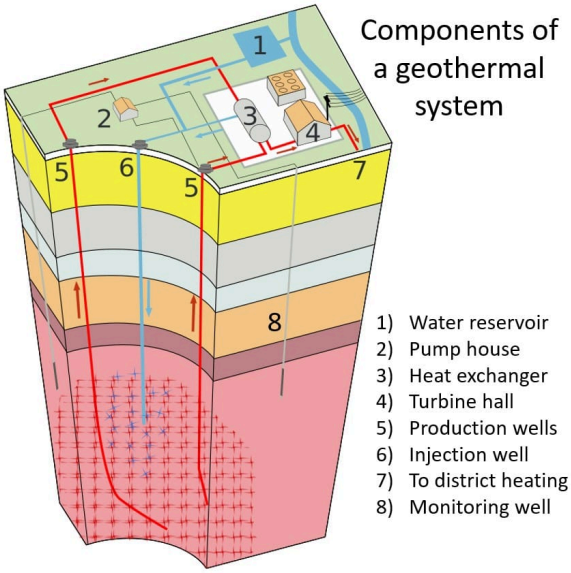


Figure 9.4.2 The Components of a Typical Binary Cycle Geothermal System

The components of a typical geothermal system are illustrated on Figure 9.4.2. The heat at depth (hundreds to a few thousand metres) is accessed via deep production wells. Water from within that rock (5) is pumped to surface and its heat is used to boil the working fluid to power the turbines (4). The original water is returned to the ground via an injection well (6) along with any additional surface water needed to maintain volume (1). Most geothermal plants have numerous production wells (dozens in some cases). It is common for wells to be cycled on and off to allow for recovery of the heat reservoir around them.

The Krafla power station in northern Iceland (Figure 9.4.3) is a 60 MW flash steam system (the hot water from depth boils at surface). It is situated in a very active volcanic region on the mid-Atlantic spreading ridge. An eruption episode that lasted from 1975 to 1984 almost led to cancellation of the project while it was under construction.



Figure 9.4.3 The Krafla Geothermal Plant in Iceland

The contribution of geothermal to total electricity production is important in some countries, especially in Iceland, where 30% of electricity is generated by geothermal (with most of the rest coming from hydro), and also the Philippines, at 27%, and El Salvador at 25%. In Costa Rica, Kenya and Nicaragua and New Zealand geothermal makes up 14, 11, 10 and 10% of electrical energy.[1] These are all countries with active volcanoes and hence significantly high heat flow.

In the past 10 years global geothermal energy capacity has grown by an average of 3.75% per year. That is significant growth, although lower than for wind and solar, both of which have grown by an average of 20% per year in this century. But the potential

for sustained growth is limited by the limited geothermal resource, and by the high capital cost of geothermal facilities.

> Exercise 9.4 Geothermal Origins

As noted above, a significant proportion of the electricity is from geothermal sources in Iceland, Philippines, El Salvador, Costa Rica, Kenya, Nicaragua and New Zealand. Explain how the plate-tectonic situation in these regions contributes to that source of energy.

Country	Plate tectonic explanation for the geothermal energy
Iceland	
Philippines	
El Salvador	
Costa Rica	
Kenya	
Nicaragua	
New Zealand	

Exercise answers are provided Appendix 2.

Geo-Exchange

The first several metres of the ground beneath us represents a reservoir of thermal energy that is maintained by heat from the sun and stays nearly constant year-round. We can take advantage of that thermal reservoir by living in caves or—like Hobbits—digging deep into the sides of hills to build homes. Alternatively, we can stay above ground and install plumbing systems that allow us to tap into that stored warmth and bring it inside. The concept of geo-exchange is illustrated on Figure 9.4.4. An exchange loop can be vertical, with pipes installed in drilled holes, or horizontal, with pipes installed in an excavation at a depth of around 2 m.

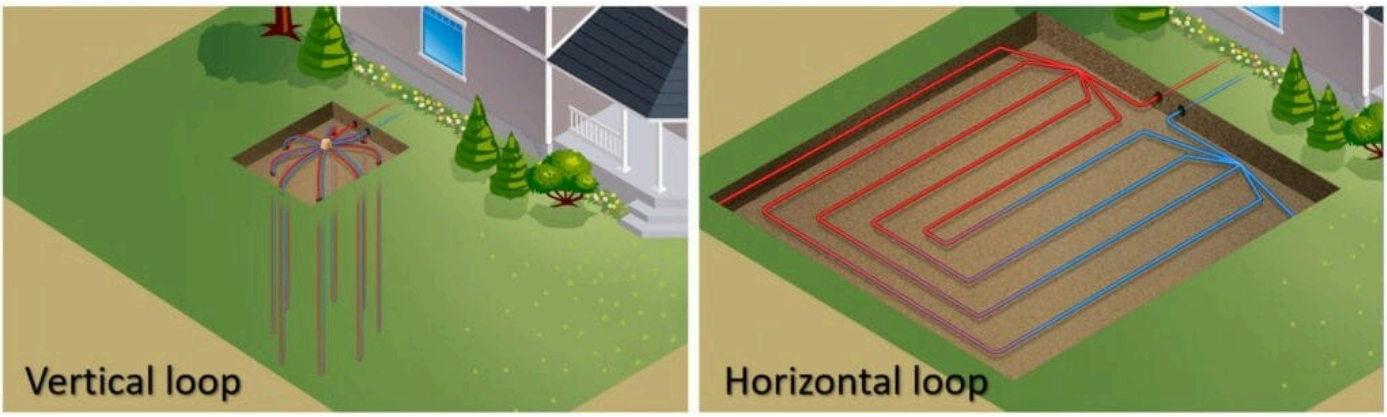


Figure 9.4.4 Conceptual Vertical and Horizontal Geo-Exchange Loops

As shown on Figure 9.4.5, a geo-exchange loop can be used for both heating and cooling. For heating relatively warm fluid is pumped from the ground and then passed through a heat exchanger and/or heat-pump in the building to provide heating. For cooling relatively cool fluid is pumped from the ground and then passed through a heat exchanger for cooling. In fact, the “relatively warm” and “relatively cool” fluid may be approximately the same temperature, but it will be warmer than the outside air in winter, so useful for heating, and cooler than the outside air in summer, so useful for cooling.

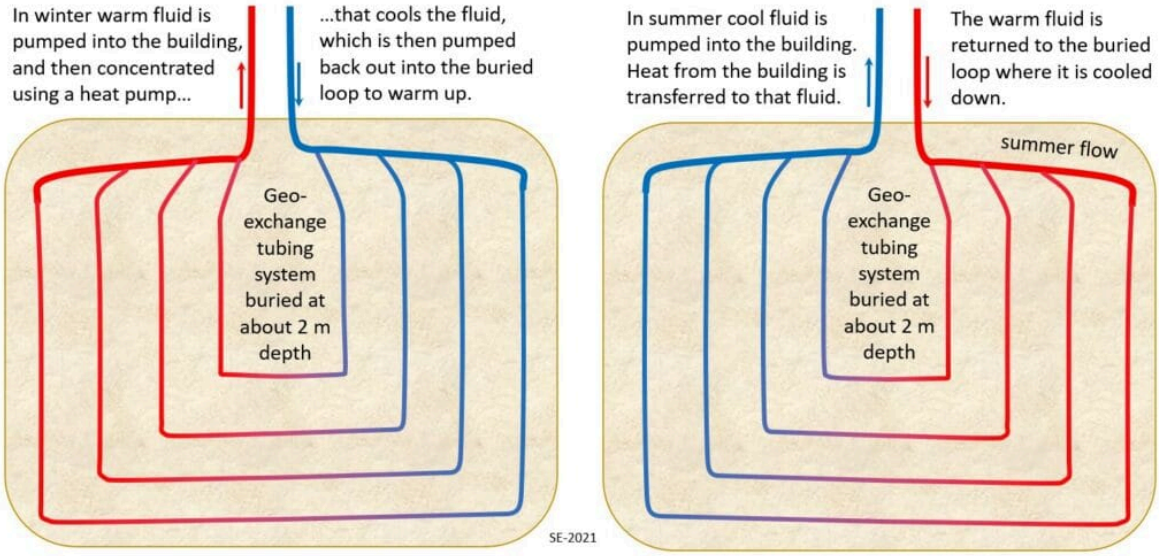


Figure 9.4.5 Use of a Geo-Exchange Loop for Heating and Cooling

Geo-exchange is not a source of energy, but it is a way to provide significant savings in heating and cooling energy costs, both financial and from the perspective of climate change and the environment. According to the Geothermal Exchange Organization, a geo-exchange system can save building owners between 30 and 70% in heating costs and between 25 and 50% in cooling costs.[2] The organization states that there are currently 750,000 geo-exchange systems in place, although it isn't clear about what date or which jurisdiction that number refers to.

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1. International Renewable Energy Agency, https://www.irena.org/ ↩
2. Geothermal Exchange Organization, https://www.geoexchange.org/ ↩

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8.14: Energy and Resources- Our Energy Future

We have some important choices to make in the next few decades because we have no option but to stop using fossil fuels as an energy source very soon, and we have to decide what mix of other energy sources, or other strategies, can be used to fill the gap. Some of our alternatives—wind and solar—are attractive because they are already cost effective, and are becoming more cost effective every year, but they are only available to us when the wind is blowing or the sun is shining. Wave and tidal, are more reliably available, but their development has been slow, even though the potential is significant. Large-scale hydro is attractive because it is readily dispatchable, so can be used to fill the gaps in the wind and solar supply, but there are environmental, social and practical limits to the amount that can be developed. Geothermal is an obvious choice in some regions. Nuclear fission is a reliable source of energy, but it has a bad reputation due to some serious past accidents and because of significant issues with disposal of nuclear waste. Nuclear fusion is still decades away, so is not going to be a candidate to replace fossil-fuels.

It is evident that we need to keep working on all of these options. That includes rapidly expanding solar and wind (and tidal and wave), and then ensuring that we have enough dispatchable energy (e.g., hydro) or continuous energy (e.g., nuclear) to fill the gaps. There are some other strategies that will be important to make it work, as follows.

a. We—especially those of us in North America—can start by using much less energy, and that means driving less and flying less, living in smaller homes that are more energy-efficient, taking advantage of passive solar heating (and shading in hot seasons), and buying much less of the manufactured stuff that we don't need.
b. As shown on Figure 9.6.1, energy demand varies significantly from season to season and also from hour to hour within any day. In warm climates like California the electricity demand is lower in the winter than in the summer (mostly because of air conditioning). It is lowest in the middle of the night (1 am to 6 am) and highest in the evening (6 pm to 10 pm). There is also an afternoon low, but only in winter. In colder climates, where heating is needed through the winter, and where air conditioning is not widely used, the demand is typically higher in the cold part of the year. Electricity providers have to be very nimble to make sure that they can meet the demand at any time, but not generate more than what is needed. In the example shown for northern California, the demand ranges from a low of 7,900 MW on a Saturday afternoon in February, to a high of 15,400 MW on a Monday evening in July. Based only on this limited data, we can see that Pacific Gas and Electric (PG&E) has to be able to produce at least 16,000 MW for this market, but typically needs to produce less than 13,000 MW, and often less than 10,000 MW. If the demand curve could be smoothed out PG&E (and other utilities) could get by with less generating capacity overall and especially less peaking capacity, much of which is currently met with fossil fuel sources. Utilities can lower the peaks by charging more in the evenings (as PG&E does), and electricity users can play an important role by reducing their demand at peak times. For example, they could cook evening meals before 6 pm, or turn the a/c off between 7 and 9 and spend time outdoors on summer evenings, or not charge electric cars until after 10 pm. For most people, these types of changes would not represent a reduction in quality of life, just a change in habits.

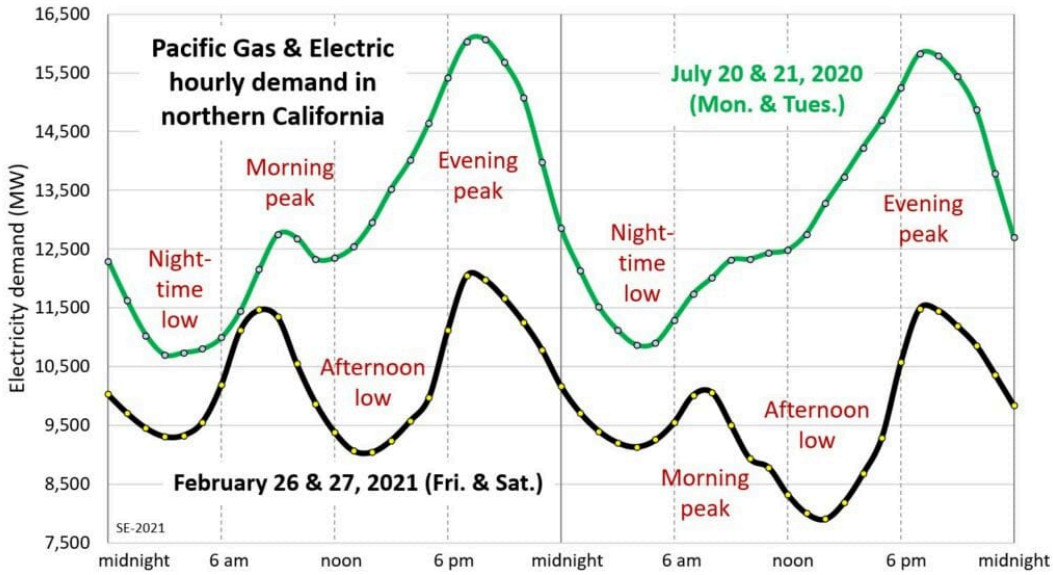


Figure 9.6.1 Electricity Demand for Pacific Gas and Electric Customers on Two Days in July 2020 and Two Days in February 2021

c. Another way to even out demand, and also maximize the benefit of sources such as solar and wind, is to store energy for short periods. An example of this is the Hornsdale wind farm in Southern Australia. When electricity production exceeds demand the energy is stored in a 100 MWh Li-ion battery (the world's largest). That stored energy is used when demand exceeds production. Some of the presently available energy-storage options are listed in Table 9.6.1. It should be noted that these options can provide for storage of energy for a few hours to a few days, and so can help to smooth out daily changes in demand, but that they do not have the capacity for longer-term storage so as to smooth out seasonal changes in demand.While the options in Table 9.6.1 are described as "utility-scale", lithium-ion batteries can be used for household-scale energy storage to help individuals avoid peak-time electricity rates, and even smooth the curve a little. The Tesla Powerwall has software that allows the user to store energy during low-tariff periods and discharge energy during high-tariff periods, and therefore provides an opportunity to save money and help reduce utility peaks.

Table 9.6.1 Utility-scale energy storage options
Data from the Environmental and Energy Study Institute (EESI)

Type of Storage	Efficiency	Lifetime or Number of Cycles	Limitations
Pumped hydro	70-85%	Many decades	Topography and land needed
Compressed air	40-70%	A few decades	Low efficiency
Molten salt	80-90%	A few decades	Heat source needed
Li-ion battery	85-95%	1,000-10,000 cycles	Expensive at present, limited cycles
Flow battery	60-85%	12,000-14,000 cycles	
Hydrogen	25-45%	A few decades	Low efficiency

d. Another way to smooth peaks in electricity demand and in supply is to share electricity over wide areas. This way, for example, solar electricity produced in the afternoon in western and central North America could be used to help supply the peak evening demands of eastern North America. This type of sharing would involve the construction of super grids with efficient high voltage direct current transmission (which suffer energy losses of less than 2% per 1000 km). One example of this type of connection is the Québec–New England transmission line which has a capacity of 2250 MW and brings hydro power from northern Québec to the eastern USA. Another is the Pacific DC Intertie that brings 3100 MW of power from the Pacific Northwest to southern California.

Exercise 9.5 Energy Sources by Region

Use the internet to find out what sources of energy are currently used in your province, state or country. (Try searching with something like: "energy sources Latvia", for example.)

1. How dependent is your region on fossil fuels, and can you find out what steps are being taken to reduce that dependence?
2. In most such searches you may only be able to find information on the sources of energy for production of electricity. What are the other major uses of energy in your region?
3. What important steps could you take to reduce your personal GHG emissions?

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INDEX

A

annotation:hypothesis
- 3.8: Ocean Circulation
- 4.3: Atmospheric Circulation
- 6.6: What Makes the Climate Change?
- 6.7: Prehistoric Climate Change and Proxys for Studying Past Climates
- 6.8: Anthropogenic Climate Change
- 6.9: Implications of Climate Change

atmosophere
- 6.4: Weather vs Climate

autonumheader:yes1
- 1.10: Understanding Science- What is it?
- 1.11: Understanding Science- The Scientific Method
- 1.13: Understanding Science- Early Scientific Thought
- 1.14: Understanding Science- Foundations of Earth Science
- 1.15: Understanding Science- Denial and Evaluating Sources
- 1.9: Understanding Science
- 3.26: Surface Water
- 3.27: Groundwater

B

biosphere
- 6.4: Weather vs Climate

C

carbon cycle
- 6.5: Earth's Heat Budget and the Greenhouse Effect

climate
- 6.4: Weather vs Climate

Climate sensitivity
- 6.5: Earth's Heat Budget and the Greenhouse Effect

climate system
- 6.4: Weather vs Climate

cloud feedback
- 6.5: Earth's Heat Budget and the Greenhouse Effect

D

diurnal tide
- 3.25: Tide Classification

E

Energy balance models
- 6.5: Earth's Heat Budget and the Greenhouse Effect

extreme events
- 6.4: Weather vs Climate

F

feedback
- 6.5: Earth's Heat Budget and the Greenhouse Effect

firn
- 3.30: Glacier Formation and Movement

forcings
- 6.5: Earth's Heat Budget and the Greenhouse Effect

G

glaciation
- 3.33: Ice Age Glaciations

greenhouse effect
- 6.5: Earth's Heat Budget and the Greenhouse Effect

greenhouse gases
- 6.5: Earth's Heat Budget and the Greenhouse Effect

H

hydrologic cycle
- 3.4: The Hydrologic Cycle

I

ice ages
- 3.33: Ice Age Glaciations

interglacials
- 6.7: Prehistoric Climate Change and Proxys for Studying Past Climates

IR emission
- 6.5: Earth's Heat Budget and the Greenhouse Effect

L

lapse rate feedback
- 6.5: Earth's Heat Budget and the Greenhouse Effect

lithosphere
- 6.4: Weather vs Climate

M

Milankovitch cycles
- 3.33: Ice Age Glaciations

Mixed semidiurnal tides
- 3.25: Tide Classification

O

ocean
- 6.4: Weather vs Climate

Online Consortium of Oklahoma
- 5.2: Weather Processes and Systems

P

Planck feedback
- 6.5: Earth's Heat Budget and the Greenhouse Effect

precession
- 3.33: Ice Age Glaciations

R

radiative feedback
- 6.5: Earth's Heat Budget and the Greenhouse Effect

S

science
- 1.10: Understanding Science- What is it?

scientific method
- 1.11: Understanding Science- The Scientific Method

semidiurnal tide
- 3.25: Tide Classification

Snowball Earth hypothesis
- 6.7: Prehistoric Climate Change and Proxys for Studying Past Climates

solar irradiance
- 6.5: Earth's Heat Budget and the Greenhouse Effect

solar radiation
- 6.4: Weather vs Climate

Solar spectrum
- 6.5: Earth's Heat Budget and the Greenhouse Effect

T

tidal currents
- 3.25: Tide Classification

V

Vibrational modes
- 6.5: Earth's Heat Budget and the Greenhouse Effect

W

water cycle
- 3.4: The Hydrologic Cycle

weather
- 6.4: Weather vs Climate

Wilson Cycle
- 2.9: Plate Tectonics- The Wilson Cycle

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    - 2.1: Introduction to Geosphere and Objectives - *Undeclared*
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- 3.6: Review and Additional Resources - *CC BY-SA 4.0*
- 3.7: Overview of the Oceans - *CC BY 4.0*
- 3.8: Ocean Circulation - *CC BY-NC-SA 4.0*
- 3.9: Waves - *CC BY 4.0*
- 3.10: Wave Basics - *CC BY 4.0*
- 3.11: Waves at Sea - *CC BY 4.0*
- 3.12: Waves on the Shore - *CC BY 4.0*
- 3.13: Tsunamis - *CC BY 4.0*
- 3.14: Coastal Oceanography - *CC BY 4.0*
- 3.15: Beaches - *CC BY 4.0*
- 3.16: Longshore Transport - *CC BY 4.0*
- 3.17: Landforms of Coastal Erosion - *CC BY 4.0*
- 3.18: Landforms of Coastal Deposition - *CC BY 4.0*
- 3.19: Human Interference with Shorelines - *CC BY 4.0*
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- 4.2: Atmosphere- Composition and Properties - *Undeclared*
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- 6.3: The Sun and the Earth-Moon System - *Undeclared*
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    - Table of Contents - *Undeclared*
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    - Book Introduction - *Undeclared*
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    - 2.1: Introduction to Geosphere and Objectives - *Undeclared*
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    - 2.15: Measuring Geological Time- Fossils and Evolution- Dating Rocks Using Fossils - *CC BY 4.0*
    - 2.16: Measuring Geological Time- Isotopic

Dating Methods - *CC BY 4.0*
- 2.17: Measuring Geological Time- Other Dating Methods - *CC BY 4.0*
- 2.18: Measuring Geological Time- Understanding Geological Time - *CC BY 4.0*
- 2.19: Measuring Geological Time- Summary - *CC BY 4.0*

◦ 3: The Hydrosphere - *Undeclared*
- 3.1: Introduction to the Hydrosphere and Objectives - *Undeclared*
- 3.2: Distribution of Earth's Water - *Undeclared*
- 3.3: Properties of Water - *CC BY 4.0*
- 3.4: The Hydrologic Cycle - *CC BY-SA 4.0*
- 3.5: Water Resources and Climate Change - *CC BY-SA 4.0*
- 3.6: Review and Additional Resources - *CC BY-SA 4.0*
- 3.7: Overview of the Oceans - *CC BY 4.0*
- 3.8: Ocean Circulation - *CC BY-NC-SA 4.0*
- 3.9: Waves - *CC BY 4.0*
- 3.10: Wave Basics - *CC BY 4.0*
- 3.11: Waves at Sea - *CC BY 4.0*
- 3.12: Waves on the Shore - *CC BY 4.0*
- 3.13: Tsunamis - *CC BY 4.0*
- 3.14: Coastal Oceanography - *CC BY 4.0*
- 3.15: Beaches - *CC BY 4.0*
- 3.16: Longshore Transport - *CC BY 4.0*
- 3.17: Landforms of Coastal Erosion - *CC BY 4.0*
- 3.18: Landforms of Coastal Deposition - *CC BY 4.0*
- 3.19: Human Interference with Shorelines - *CC BY 4.0*
- 3.20: Estuaries - *CC BY 4.0*
- 3.21: Sea Level Change - *CC BY 4.0*
- 3.22: Tides - *CC BY 4.0*
- 3.23: Tidal Forces - *CC BY 4.0*
- 3.24: Dynamic Theory of Tides - *CC BY 4.0*
- 3.25: Tide Classification - *CC BY 4.0*
- 3.26: Surface Water - *CC BY-NC-SA 4.0*
- 3.27: Groundwater - *CC BY-NC-SA 4.0*
- 3.28: Prelude to Galciers - *Undeclared*
- 3.29: Types of Glaciers - *CC BY-NC-SA 4.0*
- 3.30: Glacier Formation and Movement - *CC BY-NC-SA 4.0*
- 3.31: Glacial Budget - *CC BY-NC-SA 4.0*
- 3.32: Glacial Landforms - *CC BY-NC-SA 4.0*
- 3.33: Ice Age Glaciations - *CC BY-NC-SA 4.0*
- 3.34: Anthropogenic Effects on Water Quality - *CC BY-NC-SA 4.0*

◦ 4: The Atmosphere - *Undeclared*
- 4.1: Introduction to the Atmosphere and Objectives - *Undeclared*
- 4.2: Atmosphere- Composition and Properties - *Undeclared*
- 4.3: Atmospheric Circulation - *CC BY-NC-SA 4.0*
- 4.4: Atmospheric Pollution - *CC BY-NC 4.0*

◦ 5: Weather - *Undeclared*
- 5.1: Introduction to Weather and Objectives - *Undeclared*
- 5.2: Weather Processes and Systems - *CC BY-SA 4.0*
- 5.3: Extreme Weather Events - *CC BY-NC-SA 4.0*
- 5.4: Collecting Weather Data and Forecasting Weather - *Undeclared*

◦ 6: Climate and Climate Change - *Undeclared*
- 6.1: Introduction to Climate Change and Objectives - *Undeclared*
- 6.2: The Sun – Earth Relationship and the Seasons - *Undeclared*
- 6.3: The Sun and the Earth-Moon System - *Undeclared*
- 6.4: Weather vs Climate - *CC BY-NC-SA 4.0*
- 6.5: Earth's Heat Budget and the Greenhouse Effect - *CC BY-NC-SA 4.0*
- 6.6: What Makes the Climate Change? - *CC BY-NC-SA 4.0*
- 6.7: Prehistoric Climate Change and Proxys for Studying Past Climates - *CC BY-NC-SA 4.0*
- 6.8: Anthropogenic Climate Change - *CC BY-NC-SA 4.0*
- 6.9: Implications of Climate Change - *CC BY-NC-SA 4.0*

◦ 7: Universe and Solar System - *CC BY-NC-SA 4.0*
- 7.1: Introduction to the Universe and Objectives - *Undeclared*
- 7.2: The Universe - *CC BY-NC-SA 4.0*
- 7.3: Galaxies and Stars - *CC BY-NC-SA 4.0*
- 7.4: The Solar System - *CC BY-NC-SA 4.0*
- 7.5: The Sun - *CC BY-NC-SA 4.0*
- 7.6: Terrestrial Planets - *CC BY-NC-SA 4.0*
- 7.7: Gas Giants - *CC BY-NC-SA 4.0*
- 7.8: Other Objects in the Solar System - *CC BY-NC-SA 4.0*
- 7.9: Attributions and References - *CC BY-NC-SA 4.0*

◦ 8: Resources and Energy - *Undeclared*
- 8.1: Energy and Resources- Why It Matters- Geological Resources - *CC BY 4.0*
- 8.2: Energy and Resources- Ecosystems and Humans - *CC BY-NC 4.0*
- 8.3: Energy and Resources- Metal Deposits - *CC BY-NC-SA 4.0*
- 8.4: Energy and Resources- Mining and Ore Processing - *CC BY-NC-SA 4.0*
- 8.5: Energy and Resources- Industrial Minerals - *CC BY-NC-SA 4.0*
- 8.6: Energy and Resources- Reading- Effects of Mining - *CC BY 4.0*
- 8.7: Energy and Resources- The Implications of Resource Extraction for the Climate and Earth Systems - *CC BY-NC-SA 4.0*
- 8.8: Energy and Resources- Fossil Fuels - *CC BY-NC-SA 4.0*
- 8.9: Energy and Resources- Nuclear Energy - *CC*

BY-NC-SA 4.0
- 8.10: Energy and Resources- Solar and Wind - *CC BY-NC-SA 4.0*
- 8.11: Energy and Resources- Hydro - *CC BY-NC-SA 4.0*
- 8.12: Energy and Resources- Wave and Tidal Energy - *CC BY-NC-SA 4.0*
- 8.13: Energy and Resources- Geothermal and Geo-Exchange - *CC BY-NC-SA 4.0*
- 8.14: Energy and Resources- Our Energy Future - *CC BY-NC-SA 4.0*

◦ Back Matter - *Undeclared*
- Index - *Undeclared*
- Glossary - *Undeclared*
- Detailed Licensing - *Undeclared*
- Detailed Licensing - *Undeclared*

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