Investigations in Climate Change

Neel Desai and Alicia Mullens

De Anza College

Geosciences

CC BY 4.0



Investigations in Climate Change

Neel Desai and Alicia Mullens

De Anza College

This text is disseminated via the Open Education Resource (OER) LibreTexts Project (https://LibreTexts.org) and like the thousands of other texts available within this powerful platform, it is freely available for reading, printing, and "consuming."

The LibreTexts mission is to bring together students, faculty, and scholars in a collaborative effort to provide an accessible, and comprehensive platform that empowers our community to develop, curate, adapt, and adopt openly licensed resources and technologies; through these efforts we can reduce the financial burden borne from traditional educational resource costs, ensuring education is more accessible for students and communities worldwide.

Most, but not all, pages in the library have licenses that may allow individuals to make changes, save, and print this book. Carefully consult the applicable license(s) before pursuing such effects. Instructors can adopt existing LibreTexts texts or Remix them to quickly build course-specific resources to meet the needs of their students. Unlike traditional textbooks, LibreTexts' web based origins allow powerful integration of advanced features and new technologies to support learning.



LibreTexts is the adaptable, user-friendly non-profit open education resource platform that educators trust for creating, customizing, and sharing accessible, interactive textbooks, adaptive homework, and ancillary materials. We collaborate with individuals and organizations to champion open education initiatives, support institutional publishing programs, drive curriculum development projects, and more.

The LibreTexts libraries are Powered by NICE CXone Expert and were supported by the Department of Education Open Textbook Pilot Project, the California Education Learning Lab, the UC Davis Office of the Provost, the UC Davis Library, the California State University Affordable Learning Solutions Program, and Merlot. This material is based upon work supported by the National Science Foundation under Grant No. 1246120, 1525057, and 1413739.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation nor the US Department of Education.

Have questions or comments? For information about adoptions or adaptions contact info@LibreTexts.org or visit our main website at https://LibreTexts.org.

The LibreTexts name, logo, and book covers are trademarked by LibreTexts, Inc. (a 501(c)(3) not-for-profit organization) and protected against unauthorized use.

This text was compiled on 09/04/2026

Program Page

De Anza College sits in the heart of Silicon Valley, where innovation and opportunity are part of daily life, and also has one of the highest costs of living in the country. For our students, that makes every dollar count, and the price of a textbook can be the difference between staying enrolled or dropping a class. Our Zero Textbook Cost (ZTC) program closes that gap by giving students full access to high-quality, faculty-created course materials at no cost from the first day of class.

De Anza is proud of its diverse student community, and we hold our ZTC materials to the same standard of excellence that defines the college. Faculty across departments write, adapt, and review these resources themselves, keeping them accurate, current, and grounded in the perspectives of the students who use them, with accessibility and inclusive design built in from the start.

This program reflects the time and care our faculty invest in their students. If you have questions, feedback, or come across any issues with a ZTC resource, contact De Anza College's ZTC Grants Coordinator, Shagun Kaur.

Learn more about De Anza ZTC Program [www.deanza.edu/academic-services/oer/]

Note: The De Anza logo is a copyrighted trademark of De Anza College and may not be reproduced without permission.

This page titled Program Page is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

TABLE OF CONTENTS

Program Page

Licensing

Accessibility Statement

About the Lab Manual

About the Authors

1: Orientation Lab

1.1: Lab Procedures

1.2: Maps and Geography

1.3: Longitude and Latitude

1.4: Global Warming vs. Climate Change

1.5: Accessible Descriptions

2: Defining Earth's Climate

2.1: Factors affecting the Climate

2.2: Climate Zones

2.3: Precipitation

2.4: Accessible Descriptions

3: Records of Climate History

3.1: Climate Data

3.2: Local Climate Data

3.3: Annual Climate

4: Heat and the Greenhouse Effect

4.1: Heat Transfer

4.2: Radiation

4.3: Selective Absorbers and Greenhouse Gases

4.4: Atmospheric Carbon Dioxide measurements

4.5: The Greenhouse Effect

4.6: Accessible Descriptions

5: Earth's Energy Budget

5.1: Energy Balance

5.2: Global Energy Balance

5.3: Energy Budget and Climate Change

5.4: Other factors affecting Earth’s Energy Budget

5.5: Accessible Descriptions

6: Water and the Climate

6.1: The Water Cycle

6.2: Ocean-Atmosphere Interaction
6.3: Accessible Descriptions

7: The Carbon Cycle

7.1: Components of the Carbon Cycle
7.2: Ocean Acidification and Short Term Carbon Cycle
7.3: Long Term Carbon Cycle
7.4: Accessible Descriptions

8: Global Circulation and El Niño

8.1: Why the wind blows
8.2: Other forces acting on the wind
8.3: Atmospheric Circulation
8.4: El Niño-Southern Oscillation
8.5: Accessible Descriptions

9: Predicting the Future

9.1: Analog Forecasting
9.2: Emissions Scenarios
9.3: Accessible Descriptions

Index

Glossary

Detailed Licensing

This page titled Investigations in Climate Change is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

Licensing

A detailed breakdown of this resource's licensing can be found in ***Back Matter/Detailed Licensing***.

This page titled Licensing is shared under a Public Domain license and was authored, remixed, and/or curated by LibreTexts.

Accessibility Statement

Accessibility

De Anza College is dedicated to creating learning materials that are accessible and benefit all students. Our materials follow the Web Content Accessibility Guidelines (WCAG) 2.1 Level AA. Our authors and contracted accessibility specialists checked all resources using this ASCCC OERI checklist, the accessibility tool in LibreTexts, WAVE, JAWS, and other more detailed checks for complex materials such as interactive components.

We selected LibreTexts as our preferred platform because of its commitment to accessibility. In addition to the platform's inherent accessibility, we collaborated with the LibreTexts team to fix any accessibility issues we found.

Our Accessibility Review Process

Accessibility was built into the resource as it was written. This resource went through the following stages of review:

1. **Template check.** The project coordinator and instructional designers checked the first chapter for accessibility as a model to ensure later chapters meet accessibility standards.
2. **Progress checks.** The manuscript was checked at approximately 40%, 60%, and 80% completion to catch and correct accessibility issues in production.
3. **Specialist review.** Once the manuscript was complete, an accessibility expert conducted an accessibility check.
4. **Remediation.** The author and the project manager who conducted the earlier progress checks worked together to remediate the issues identified by the accessibility expert.
5. **Final check.** The resource underwent another full check by the accessibility expert before the book was deemed ready for publication.

This process combines ongoing checks during writing with a final specialist review, so issues are caught early and confirmed fixed before publication.

Report an Accessibility Problem

We are always looking for ways to make our resources more accessible. If you run into a barrier while using this resource, please let us know so we can look into it. When you contact us, it helps to include:

- The name of the resource
- The location of the problem (a web address or page/chapter description)
- A description of the problem you encountered
- The device, browser, and any assistive technology you were using (e.g., Windows 11, Google Chrome, JAWS screen reader)

Contact us: De Anza ZTC team

This statement was last updated August 2026

This resource was project-managed by **Shagun Kaur**, overseeing scope, budget, and schedule; stakeholder coordination via monthly meetings; training and platform support (LibreTexts, troubleshooting, technical support); QA/accessibility check scheduling; and licensing and copyright governance.

A Note on Known Limitations

No accessibility check is perfect. We've made a genuine, sustained effort to catch and fix issues throughout the writing and review process described above, but some barriers may remain, especially in complex or interactive content. We'd rather be upfront about that than claim a standard of perfection we can't guarantee.

This page titled Accessibility Statement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by LibreTexts.

About the Lab Manual

How to Use This Book

This **Meteorology Laboratory Manual** is part of the **De Anza College Zero Textbook Cost (ZTC) Pathways** initiative, supporting both students and instructors with free, adaptable Open Educational Resources (OER).

We're all concerned about Climate Change and how it will affect our future lives. This laboratory manual provides a brief introduction to some of the principles and observations from an introductory climate change course. The authors of this textbook realized during their college days that learning is easier and more fun when it is hands-on rather than just in a classroom. Thus, this manual was designed to provide students with hands-on experience with climate principles and concepts, as well as historical climate data. This lab manual, along with all the included activities, is designed to be completely stand-alone and can be completed remotely, even outside of a traditional classroom setting. In this manual, you will examine a variety of climate data resources, both provided for you and retrieved independently. The goal is to provide you with an overview of the various tools available to investigate climate change for yourselves.

Each Investigation should take about 2-3 hours to complete, which is common for a traditional one-unit introductory Meteorology laboratory course. While we attempt to explain every concept and procedure in depth, we strongly recommend supplementing this material with small demonstrations and mini-lectures. Questions are presented in multiple-choice and short-answer formats to allow maximum flexibility in modality. Each investigation consists of a combination of multiple-choice and brief problem-solving/plotting/analysis questions. We've designed each component to equate to 25 points, but please feel free to adjust the scale to meet the needs of your course.

Acknowledgments

The authors would like to thank their respective spouses for their infinite patience and support during the writing of this manual. A special thanks also to the ZTC coordinators and the OER team at De Anza College for their guidance during the publication process.

This page titled About the Lab Manual is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

About the Authors

Information about the authors

Author Images	Author Bios
	**Alicia Mullens** is a Meteorology instructor at De Anza College in Cupertino, CA, and at San Jose State University, in San Jose, CA, where she has lived and worked since 2017. Growing up, Alicia always showed a deep interest in weather, oftentimes dropping anything she was doing to watch the local weather report, or running outside anytime stormy weather was in the area. Parallel to that passion about weather was her passion to tell everyone she knew about it, which led many people to tell her that she should become a teacher someday. During graduate school, she had opportunities to apply her knowledge of the atmosphere to many activities, but she found teaching about it to be her favorite activity. After graduation, she found numerous opportunities to teach various earth sciences, but was thrilled in 2017 to join De Anza as their new Meteorology professor. She holds a Master's degree in Meteorology from San Jose State University, along with a Bachelor of Science in Mathematics and a Bachelor of Arts in Geography from California State University, Long Beach. In her spare time, Alicia loves participating in LGBTQ+ activism, train travel, homebrewing, and spending time with her lovely partner, Jamie.
	**Neel Desai** is a Meteorology instructor at De Anza College in Cupertino, CA, and at San Jose State University in San Jose, CA. He is passionate about Meteorology and Climate Science, and strives to provide an enjoyable in-class learning experience for his students. He believes in a visual and hands-on approach to learning, incorporating multiple videos/in-class activities to keep students engaged. He has experience teaching students at multiple levels, including high school-to-university bridge programs at the University of Michigan, community college at De Anza, and the university level, including graduate students at SJSU. Neel received his Bachelor's degree in Mechanical Engineering from the University of Mumbai, India, a Master's degree in Aerospace Engineering from the University of Michigan, Ann Arbor, and a doctorate in Atmospheric Sciences from Michigan Technological University in Houghton, MI. His research interests include cloud physics, turbulence, and remote sensing. Outside of teaching and research, Neel enjoys traveling, hiking, and reading sci-fi novels.

This page titled About the Authors is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

1: ORIENTATION LAB

Introduction

Welcome to the Climate Change Lab! Throughout this course, we will use numerous resources from the American Meteorological Society (AMS), the National Weather Service (NWS), the National Center for Atmospheric Research (NCAR), and other agencies to work through the investigations in this lab manual. The questions in each of these investigations are mostly multiple-choice, with a few short written questions. The questions will be based on numerical data similar to Figure 1.1, which shows the famous Keeling curve.

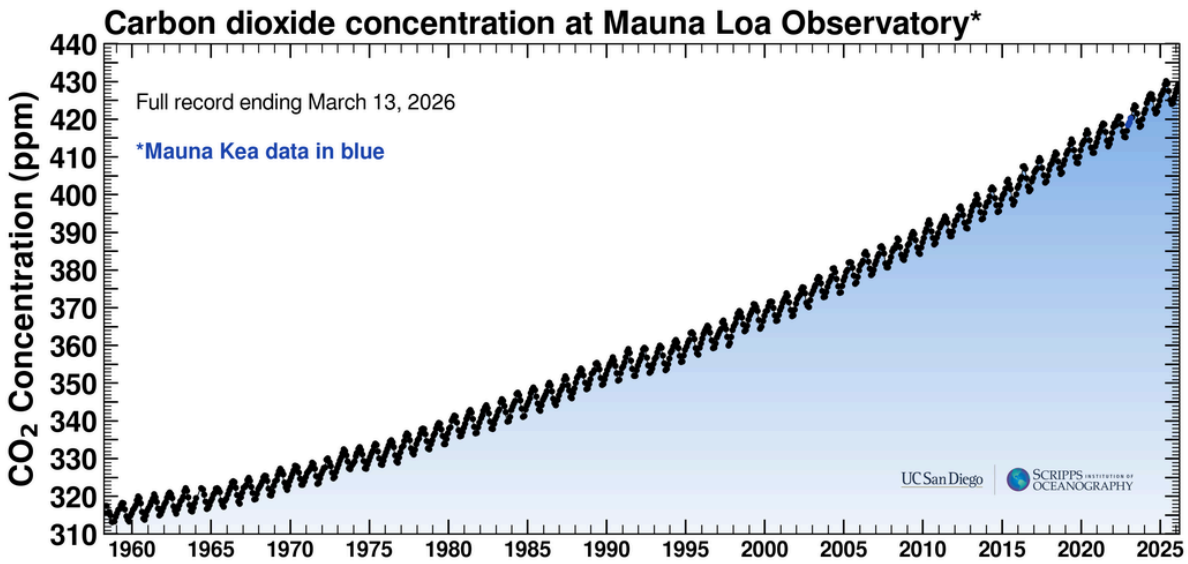


Figure 1.1: The world-famous "Keeling Curve" showing an increase in Carbon Dioxide concentrations measured at Mauna Loa Observatory from approximately 315 parts per million (ppm) in 1958 to nearly 430 ppm in 2026. While carbon dioxide concentrations have increased steadily since 1958, the curve also shows a jagged up-and-down pattern caused by seasonal changes in photosynthesis. (CC BY 4.0; Ralph Keeling via Scripps Institute of Oceanography)

In this introductory investigation, we'll define some basic standards, statistical measures, and tools that will make your life easier as you go through this course.

Learning Objectives

- Learn the basic procedures for submitting lab coursework as outlined by your instructor.
- Interpret global climate maps.
- Distinguish Global Warming from Climate Change.

Navigational Note

Investigation 0 has 21 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

1.1: Lab Procedures
1.2: Maps and Geography

1.3: Longitude and Latitude
1.4: Global Warming vs. Climate Change
1.5: Accessible Descriptions

This page titled 1: Orientation Lab is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

1.1: Lab Procedures

Lab Investigations

This lab manual is split up into nine investigations, each consisting of a number of activities that you'll do, with a combination of multiple choice and written/problem solving questions that you will answer based on the results of the activities. Many of these activities will be done directly in the lab manual, but a handful will require accessing an exterior website to gather climate data, run a climate model, or perform another activity. While this lab manual is up to date as of March, 2026, external websites used for activities may change over time. Contact your instructor if you run into any problems with a website.

Because each instructor will have a different set of policies and procedures for submitting lab work, please follow their directions on how to submit lab work.

Note for Instructors

This section is a good place to add a few questions regarding your individual procedures and policies to Investigation 0. The rest of this investigation is a little shorter than a typical investigation to allow for you to include a set of questions related to your policies and procedures.

This page titled 1.1: Lab Procedures is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

1.2: Maps and Geography

Tools for reading maps

Numerous lab exercises in this class rely on a somewhat in-depth geography of planet Earth (primarily continents, countries, major cities, and spatial orientation). Rather than having you memorize a bunch of states/cities, this portion of the lab will simply introduce you to the numerous tools/techniques/rules for how Geography is used in this course. You will be allowed to use any/all of these tools on any assignment/quiz in this course, so the key for this lab is to get comfortable with how to use them.

First Tool: Spatial Orientation

Have you ever wondered what direction West/East/North/South is relative to where you were at? You can often use landmarks/geographical features (such as the surrounding hills) as a reference point; for example, in Silicon Valley, the hills that have lots of tall trees/forest are to the west of the city, while the hills that have lots of brown grass (may be green in winter) are to the east of the city. You can then quickly determine which direction is North and which is South.

For this class, you won't have to do that. You just need to follow one simple rule: *for any map you see in this class, north will be on the top, south will be on the bottom, west will be on the left, and east will be on the right.* Depending on the map projection used, there may be a very slight deviation from this, but not enough to make a real difference (and it will be mentioned in the textbook when that deviation occurs). This orientation is shown in Figure 1.2.1.

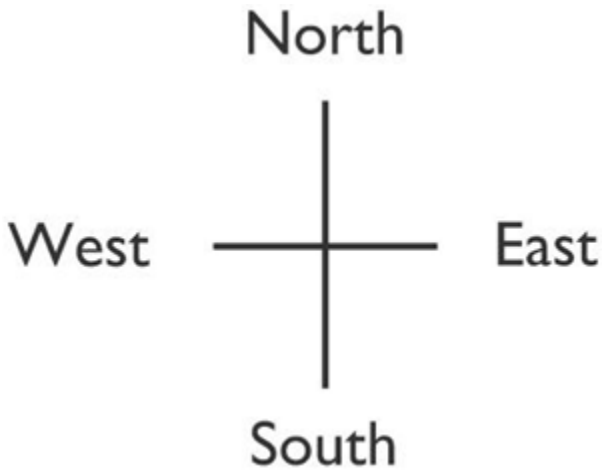


Figure 1.2.1: Cardinal Points on all maps in this class. North at the top, south at the bottom, east on the right, and west on the left. (Public Domain; Alicia Mullens)

Second Tool: Continent and Country Maps

You'll often see questions asking which continent a particular weather/climate feature is located in. You can always refer to Figure 1.2.2 for quick reference.

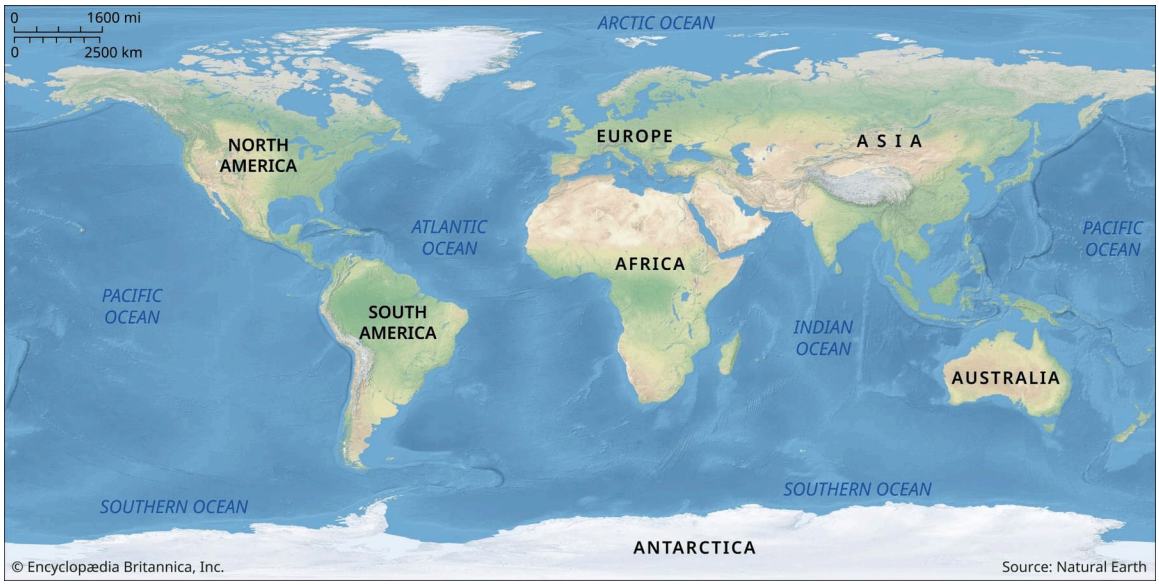


Figure 1.2.2: Map of all of the Continents. (CC0 1.0; Atharva Kurhe via Wikimedia Commons).

We need to examine the world as a whole to better understand Climate Change. The good news is that, while the class's geographical scope is global, the content won't be any more difficult or rigorous than a typical Meteorology lab. It's just that we need to look at the globe to understand *global warming*.

Third Tool: Averages and Anomalies Maps

Climate is the description of the *average* conditions of the atmosphere for a given region (such as temperature and precipitation)... what would be considered normal. Because of this, a key indicator of changes in a location's climate is the presence of anomalies. Usually, when discussing global warming, someone will say, "It's warmer than it used to be!" Such a statement would be valid if a location has been experiencing abnormally warm conditions for a prolonged period. To determine whether a location has become warmer, we need two main pieces of information: the location's average temperature and how much warmer it is now. That second piece of information is called an *anomaly* – a deviation from the average. We will examine various averages and anomaly maps in this course, but just to get you acclimated to them, let's examine a few now:

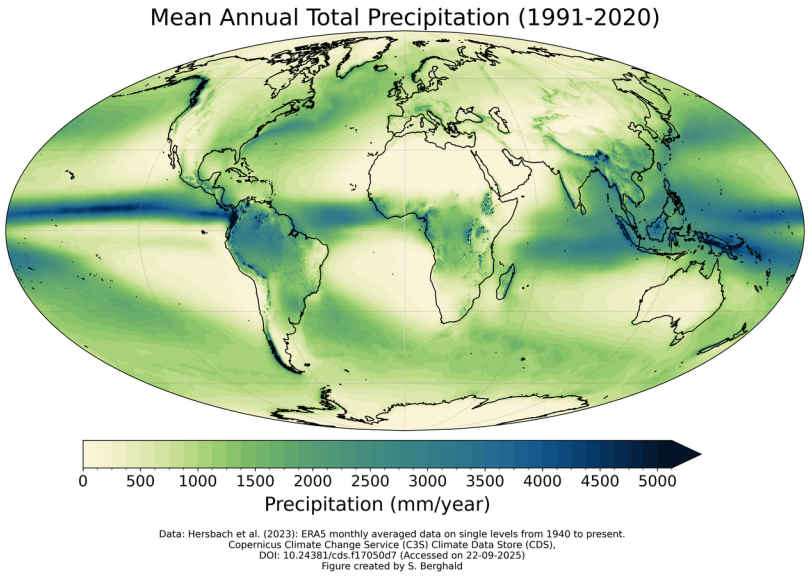


Figure 1.2.3: Global average annual precipitation map. (CC BY 4.0; S. Berghald via Wikimedia Commons). Alternative description of image.

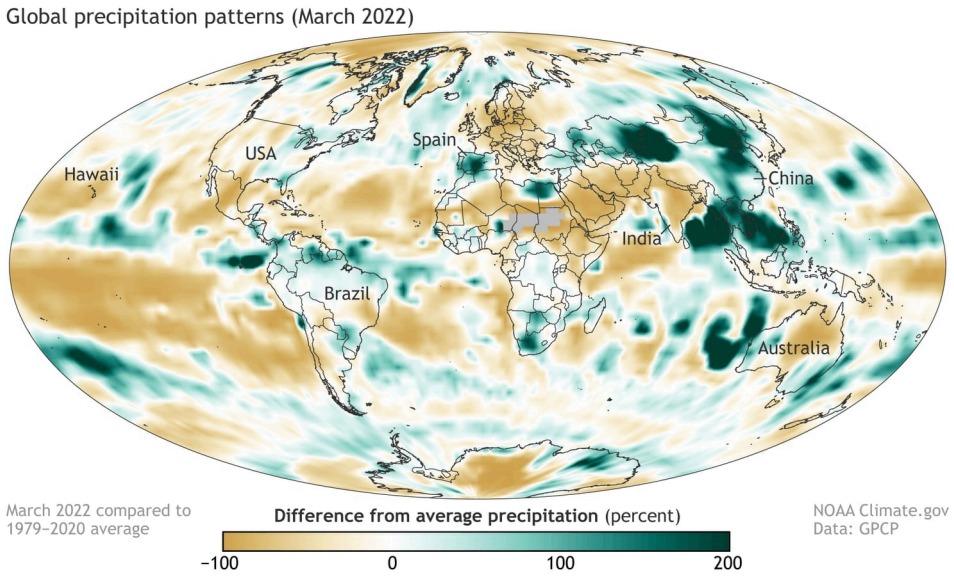


Figure 1.2.4: Global precipitation anomalies map for March of 2022. (Public Domain; NOAA Climate.gov). Alternative description of image.

Figure 1.2.3 displays the average precipitation for locations all over the world for the 30-year period ending in 2020, while Figure 1.2.4 displays the differences from average in precipitation amounts for March of 2022. Note that averages are taken over a long period of time while anomalies are determined for a short period of time. We'll actually cover the difference between Weather and Climate in Investigation 1, but an anomaly is determined by comparing the condition of the atmosphere at a given time, it's "weather," to the average condition over a long period of time, of the "climate". Also note that, while this book will strive to keep map projections as consistent as possible, there will be some variation because information is drawn from a large number of sources. But the rule shared earlier in this section will *always* apply: North at the top, South at the bottom, West on the left, East on the right, regardless of projection.

The last thing to note before we work with these maps is the color shading. Any map with color shading will include a legend explaining the colors. For Figure 1.2.3, the legend is somewhat blurry, but the driest locations are shaded in red (on the left of the legend) while the wettest locations are shaded in blue (on the right of the legend). For figure 1.2.4, below-average precipitation (negative anomalies) are located on the left of the legend in increasing shades of brown, while above-average precipitation (positive anomalies) are located on the right of the legend in increasing shades of green.

During the investigations in this book, you will be presented with similar maps/images that show weather/climate data from around the world. You need to be able to interpret these maps based on the information shown. Some questions will then be asked to check your understanding of the data presented. Based on Figures 1.2.3 and Figure 1.2.4, let's answer the following questions.

1. On average, the driest locations on Earth are located in which areas?
    a. Eastern North America and the northern portion of South America
    b. Central Asia and sub-Saharan Africa
    c. Western South America and Northern Africa
    d. Australia and North Asia
2. Meanwhile, the wettest locations on Earth are located in which areas?
    a. Western North America and sub-Saharan Africa
    b. Northern South America and the maritime East Asia regions
    c. Northern Africa and Western North America
    d. Middle East and Arabian Peninsula

The previous two questions were based on averages. Now, let's examine the anomalies.

3. In March of 2022, locations that were significantly drier than average include:
    a. The Middle East and Arabian Peninsula
    b. China and Southeast Asia
    c. The Eastern United States and Northern Brazil
    d. Western Australia
4. Meanwhile, locations that were significantly wetter than average include:

a. The entire United States and Australia
b. India and Northern Africa
c. The Equatorial Pacific (West of South America)
d. Most of China and Southeast Asia

5. Finally, let's focus on the USA. The Precipitation Anomalies across the United States show:
   a. Drier than average conditions across the entire United States
   b. Wetter-than-average conditions across the entire United States
   c. Drier than average in the West and average to slightly wetter than average across the Eastern United States
   d. Wetter than average in the West and Drier than average in the East.

We'll come back to averages and anomalies later in this investigation. While the information may seem trivial, it's good to get comfortable interpreting such maps.

This page titled 1.2: Maps and Geography is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

1.3: Longitude and Latitude

Fourth Tool: Longitude and Latitude

To identify the locations of different climate phenomena, we need a coordinate system. While this may sound a bit intimidating, the fact is that you already use coordinate systems in your everyday life. Assume you didn't have access to Google Maps (or your GPS of choice). If you had to explain where you lived, you would probably use the intersection of two major streets/highways. For example, when people ask where De Anza is located, the answer is typically "Stevens Creek and CA-85" because those are the two most well-known highways. The intersection of those two main highways is a coordinate. You are also likely familiar with coordinates because you've likely used them at one point in a math class. Thankfully, the coordinate system of latitude and longitude that Meteorologists, Pilots, Geographers, Biologists, your GPS, and many others use is very similar to the X-Y coordinate system in your math classes. And plotting points on a map is just as easy as plotting points on an X-Y graph. Figure 1.3.1 shows how the globe is gridded into a coordinate system:

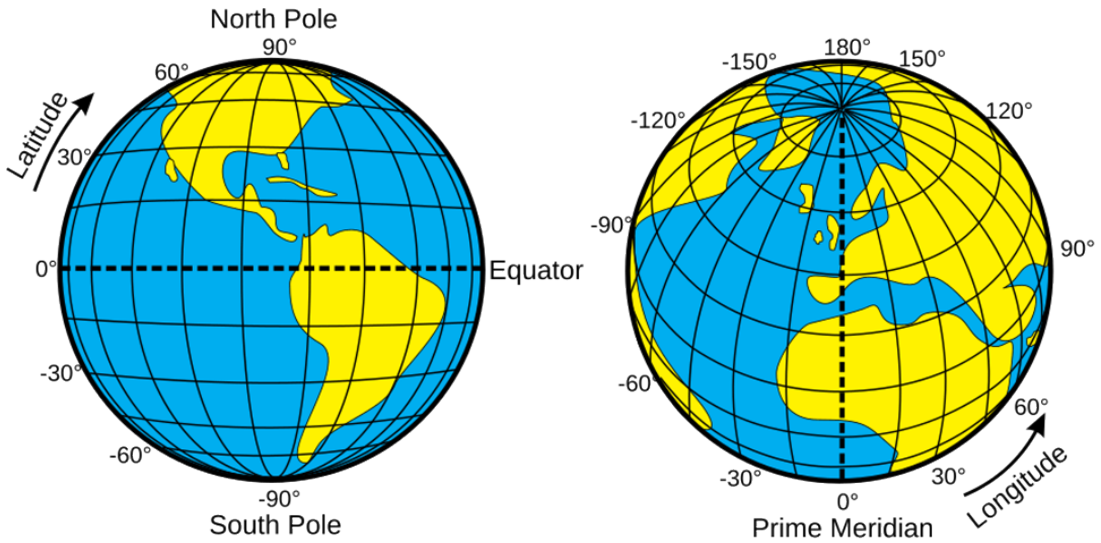


Figure 1.3.1: Longitude lines run from 0°-180°W or E of the Prime Meridian. 180°W/E of the Prime Meridian is called the International Date Line. It's exactly 180° (on the other side of) the Prime Meridian. Latitude Lines run from 0°-90° North or South of the Equator. 90°N is the North Pole, and 90°S is the South Pole. (Public Domain; Djexplo via Wikimedia Commons).

There are two coordinates that you need to identify a location:

- Longitude: The distance east (to the right of) or west (to the left of) the Prime Meridian, a line that runs from the North Pole, through Greenwich, England, and then to the South Pole.
- Latitude: The distance north (above) or south (below) of the Equator. Latitude lines run from 0°-90° North or South of the Equator. 90°N is the North Pole, and 90°S is the South Pole.

Put together, a latitude-longitude map of Earth looks like Figure 1.3.2.

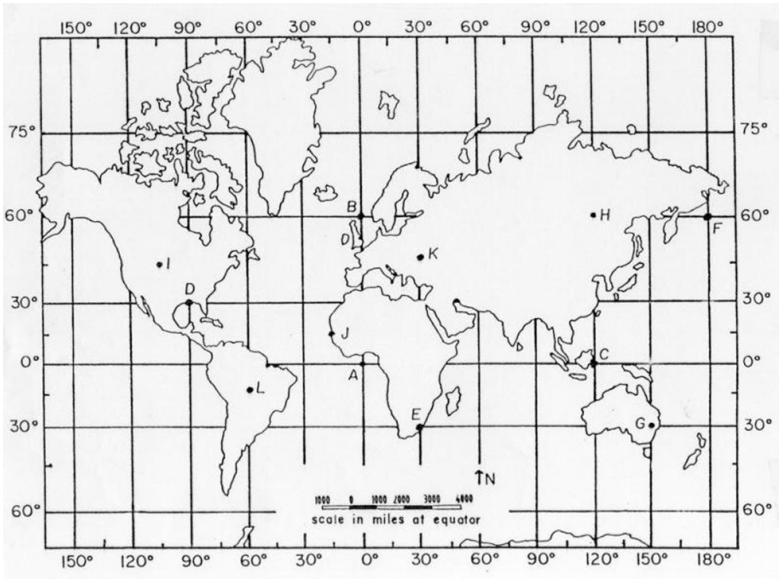


Figure 1.3.2: World Map with lines of latitude and longitude. (CC-BY-NC-SA 4.0; Johnson et al. via Introduction to Historical Geology). Alternative description of image.

And to identify a point on this map, you simply start at 0° Longitude and 0° Latitude, and then travel to the appropriate longitude... and then move up to the appropriate latitude. For Example, 45°N, 45°E would look like the location starred on 1.3.3

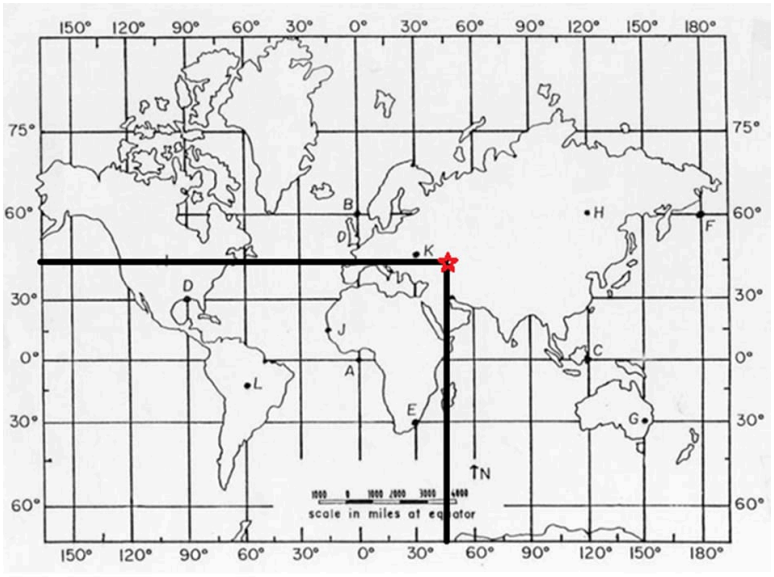


Figure 1.3.3: World Map with lines of Longitude and Latitude, and longitude 45°N/latitude 45°E starred. (CC-BY-NC-SA 4.0; Johnson et al. via Introduction to Historical Geology). Alternative description of image.

And 35°S, 120°W would look like the location starred on Figure 1.3.4:

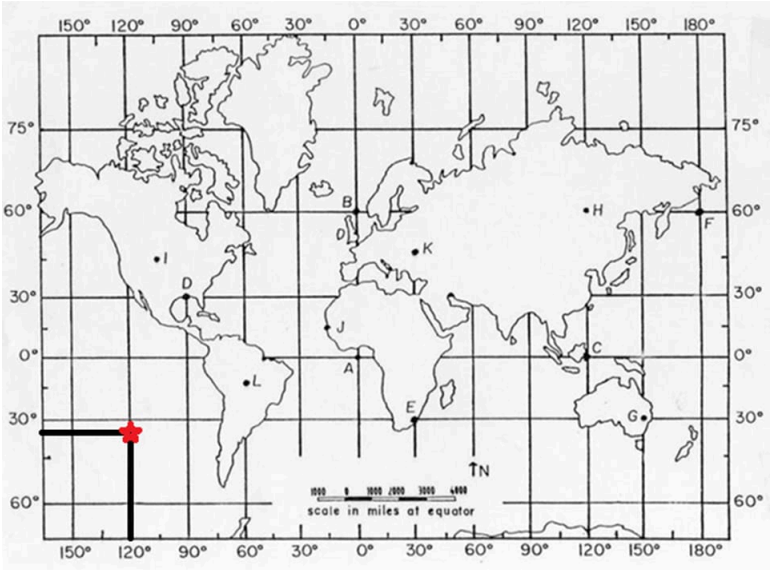


Figure 1.3.4: World Map with lines of Longitude and Latitude, and longitude 35°S/latitude 120°W starred. (CC-BY-NC-SA 4.0; Johnson et al. via Introduction to Historical Geology). Alternative description of image.

Remember, Figures 1.3.2 through 1.3.4 are oriented with North on the top, South on the bottom, East on the right, West on the left. Based on this, let's answer the following questions.

6. Traveling South-to-North, the latitude North of the Equator (0°N/S) _____.
   a. Increases
   b. Decreases
7. Therefore, if you are traveling North in the United States, you are getting _____ from the Equator (0°N/S).
   a. Closer
   b. Further
8. Traveling West-to-East (left to right), the longitude West of the Prime Meridian _____ (the 0° Longitude line).
   a. Increases
   b. Decreases
9. Therefore, if you are traveling East in the United States you are getting _____ from the Prime Meridian (0°E/W).
   a. Closer
   b. Further
10. Which of the following places (labeled on the map) is located at 45°N (Lat), 105°W (Lon)
    a. A
    b. E
    c. I
    d. L
11. H is located at which lat/lon coordinate?
    a. 30°N, 90°W
    b. 60°N, 120°E
    c. 30°S, 30°E
    d. 15°S, 60°W

One major “trick” about the coordinate system comes from the fact that the Earth is a sphere rather than a flat surface. So quickly ask yourself... what happens if you start at the Prime Meridian and keep going west on a map of the world? Obviously, you don’t fall off the edge of the map, but what does happen? Try it with a globe... what happens then? The answer is that you end up all the way on the other side of the map! At some point, you’ve traveled so far west that you are now closer to the Prime Meridian from the East side (and therefore have an Eastern Longitude). A great example of this can be seen in a map of the Equatorial Pacific Ocean, such as Figure 1.3.5.

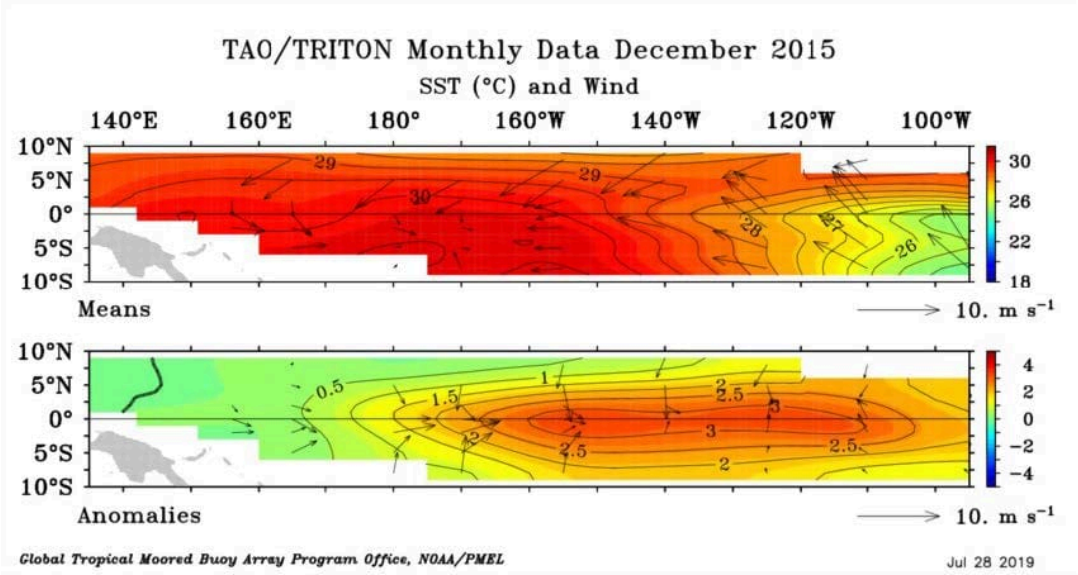


Figure 1.3.5: Sea-surface temperatures and anomalies for December 2015. (Public Domain; Monthly mean SST and Winds via NOAA/PMEL). Alternative description of image.

We use these maps to indicate the presence of a phenomenon called El Niño (we'll cover that in a future investigation), but for now, let's just focus on the coordinates. Again, the rule given earlier is still true. North is at the top, South at the bottom, West on the left, East on the right!

12. The eastern (right) side of this map is located in the _____ hemisphere and therefore has a _____ longitude coordinate.
    a. Eastern, West
    b. Eastern, East
    c. Western, West
    d. Western, East
13. The western (left) side of the map is located in the _____ hemisphere and therefore has a _____ longitude coordinate.
    a. Eastern, West
    b. Eastern, East
    c. Western, West
    d. Western, East

So what happened here? If you notice the 180° longitude line, everything to the left of it has an eastern coordinate while everything to the right has a western coordinate... that line is called the International Date Line... you can literally sail your way into tomorrow by crossing it because it is located exactly 180° (half way across the world) from the Prime Meridian and, since it's almost entirely all ocean, few people are negatively impacted by switching a day as you travel across it. Pretty cool, huh?

This page titled 1.3: Longitude and Latitude is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

1.4: Global Warming vs. Climate Change

One last tool... two very important definitions

The last tool needed is the definitions of Global Warming and Climate Change, which can be summarized in Figures 1.4.1 and 1.4.2.

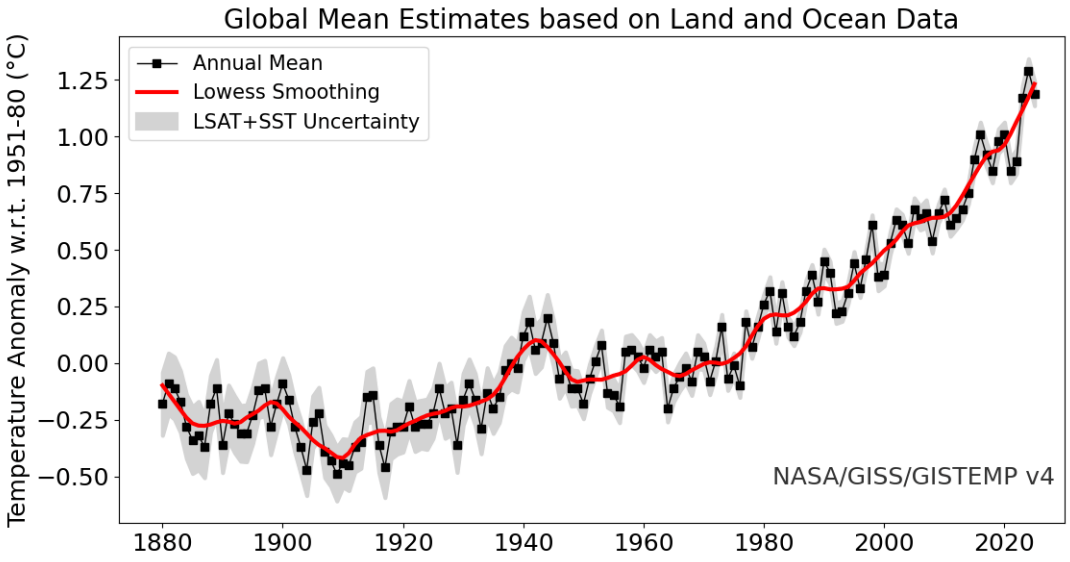


Figure 1.4.1: Global Average Temperature Anomalies, with respect to the 1951-1980 average temperature. (Public Domain; via NASA/GISS). Alternative description of image.

Figure 1.4.1 is essentially the entire definition of Global Warming, which is the increase in global average temperatures! The graph shows global mean temperature anomalies (deviations from the mean) from 1880 to the present, relative to the 1951–1980 base period. While there is some year-over-year variability, global temperatures have increased notably, with the warmest temperatures occurring in recent years. Let's answer the following few questions based on Figure 1.4.1.

14. While there is some variation from year-to-year, in general, Global Mean Temperature Anomalies have:
    a. Increased since 1880
    b. Decreased since 1880
    c. Haven't changed since 1880
15. While there is a noticeable change in temperatures from 1880 to 2025, a warming trend becomes very noticeable after approximately:
    a. 1940
    b. 1960
    c. 1900
16. In fact, 2024 was the warmest year on record with a temperature anomaly of approximately:
    a. 0.3°C
    b. 0.5°C
    c. 1.0°C
    d. 1.2°C

So yes, over the past 145 years, there has certainly been an upward trend in the average temperature. So yes, Global Warming is real! However, a comparison between Figure 1.4.1 and Figure 1.4.2 shows a flaw in the concept of Global Warming. Before we delve into that concept, let's consider a scenario: Rather than giving you the grade that you individually earned in this class, your instructor instead takes the class average and gives everyone that same grade! Take a moment and let that thought sink in. How do you feel about that? Is that fair? Is that accurate? Of course not!

But that's exactly what the concept of Global Warming does: It essentially uses one number (global average temperature anomaly) to define the entire state of Earth's Climate. That is extremely misleading and allows people to make pseudoscientific claims, such as "it's cold outside... so global warming must be fake!" Figure 1.4.2, on the other hand, provides a more nuanced view of Earth's temperature anomalies (Legend: Redder means warmer, Bluer means Colder).

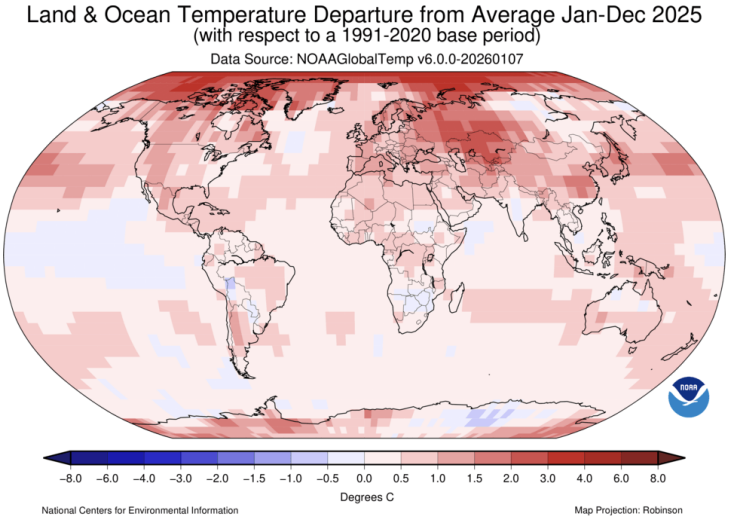


Figure 1.4.2: Temperature Anomalies for 2022 with respect to the 1991-2020 base period. (Public Domain; NOAA via National Center for Environmental Information). Alternative description of image.

Let's answer the following true or false questions based on Figure 1.4.2.

17. Everywhere on Earth experienced above-average temperatures in 2025.
    a. True
    b. False
18. Some locations such as the Central United States, the Equatorial Pacific Ocean, and the North Atlantic, experienced cooler-than-average temperatures.
    a. True
    b. False

This dichotomy underscores the importance and usefulness of the term Climate Change, or, more formally (for this course), Anthropogenic Climate Change. Climate Change refers to changes in average atmospheric conditions (temperature, precipitation, etc.) for a given region. It considers the fact that not everywhere on Earth is warming. Some places are, in fact, cooling. While Figure 1.4.1 shows that 2025 was a very warm year, Figure 1.4.2 shows that some locations on Earth were not warmer than average, and some were even cooler than average! So we can't simply summarize the entire state of Earth in a single graph or number, even if that may be more convenient.

The purpose of this course will be to introduce you to the numerous data sources, such as Carbon Dioxide and Methane Concentrations, and the tools that climate scientists use to analyze and predict changes in Earth's Climate. Because this is an introductory level course, much of what we do is very simplified, but should still be sufficient to give you a taste of how Climate Science works! A few last questions to complete this introductory Investigation.

19. Wrapping things up: What do you think you are going to enjoy about this class?
20. What do you think you may struggle with?
21. What are some ways your instructor can help?

This page titled 1.4: Global Warming vs. Climate Change is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

1.5: Accessible Descriptions

Figure 0.2.3: Average Global Precipitation Map

Global map titled “Mean Annual Total Precipitation (1991–2020)” showing the average yearly precipitation across the Earth’s surface for the period 1991–2020. Continents and oceans are displayed, with precipitation amounts represented on a continuous scale ranging from 0 to over 5000 millimeters per year. The highest precipitation occurs in equatorial and tropical regions, including the Amazon Basin, central Africa, South and Southeast Asia, and parts of island regions and coastal mountain areas. Moderate precipitation appears across many temperate regions such as the east coast of North America, Central America, southern Africa, Europe, and Central Asia and large areas of the oceans. Lower precipitation occurs in major desert regions in the US Southwest, Mexico, sub-Saharan Africa, Australia, and Central Asia, interior continental areas, and polar regions. A horizontal legend below the map shows the precipitation scale with labeled values from 0 to 5000 millimeters per year. Additional text below the legend cites the data source as ERA5 monthly-averaged data from the Copernicus Climate Change Service, includes a DOI reference and an access date, and credits the figure creator.

Figure 0.2.4: Global Precipitation Anomalies Map

World map titled “Global precipitation patterns (March 2022)” showing how precipitation during March 2022 differed from the long-term average for 1979–2020. The map displays continents and oceans with several country labels, including the United States, Brazil, Spain, India, China, Australia, and Hawaii. Precipitation differences are shown using a percentage scale ranging from –100 to 200. Areas with above-average precipitation appear across parts of Asia, the western Pacific region, sections of Africa, and parts of the southern oceans. Areas with below-average precipitation are found across portions of North and South America, the Atlantic and Pacific Oceans, and some regions of Africa and Eurasia. A legend below the map shows the percentage scale for the difference from the average precipitation. Text beneath the map notes that the comparison is between March 2022 and the 1979–2020 average, and includes a source attribution to NOAA Climate.gov with data from the Global Precipitation Climatology Project (GPCP).

Figure 0.3.1: Longitude and Latitude lines

Two globe diagrams placed side by side, each overlaid with a latitude–longitude grid.

One diagram shows landmasses including North and South America, with a dashed line encircling the globe's midpoint to indicate the equator, which divides the planet into two hemispheres. The other diagram shows landmasses including Europe, Africa, and parts of Asia, with a dashed line connecting opposite points on the globe to indicate the prime meridian, which divides the planet into two hemispheres.

Figure 0.3.2: World Map with lines of longitude and latitude

World map overlaid with evenly spaced latitude and longitude lines, with degree values marked along the borders. Landmasses include the Americas (Approximately 45°N, 105°W), Europe (Approximately 45°N, 15°E), Africa (Approximately 0°, 30°E), Asia (Approximately 45°N, 90°E), and Australia (Approximately 20°S, 135°E).

A distance scale labeled for measurements at the equator is shown near the bottom, along with a north reference indicator.

Figure 0.3.3: World Map with lines of longitude and latitude, and 45°N and 45°E marked

World map from Figure 0.3.2, but with a marked location near the eastern Mediterranean where two thick lines intersect. One line traces a parallel (line of latitude) across the map, and the other traces a meridian (line of longitude) from pole to pole, indicating the coordinates of that point. The intersection aligns approximately with 45 degrees north latitude and 45 degrees east longitude, demonstrating how a location is identified using geographic coordinates. Multiple labeled points A through L mark locations

across regions that will be used to answer questions related to visual map reading lower down on page 0.3.

Figure 0.3.4: World Map with lines of longitude and latitude, and 35°S and 120°W marked

World map with a latitude–longitude grid and degree labels around the edges. Landmasses include the Americas, Europe, Africa, Asia, and Australia, with multiple labeled points A through L marking locations across regions.

A highlighted location near the eastern Mediterranean is marked where two thick lines intersect. One line traces a parallel (line of latitude) across the map, and the other traces a meridian (line of longitude) from pole to pole, indicating the coordinates of that point. The intersection aligns approximately with 35 degrees south latitude and 120 degrees west longitude, demonstrating how a location is identified using geographic coordinates. A scale bar for distance at the equator and a north reference indicator are shown below the map.

Figure 0.3.5 Sea Surface Temperatures and Anomalies for December 2015

This figure shows sea surface temperature (SST) and wind data across the equatorial Pacific Ocean during December 2015, based on measurements from the TAO/TRITON buoy array. The data is presented in two horizontal panels:

Top Panel – "Means" (Sea Surface Temperature and Wind):

- This panel shows average SSTs (in °C) and surface winds between 10°N and 10°S latitude, from 140°E to 100°W longitude.
- The SSTs are displayed using a color gradient from:
  - 30°C in the western and central Pacific,
  - 26–28°C in the east,
  - 18–22°C near South America.
  - Isotherms (contour lines) mark temperatures at 1°C intervals (e.g., 30°C, 29°C, 28°C).
  - Wind vectors (arrows) show the direction and magnitude of surface winds:
- Arrows mostly point from west to east across the central and eastern Pacific,
- Indicating weakened or reversed trade winds, which are typical of El Niño events.

Bottom Panel – "Anomalies" (SST and Wind):

- This panel shows deviations from the average (climatological) conditions.
- Color shading indicates SST anomalies (in °C), with:
  - Positive anomalies (+2 to +3.5°C) in the central and eastern equatorial Pacific.
  - The strongest warming occurs between 160°W and 100°W, peaking at about +3.5°C.
  - Areas with cooler-than-normal SSTs (very limited in this case).
- Contour lines trace SST anomaly values (e.g., 1.5, 2.0, 3.0).
- Wind anomaly vectors point eastward, indicating weakened or reversed easterly winds, consistent with El Niño.

Figure 0.4.1: Global Average Temperature Anomalies from 1880-2025

Line graph showing global temperature change over a long time period, with years progressing along one axis and temperature difference from a baseline along the other.

Individual yearly values are marked and connected to show short-term variation, while a smoothed line highlights the long-term trend. A shaded region around the yearly values represents measurement uncertainty. The data show repeated short-term ups and downs, but an overall upward trend across the full period. The increase becomes steeper in the later portion of the record, with the most recent years reaching the highest values shown. A legend explains the yearly data, the smoothed trend, and the uncertainty range, and the dataset is identified as NASA GISS GISTEMP.

The data plotted on Figure 0.4.1 is provided in Table 0.5.1

Table 0.5.1. Global Land-Ocean Temperature Index Anomalies (°C)

Year	No Smoothing (°C)	Lowess (5) (°C)
1880	-0.18	-0.10
1881	-0.09	-0.14
1882	-0.11	-0.17
1883	-0.18	-0.21
1884	-0.28	-0.24
1885	-0.34	-0.27
1886	-0.32	-0.28
1887	-0.36	-0.28
1888	-0.18	-0.27
1889	-0.11	-0.26
1890	-0.36	-0.26
1891	-0.23	-0.26
1892	-0.27	-0.27
1893	-0.31	-0.26
1894	-0.30	-0.24
1895	-0.23	-0.22
1896	-0.12	-0.21
1897	-0.11	-0.19
1898	-0.28	-0.17
1899	-0.18	-0.18
1900	-0.09	-0.20
1901	-0.15	-0.23
1902	-0.28	-0.26
1903	-0.37	-0.28
1904	-0.48	-0.31
1905	-0.27	-0.34
1906	-0.23	-0.36
1907	-0.39	-0.38
1908	-0.43	-0.40
1909	-0.49	-0.41
1910	-0.44	-0.42
1911	-0.45	-0.40
1912	-0.37	-0.36
1913	-0.35	-0.33
1914	-0.16	-0.32
1915	-0.15	-0.31

Year	No Smoothing (°C)	Lowess (5) (°C)
1916	-0.36	-0.30
1917	-0.46	-0.30
1918	-0.30	-0.30
1919	-0.28	-0.30
1920	-0.28	-0.28
1921	-0.19	-0.27
1922	-0.29	-0.26
1923	-0.27	-0.24
1924	-0.27	-0.23
1925	-0.22	-0.22
1926	-0.11	-0.22
1927	-0.22	-0.21
1928	-0.20	-0.20
1929	-0.36	-0.19
1930	-0.16	-0.19
1931	-0.10	-0.19
1932	-0.16	-0.18
1933	-0.29	-0.17
1934	-0.13	-0.16
1935	-0.20	-0.14
1936	-0.15	-0.11
1937	-0.03	-0.06
1938	0.00	-0.02
1939	-0.02	0.03
1940	0.12	0.06
1941	0.18	0.09
1942	0.06	0.10
1943	0.09	0.10
1944	0.20	0.07
1945	0.09	0.04
1946	-0.07	0.00
1947	-0.03	-0.04
1948	-0.11	-0.07
1949	-0.11	-0.08
1950	-0.17	-0.08
1951	-0.07	-0.07
1952	0.01	-0.07

Year	No Smoothing (°C)	Lowess (5) (°C)
1953	0.08	-0.07
1954	-0.13	-0.07
1955	-0.14	-0.06
1956	-0.19	-0.05
1957	0.05	-0.04
1958	0.06	-0.01
1959	0.03	0.02
1960	-0.02	0.03
1961	0.06	0.01
1962	0.03	-0.01
1963	0.05	-0.03
1964	-0.20	-0.04
1965	-0.11	-0.05
1966	-0.06	-0.06
1967	-0.02	-0.05
1968	-0.08	-0.03
1969	0.05	-0.02
1970	0.03	-0.00
1971	-0.08	0.00
1972	0.01	0.00
1973	0.16	-0.00
1974	-0.07	0.01
1975	-0.01	0.02
1976	-0.10	0.04
1977	0.18	0.07
1978	0.07	0.12
1979	0.16	0.16
1980	0.25	0.19
1981	0.32	0.21
1982	0.14	0.21
1983	0.31	0.21
1984	0.15	0.21
1985	0.12	0.22
1986	0.18	0.24
1987	0.32	0.27
1988	0.39	0.31
1989	0.27	0.33

Year	No Smoothing (°C)	Lowess (5) (°C)
1990	0.45	0.33
1991	0.41	0.33
1992	0.22	0.33
1993	0.23	0.33
1994	0.31	0.34
1995	0.44	0.36
1996	0.33	0.40
1997	0.46	0.42
1998	0.61	0.44
1999	0.38	0.47
2000	0.39	0.50
2001	0.53	0.52
2002	0.63	0.54
2003	0.61	0.58
2004	0.53	0.61
2005	0.68	0.62
2006	0.64	0.62
2007	0.66	0.63
2008	0.54	0.64
2009	0.66	0.64
2010	0.72	0.65
2011	0.61	0.67
2012	0.65	0.70
2013	0.68	0.74
2014	0.75	0.79
2015	0.90	0.83
2016	1.01	0.87
2017	0.91	0.91
2018	0.85	0.93
2019	0.98	0.94
2020	1.01	0.96
2021	0.85	1.01
2022	0.89	1.06
2023	1.17	1.12
2024	1.28	1.17
2025	1.19	1.23

Figure 0.4.2: 2025 Temperature Anomalies

World map showing differences in land and ocean temperatures for 2025 compared to the 1991–2020 average. The map is divided into small grid cells across all continents and oceans, with each cell representing how much warmer or cooler that area is relative to the baseline. Most regions show higher-than-average temperatures, indicating widespread warming.

The largest increases occur across northern parts of North America, Europe, and Asia, as well as the Arctic. Smaller areas in the Central United States, and parts of the oceans, such as the North Atlantic and the Equatorial Pacific, and some regions in the Southern Hemisphere (such as central south America, South Africa, South India, Australia, and the Antarctic show temperatures closer to or slightly below the baseline. A scale bar indicates temperature difference values in degrees Celsius, ranging from much cooler than average to much warmer than average. The data source is NOAA, and the map uses a global projection.

This page titled 1.5: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

2: DEFINING EARTH'S CLIMATE

Introduction

Climate represents the long-term weather pattern in a region, typically averaged over 30 years. While many meteorological factors, such as atmospheric pressure, humidity, wind, etc., determine a region's climate, much of what we experience can be reduced to just temperature and precipitation. Think of a desert – chances are you pictured a hot, dry place. If you imagine a rainforest, it will be warm and wet. In the United States, the regional climate varies considerably, as shown in Figure 2.1. The West Coast enjoys plenty of sunshine, but also suffers from wildfires. Midwestern states are known for flat landscapes and fertile soil, which support the agricultural and meat industries. The southeastern states experience year-long hot, humid conditions, while the northeastern states experience humid summers but snowy, cold winters.



Figure 2.1: In the United States, climate changes regionally. (CC BY 4.0; Getty Images via Grist) Alternative description of the image.

A good demonstration of climate would be thinking of your hometown, or the place that you've lived in the longest in your life. If you've lived in a region for quite a bit of time, you're probably used to how the weather changes from season to season; when you need an umbrella, jacket, boots, or when you'd prefer shorts and a t-shirt. To define your region's climate, let's begin with a few open-ended questions to help you explain the climate of your hometown or the place that you've spent most of your life in. For these questions, don't think of extremes like the day it was 115°F in San Jose; think of what is typical.

1. How warm is a typical day during the warmest time of year? What time of year (month or two) does it occur?
2. How cold is a typical day during the coldest time of year? What time of year does it occur?
3. What time of year (a month or two) do you get the most precipitation? What kind of precipitation (rain, snow, hail, etc.) is typical during that season?

Piecing those questions together, you can get a fairly good description of your hometown's climate. While a location's weather can change very rapidly, such as a 25°F temperature drop as a front passes overhead, a location's climate doesn't change nearly as quickly. But Earth's climate does change, and it has changed in the past. Archaeologists have found plant fossils from temperate regions, dinosaur fossils in Antarctica, and Woolly mammoths in California. But the natural changes that cause such climate shifts often take tens of thousands, if not millions of years. We'll talk more about natural climate changes and cycles later in this course. However, in this course, our focus is on a particular type of climate change – Anthropogenic Climate Change – which is defined as the Climate System's response to human-induced changes in land cover, atmospheric chemistry, and other human alterations. But first, in this investigation, let us examine what climate is and the factors that determine a region's climate.

Learning Objectives

By the end of this investigation, you should be able to:

1. Identify the primary factors that determine a region's climate
2. Name the three main climate zones.
3. Name the factors that affect a region's precipitation.

Navigational Note

Investigation 1 has 23 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

2.1: Factors affecting the Climate

2.2: Climate Zones

2.3: Precipitation

2.4: Accessible Descriptions

This page titled 2: Defining Earth's Climate is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

2.1: Factors affecting the Climate

Latitude and Angle of Insolation

The latitude of a location plays a major role in determining the region's climate. The farther you are from the Equator, the higher your latitude. Figure 2.1.1 displays lines of latitude on Earth for the Northern Hemisphere.

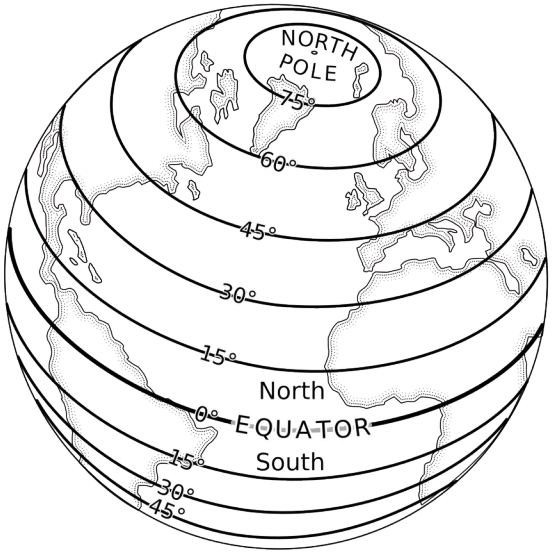


Figure 2.1.1: Latitudes increase from 0° at the Equator to 90° at the north pole and decrease to -90° at the south pole. (Public Domain; Gregors via Wikimedia Commons). Alternative description of the image.

Your latitude determines the angle of incoming sunlight, which is known as the angle of insolation. A higher angle (closer to 90° or directly overhead) concentrates solar energy into a smaller area, resulting in higher, hotter temperatures, while a lower, oblique angle spreads energy over a larger area, resulting in lower temperatures. To demonstrate the importance of the angle of insolation, let's conduct the following experiment: Using a flashlight and in a dark room, hold the flashlight so that the light is directly over the ground, as shown in Figure 2.1.2. Then, tilt the flashlight so it is low on the horizon, as shown in Figure 2.1.3.



Figure 2.1.2: When the flashlight is directly over the surface, the energy is concentrated. (CC BY 4.0; Alicia Mullens)

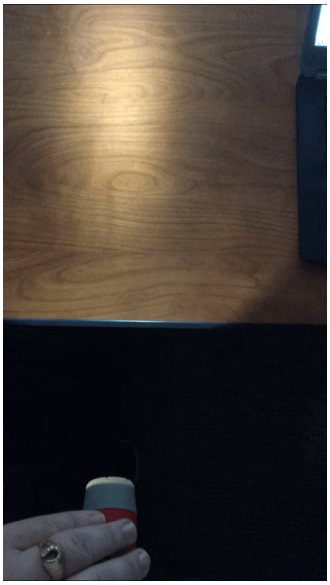


Figure 2.1.3: When the flashlight is angled over the surface, the energy is more diffuse. (CC BY 4.0; Alicia Mullens)

4. When the flashlight is shining directly above the surface (Figure 2.1.2), the area illuminated on the surface is:
   a. a small, bright circle
   b. a large, dim area

5. When you lower the flashlight on the horizon (Figure 2.1.3). The area illuminated on the surface becomes:
   a. smaller and brighter
   b. larger and dimmer
   c. it doesn't change

6. Now let's apply this to sunlight. Sunlight would be most intense when:
   a. The Sun is directly overhead
   b. The Sun is lower on the horizon

We can also apply these conclusions to sunlight and how its intensity changes throughout the day as the sun rises and sets with low angles of insolation, but has a higher angle around noon. Thus, when the sun is high in the sky, the incoming sunlight is more intense, whereas when the sun is low on the horizon, it is less intense. Now, let's examine how this would relate to latitude. There are a few things to note here. If the Earth were *not* tilted, the sun would be directly overhead year-round, and the overall set-up of incoming sunlight would appear as shown in Figure 2.1.4.

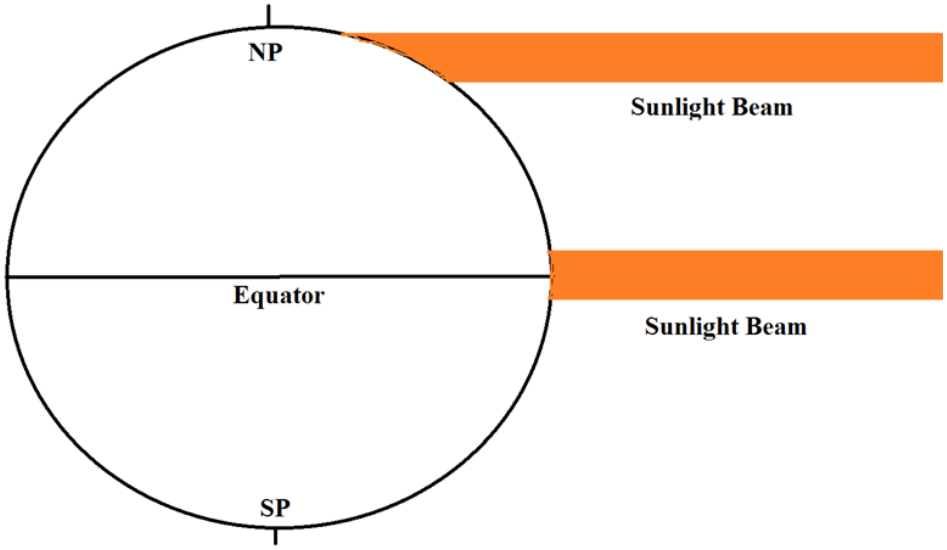


Figure 2.1.4: Sunlight over the Equator (low latitude) vs. sunlight near the poles (high latitude). The Sun is directly over the Equator. (CC BY 4.0; Alicia Mullens). Alternative description of the image.

7. Based on Figure 2.1.4, a beam of sunlight covers a _____ area over higher latitudes than near the Equator.
   a. smaller
   b. larger

8. As a result, sunlight at higher latitudes would be _____ than near the Equator.
   a. more intense
   b. less intense

9. Therefore, areas near _____ should receive more sunlight throughout the year.
   a. the Equator
   b. the Mid-latitudes
   c. the Poles

This can be further reinforced by checking how average air temperatures vary with latitude worldwide. A map of global average air temperatures is shown in Figure 2.1.5. Warmer temperatures are shown in red, while cooler temperatures are shown in blue.

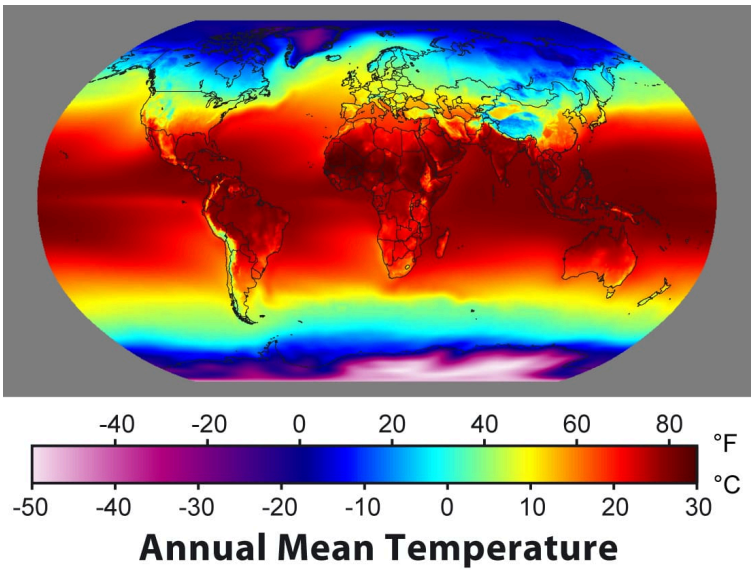


Figure 2.1.5: Global annual average air temperatures. (CC-BY-SA 3.0; Global Warming Art via Wikimedia Commons). Alternative description of the image.

10. While there is some variation caused by other factors (such as elevation, and ocean currents), the warmest temperatures are generally near the _____ while the coldest temperatures are usually near the _____.
    a. poles; equator
    b. equator; poles

11. This _____ the conclusions made in questions 4-6.
    a. confirms
    b. cannot confirm

Earth's orbit.

However, our Earth is tilted. In fact, it is tilted at an Angle of 23.5°. The result of this is that as the Earth orbits around the sun (Figure 2.1.6), the latitude at which the sun is directly overhead changes. Figure 2.1.7 represents the conditions in June, when the sun is directly over 23.5°N, while Figure 2.1.8 represents the conditions in December, when the sun is directly over 23.5°S.

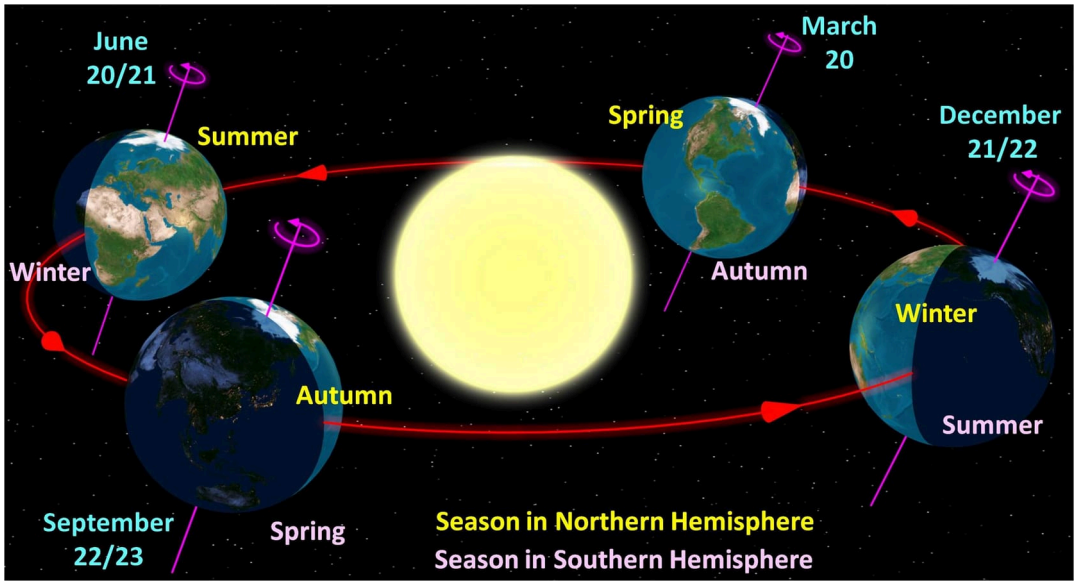


Figure 2.1.6: Earth's orbit around the sun and corresponding northern hemisphere seasons. (Public Domain; Tauʻolunga via Wikimedia Commons). Alternative description of the image.

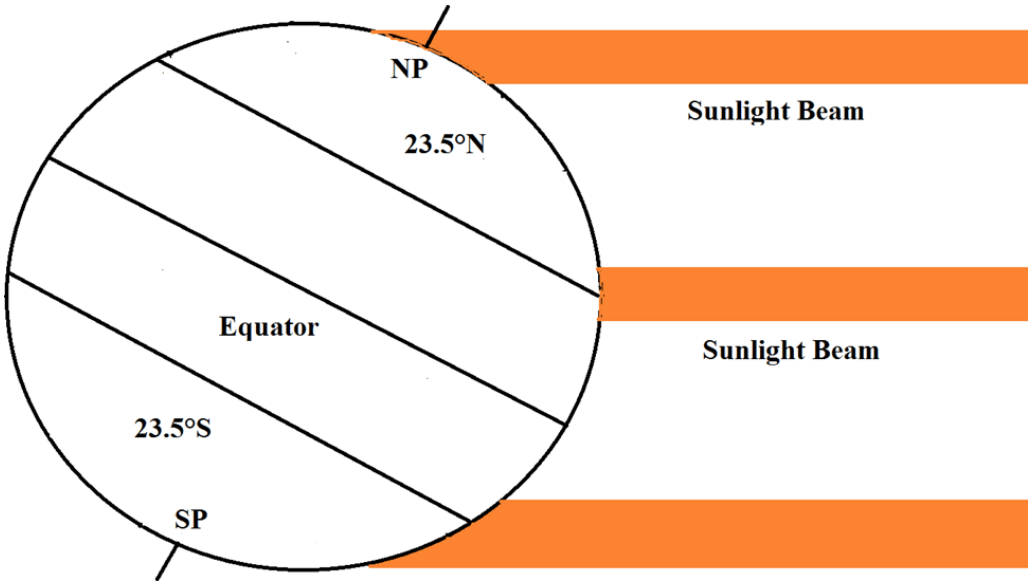


Figure 2.1.7: In June, the northern hemisphere is tilted towards the Sun. (CC BY 4.0; Alicia Mullens). Alternative description of the image.

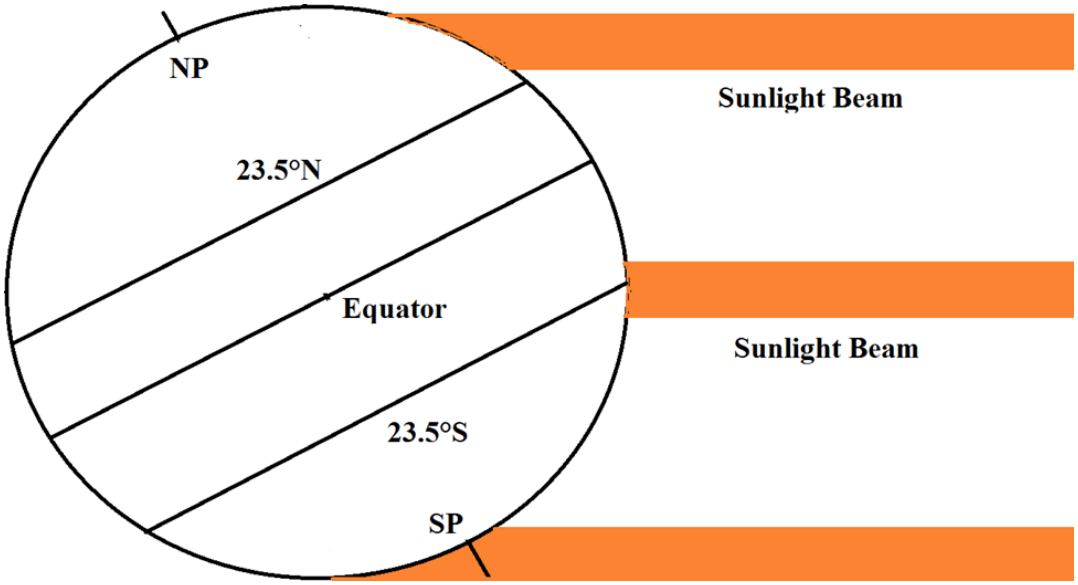


Figure 2.1.8: In December, the southern hemisphere is tilted towards the Sun. (CC BY 4.0; Alicia Mullens). Alternative description of the image.

12. Based on Figure 2.1.7, in June, the Sun is directly over:
    a. The Equator
    b. 23.5°N
    c. 23.5°S

13. Investigate the North Pole in Figure 2.1.7. Notice that it is completely covered with sunlight. Now imagine the Earth completing one 24-hour rotation around its axis. In June, the North Pole would never:
    a. experience any sunlight
    b. experience any darkness

14. Now let's investigate Figure 2.1.8, which represents conditions in December. In December, the sun is directly over:
    a. The Equator
    b. 23.5°N
    c. 23.5°S

15. Investigate the North Pole in Figure 2.1.8. Notice that it is pointing away from the Sun. As the Earth completes its 24-hour rotations around its axis, in December, the North Pole would never:

a. experience any sunlight
b. experience any darkness

This page titled 2.1: Factors affecting the Climate is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

2.2: Climate Zones

Main Climate Zones

Based on what we have learned so far about the effect of latitude, angle of insolation, and the Earth's orbit, we realize that Earth can be divided into three main Climate Zones:

- **Tropical Climate (Between the Equator and 23.5° N & S):** The tropics are generally defined as the region between 23.5° N & 23.5° S of the Equator. Here, the Sun is overhead or near overhead year-round, with ample sunlight and consistent conditions. These regions experience little to no temperature change between summers and winters. However, that does not mean every place in the tropics is hot and humid. Elevation from sea level also matters. Cities at higher elevations, such as Bogotá, Colombia, which lies at an altitude of 2,640 m (8,662 ft), experience much cooler temperatures than cities near sea level. Thus, instead of thinking of hot and humid conditions year-round for regions in the tropics, think of consistent temperatures throughout the year. Figure 2.2.1 demonstrates how temperatures vary in Iquitos, Peru, which is closer to sea-level in the tropical climate. No matter the month, the average temperature stays close to 77°F (25°C), with some diurnal variation.

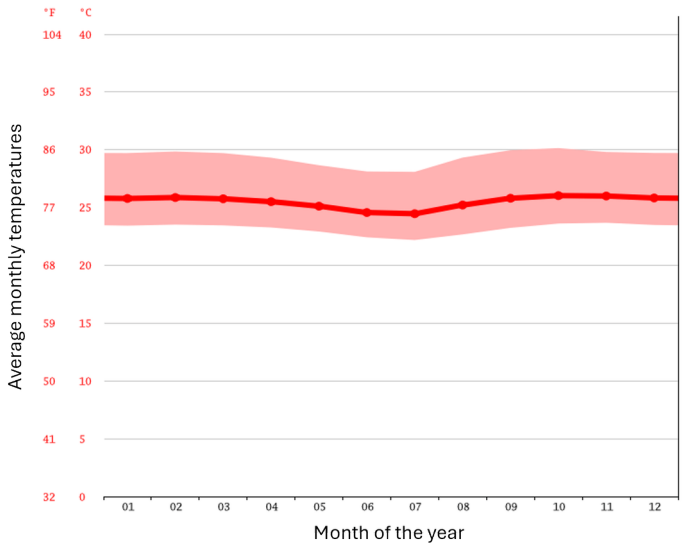


Figure 2.2.1: Average monthly temperature in Iquitos, Peru, versus month of the year. (CC BY-NC 4.0; Climate Iquitos by Climate-Data.org)
Alternative description of the image.

- **Temperate Climate (Between 23.5° and 66.5° N & S):** The mid-latitudes are defined as the regions between 23.5 ° and 66.5° N & S. These regions receive ample sunlight in the summer months but less in the winter months. There is some appreciable variation between summer and winter daylight hours, as well as the heat received from the Sun. Thus, these regions experience fairly moderate temperature variations throughout the year. Figure 2.2.2 displays monthly average temperatures for San Jose, California, in the Temperate zone. One observes that summer temperatures in San Jose are much warmer than winter temperatures.

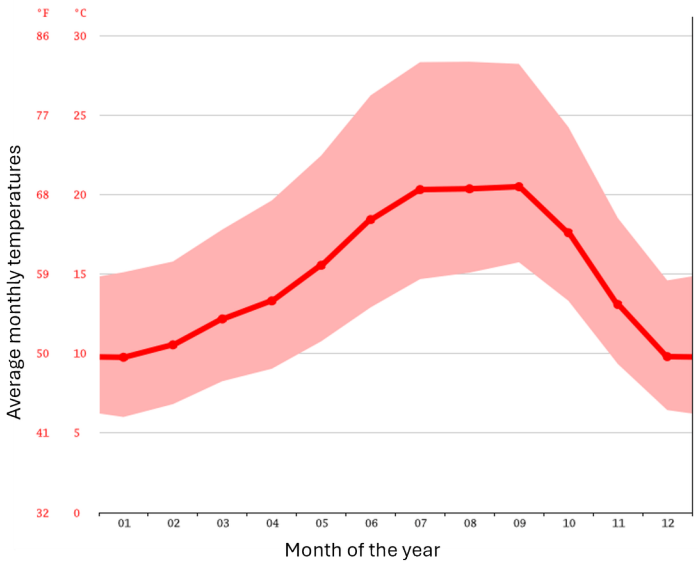


Figure 2.2.2: Average monthly temperature in San Jose, CA, versus month of the year. (CC BY-NC 4.0; Climate San Jose by Climate-Data.org)
Alternative description of the image.

- **Polar Climate (Between 66.5° and 90° N & S):** The polar regions are defined as locations that lie between 66.5° and 90° N & S. These regions experience a lot of sunlight (but at a low angle) in the summer months and almost none in the winter months. In fact, for locations above 66.5° N (the Arctic Circle) and below 66.5°S (the Antarctic Circle), there is at least one day a year where there is 24 hours of sunlight and one day a year where there is 24 hours of darkness. The number of such days with 24 hours of sunlight and darkness increases as you travel further towards the pole. Thus, these regions experience extreme temperature swings between winter and summer. Figure 2.2.3 displays average monthly temperatures for Tromso, Norway, in the Polar Climate Zone. One observes that the variation between summer and winter temperatures is most extreme in Tromso, compared to San Jose or Iquitos.

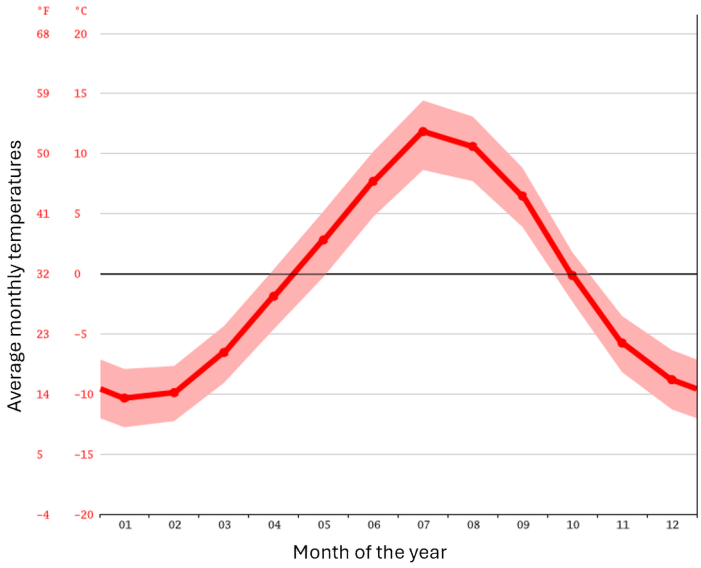


Figure 2.2.3: Average monthly temperature in Tromso, Norway, versus month of the year. (CC BY-NC 4.0; Climate Tromso by Climate-Data.org)
Alternative description of the image.

Examine Figure 2.2.1 from a Tropical Zone, Figure 2.2.2 from a Temperate Zone, and Figure 2.2.3 from a Polar Zone to answer the following question.

16. In general, the variation in yearly temperatures, i.e., the difference between warmest monthly temperatures and coldest monthly temperatures _____ the further away from the equator you get.
    a. increases

b. decreases
c. does not change

A summary of the three major climate zones based on latitude and angle of insolation is shown in Figure 2.2.4. However, many other factors, such as elevation, proximity to the ocean, and ocean currents, must also be considered when evaluating a location's climate. We'll delve into those further in future investigations.

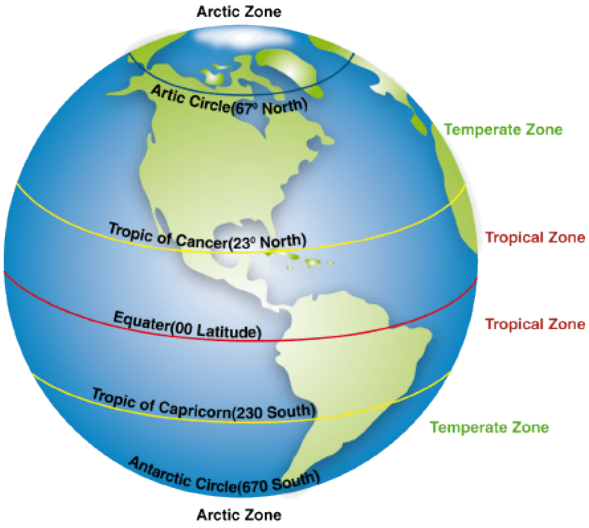


Figure 2.2.4: The three main climate zones are shown along with the latitudes that separate them. (CC BY-SA 3.0; CK-12 Foundation via South Redford Open Curriculum) Alternative description of the image.

This page titled 2.2: Climate Zones is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

2.3: Precipitation

Precipitation Variation

While the three main climate zones provide a broad perspective of climate zones, regions within these climate zones may differ from each other based on other factors like precipitation. Regional variation in precipitation is a bit more complicated than that in temperature, which is largely controlled by latitude and elevation. Precipitation is influenced by numerous factors, each with a significant impact on the amount a location receives. The list below is not exhaustive, but includes the most important ones:

- **Latitude:** Latitude also influences weather patterns, but not in the same way it influences temperature. The Equator and 60°N &S typically experience low-pressure systems, which allow significant rainfall. Meanwhile, at 30°N & S and the Poles, high-pressure systems typically prevent significant rainfall. In fact, the world's largest rainforests (Figure 2.3.1) are located near the Equator, while the world's driest deserts (Figure 2.3.2) are located near 30°N & S.

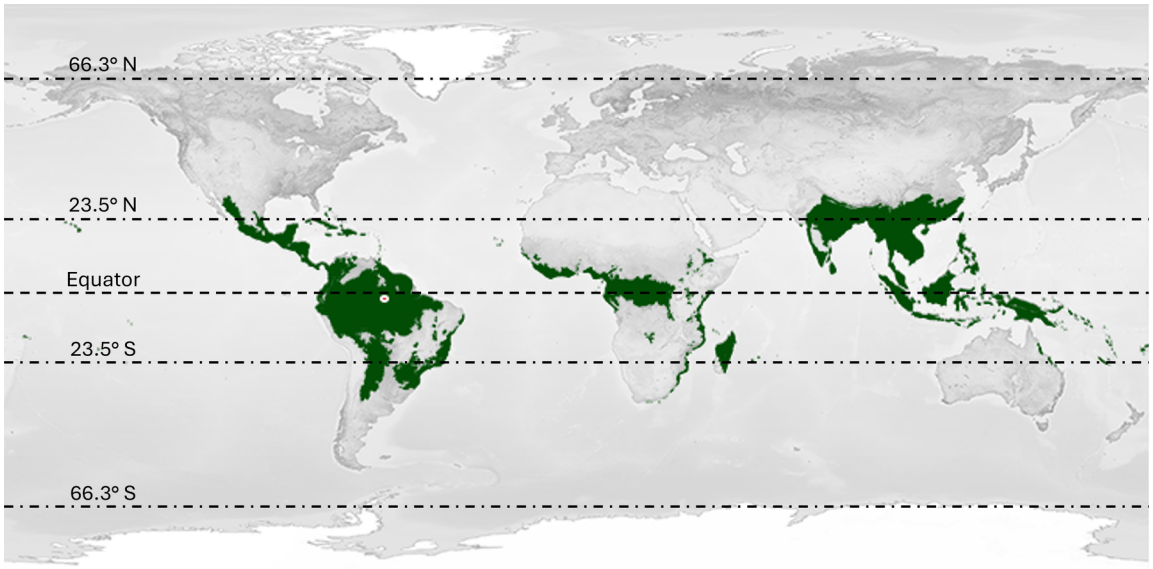


Figure 2.3.1: A map of the world's rainforests. (Public Domain; Biome Rainforest via NASA) Alternative description of the image.

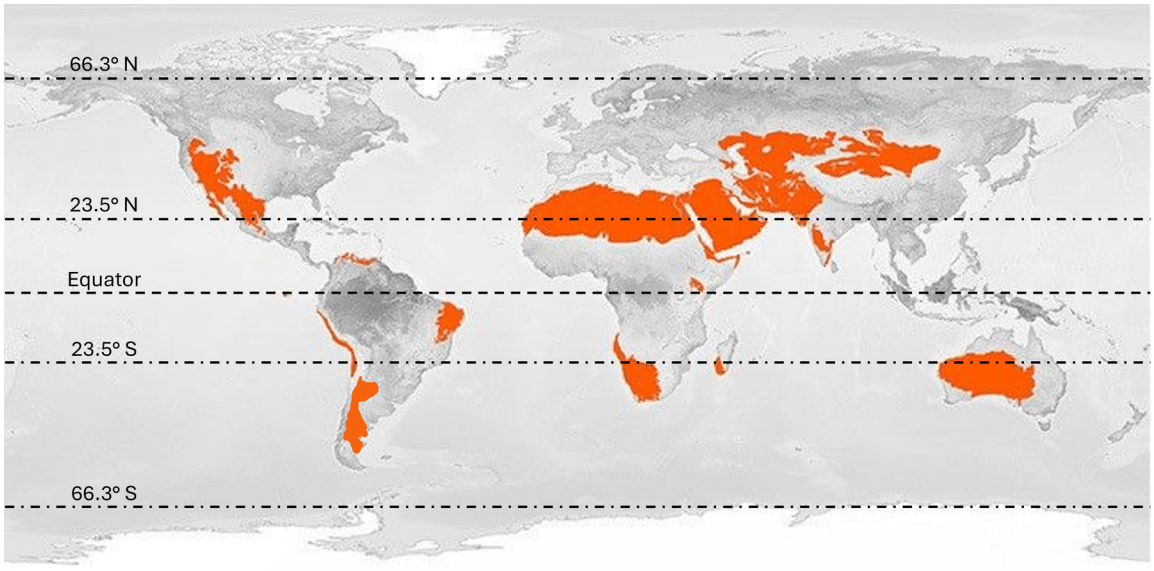


Figure 2.3.2: A map of the world's deserts. (Public Domain; Biome Desert via NASA) Alternative description of the image.

- Ocean Currents: Examine Figure 2.3.2 carefully, you will notice that the general rule that the world's largest deserts straddle 30°N & S is generally true, but not always. The west coast of South America is home to the Atacama Desert, the world's driest place. The desert stretches well north of 30°S, almost to the equator. The reasoning for this has nothing to do with high or low pressure, but instead with the nearby ocean current. Figure 2.3.3 shows the location of the world's major ocean currents. Warm ocean currents are shown in red and cold ocean currents are shown in blue. You'll notice that warm currents flow along the eastern coasts of continents, bringing warm tropical waters towards the poles. Cold water currents flow along the west coast of continents bring cold polar waters towards the tropics.

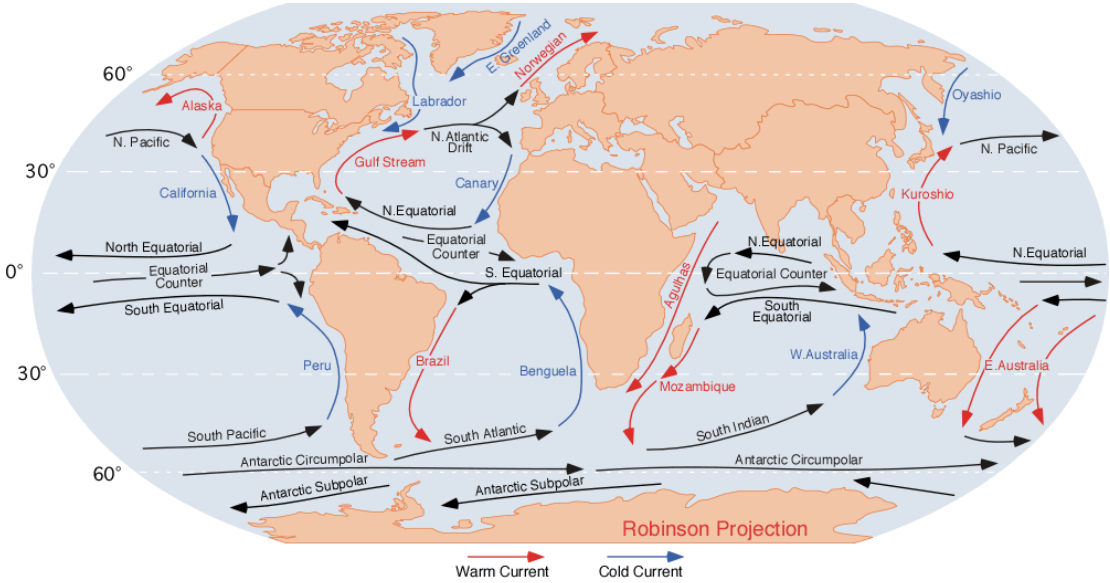


Figure 2.3.3: A map of global surface ocean currents. (Public Domain; Dr Michael Pidwirny via Wikimedia Commons) Alternative description of the image.

17. The Atacama Desert, on the West Coast of South America, is located next to a _____ ocean current. :
    a. warm
    b. cold
    c. neither warm nor cold

The average annual rainfall in Arica, Chile, is 0.76 to 1.8 mm (0.03 to 0.07 inches). On the other hand, the East Coast of South America, home to Rio de Janeiro, Brazil, lies next to the warm Brazil Current. The average annual rainfall in Rio De Janeiro, Brazil, is 1,100 to 1,300 mm (43 to 51 inches). Both cities have similar geographic features, such as coastal locations and similar latitudes and elevations, but very different rainfall patterns.

18. Compared to Arica, Chile, Rio de Janeiro, Brazil receives _____ rainfall.
    a. significantly less
    b. about the same
    c. significantly more
19. Considering what we learnt from Arica and Rio de Janeiro, cities near _____ ocean currents will experience _____ rainfall.
    a. cold; more
    b. cold; less

- **Proximity to mountain ranges:** If you live in Northern California, have you ever driven from Sacramento to Reno? If you have, you probably noticed how, during much of the drive, trees became taller and more lush, only to suddenly disappear into the desert by the time you arrived in Reno. The biggest reason for this, as you may have guessed, is the Sierra Nevada Mountain Range, which is between Sacramento and Reno. But why do mountains cause such a phenomenon? The reason is due to the Rain Shadow effect of the mountains (Figure 2.3.4). As air traveling eastward encounters a mountain, it has to rise over it. When air rises to higher elevations, it cools, condenses, and rains out on the windward side of the mountain. Towns on the windward side of such mountains receive significant orographic rainfall. Once it crosses the peak, it travels down the leeward side of the mountain. When air descends to lower elevations, it heats and dries. Thus, towns on the leeward side of the mountains receive significantly less rainfall.

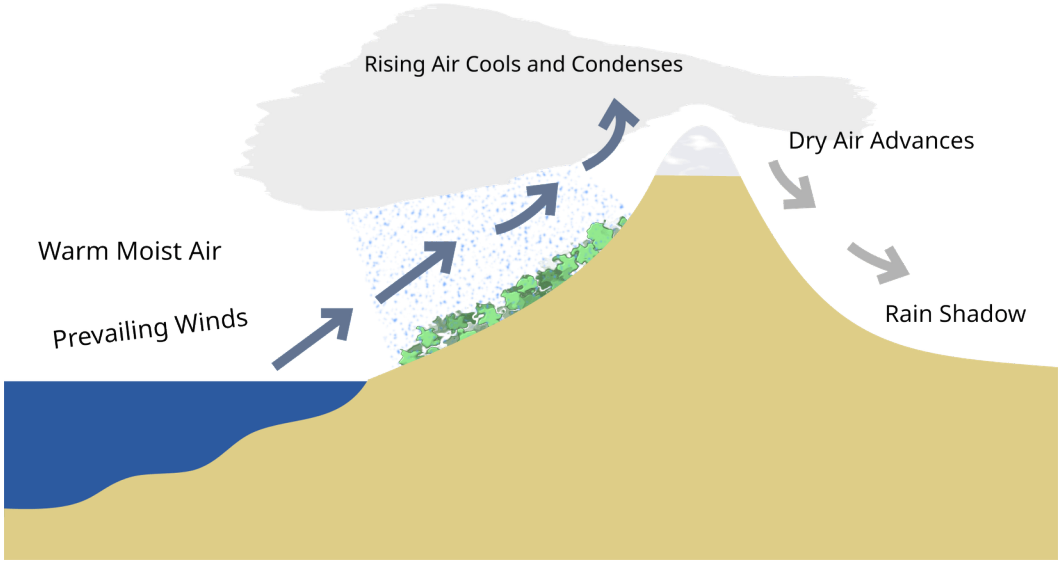


Figure 2.3.4: The Rain Shadow Effect. (CC BY 4.0; domdomegg via Wikimedia Commons) Alternative description of the image.

While there are many extreme examples of rain shadow zones around the world, let's examine the San Francisco Bay Area. San Jose, CA, in the southern San Francisco Bay Area, is on the leeward side of the Santa Cruz Mountains, while the city of Santa Cruz, CA, is on the windward side, near the Pacific Ocean. Figure 2.3.5 shows average precipitation, and Figure 2.3.6 shows the topography of the San Francisco Bay Area.

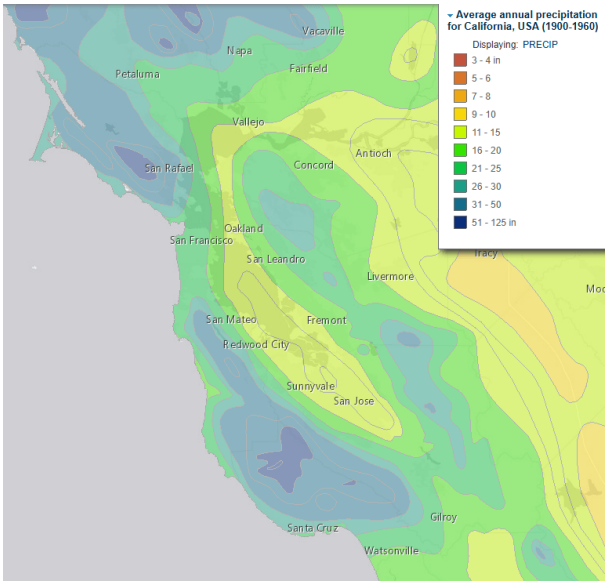


Figure 2.3.5: Annual precipitation in inches over the San Francisco Bay Area. (CC BY 3.0; USGS via databasin). Alternative description of the image.



Figure 2.3.6: Topography of the San Francisco Bay Area. (CC BY 4.0; Topographical maps via USGS). Alternative description of the image.

20. According to Figure 2.3.5, the city of Santa Cruz, California, receives between 26 and 30 inches of rain annually. Meanwhile, San Jose, in the southern San Francisco Bay Area, about 30 miles north of Santa Cruz, receives _____ inches of rain per year.
    a. 11-15
    b. 16-20
    c. 21-25

21. According to Figure 2.3.5 and Figure 2.3.6, between Santa Cruz and San Jose is a mountain range that receives ____ rainfall annually than either Santa Cruz or San Jose.
    a. significantly more
    b. significantly less

22. This occurs because air coming from the Pacific Ocean travels eastward over the Santa Cruz Mountains, and it _____ over the mountains.
    a. cools, condenses, and rains out
    b. warms and evaporates

23. Once the air sinks down the east side of the mountain, near San Jose, it is significantly _____.
    a. colder and wetter
    b. warmer and drier

This page titled 2.3: Precipitation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

2.4: Accessible Descriptions

Figure 1.1 Earth's regional climates

The continental United States is represented by a collection of overlapping photographs, each depicting a different environmental phenomenon. Alaska and Hawaii appear separately in their usual inset positions below and to the left of the mainland.

The images collectively suggest a range of climate-related hazards, including:

- Extreme heat
- Wildfires
- Forest dieback
- Flooding
- Agricultural impacts
- Drought
- Severe storms and hurricanes
- Ecosystem changes
- Melting ice

Western United States

In the Pacific Northwest and northern Rocky Mountain region:

- A large, bright white sun appears in a yellow-orange sky, suggesting extreme heat or heat waves.

Across much of the western United States:

- A large photograph shows a forest wildfire, with flames engulfing a tree and thick smoke filling the air.
- Another image depicts a landscape of dead or burned trees overlooking a body of water, suggesting forest damage from wildfire, drought, pests, or other environmental stress.

These images emphasize the increasing wildfire risk and changes in forest ecosystems.

Central United States

In the northern and central Plains:

- A photograph shows agricultural fields partially submerged, with rows of crops standing in the water.
- This suggests heavy rainfall, flooding, or waterlogged farmland.

In the southern Great Plains and Texas region:

- Aerial imagery shows cattle scattered across dry, pale-colored land, suggesting drought conditions and impacts on livestock and agriculture.

Together, these images contrast excess water in some regions with water scarcity in others.

Eastern United States

Across portions of the Northeast:

- The map is filled with an image of dense green vegetation or evergreen branches, representing forests and ecosystems that may be affected by changing climate conditions.

In the Southeast and Gulf Coast:

- A dramatic storm scene shows strong winds bending palm trees while rain and mist obscure nearby buildings.
- The image resembles a hurricane or tropical storm, with visible impacts on urban areas and coastal vegetation.

This section highlights the increasing risks posed by severe weather and coastal storms.

Alaska and Hawaii Insets

Alaska:

- The inset contains floating chunks of white ice in blue water, representing melting sea ice or glacial ice loss.

Hawaii:

- The islands are shown with small photographic textures that are difficult to distinguish individually but contribute to the overall environmental theme.

Figure 1.1.1 Earth's Latitudes

The image shows a circular view of the Earth focused on the Eastern Hemisphere, including Europe, Africa, and parts of Asia. The background is black, and the continents are outlined in thin, light-colored lines. The globe appears centered, with latitude markings prominently displayed across its surface.

Geographic Content

Visible landmasses include:

- The continents of North America and Europe lie entirely in the northern hemisphere.
- North America lies between 7°N and 85°N, while Europe lies between 35°N and 72°N latitudes.
- Meanwhile, Africa, Asia and South America extend to both sides of the equator.
- Africa extends from 37°N to 35°S, Asia from 10°S to 80°N, and South America from 12°N to 55°S.

Latitude Markings

Across the center of the globe, large white text labels the lines of latitude. These appear diagonally arranged from top to bottom and include:

75° (near the top of the globe, Northern Hemisphere), 60°, 45°, 30°, 15°, 0° – EQUATOR (centered across the middle, clearly labeled “EQUATOR”), 15° (Southern Hemisphere), 30°, 45° (near the bottom edge).

Figure 1.1.4: Sunlight When the Sun is Over the Equator

Diagram of Earth showing how sunlight hits different parts of the planet. The circle represents Earth, with "NP" (North Pole) at the top, "SP" (South Pole) at the bottom, and the Equator marked across the center. Two orange sunlight beams approach from the right. One beam hits the Equator directly, showing concentrated energy in a small area. The other beam hits Earth's upper atmosphere near the North Pole at an angle, spreading the same amount of sunlight over a larger area. This demonstrates why equatorial regions are warmer, and polar regions are colder.

Figure 1.1.5: Global Annual Average Air Temperatures

The image is a global map displaying the annual mean temperature across the Earth’s surface. The continents are shown with thin black outlines over a continuous color gradient representing temperature. The map uses an oval (Robinson-style) projection showing all continents. Below the map is a horizontal color scale (legend) labeled in both degrees Fahrenheit (°F) and degrees Celsius (°C). The title centered beneath the legend reads: “Annual Mean Temperature.”

Color Scale and Temperature Range

The legend shows temperatures ranging from:

- −50°C (−40°F) at the coldest end
- To 30°C (86°F) at the warmest end

Color progression from coldest to warmest:

- Light lavender to pink (extreme cold)
- Cyan (light blue)
- Dark red (hottest)

Both Celsius and Fahrenheit values are displayed along the scale:

- Celsius appears along the bottom (−50 to 30)
- Fahrenheit appears along the top (−40 to 80+)

Temperature Patterns by Region

Equatorial Regions (Hottest Areas)

- Central Africa
- Northern South America (Amazon Basin)
- Southeast Asia
- Northern Australia

These areas are shown in red to dark red, indicating average annual temperatures near 25–30°C (77–86°F).

Subtropical Deserts (Very Hot Areas)

- Sahara Desert (North Africa)
- Arabian Peninsula
- Parts of inland Australia

These regions are among the hottest on the map, shown in dark red, indicating some of the highest annual mean temperatures globally.

Temperate Regions (Moderate Temperatures)

- Most of the United States
- Southern Europe
- Southern South America
- Parts of China and Japan

These areas are shown in green to yellow, representing moderate average temperatures around 5–20°C (40–70°F).

Cold Regions

- Northern Canada
- Greenland
- Northern Europe
- Siberia

These regions appear in blue to dark blue, indicating average annual temperatures below freezing (below 0°C / 32°F).

Polar Regions (Coldest Areas)

- Antarctica
- Arctic Ocean region

These areas appear in purple, magenta, and light lavender, representing extreme cold, approaching −50°C (−58°F) in Antarctica.

Overall Pattern

The map shows a clear latitudinal temperature gradient:

- Warmest temperatures cluster around the Equator.
- Temperatures gradually decrease as you move toward the poles, north or south.
- Antarctica in the Southern Hemisphere is the coldest region overall.
- Land areas generally show more temperature variation than oceans.

Figure 1.1.6: Earth's Orbit Around the Sun

A diagram shows Earth's orbit around the Sun, illustrating how the tilt of Earth's axis causes seasonal changes. The Sun is at the center with four labeled Earth positions around it, each representing a different season in both hemispheres.

- June 20/21 (top left): Earth's North Pole is tilted toward the Sun. The Northern Hemisphere receives the most direct sunlight, leading to summer there. The Southern Hemisphere receives less sunlight, resulting in winter.
- September 22/23 (bottom left): Earth's axis is not tilted toward or away from the Sun. Both hemispheres receive roughly equal sunlight. This marks the autumn equinox in the Northern Hemisphere and the spring equinox in the Southern Hemisphere.
- March 20 (top right): Similar to September, sunlight is evenly distributed between hemispheres. It is the spring equinox in the Northern Hemisphere and autumn equinox in the Southern Hemisphere.
- December 21/22 (bottom right): Earth's South Pole is tilted toward the Sun. The Southern Hemisphere receives the most direct sunlight and experiences summer, while the Northern Hemisphere receives less sunlight and experiences winter.

Each Earth in the diagram shows a consistent tilt in its axis. Seasons in the Northern Hemisphere are labeled in yellow, and corresponding Southern Hemisphere seasons are labeled in lavender. A red arrow shows Earth's orbital direction around the Sun.

Figure 1.1.7: Conditions in June

Diagram of Earth tilted on its axis, showing how sunlight reaches different latitudes. The Earth is drawn as a circle tilted to the right. The North Pole (NP) is at the top, the South Pole (SP) is at the bottom, and the Equator is labeled in the center. Two additional latitude lines are shown: 23.5 degrees North (Tropic of Cancer) and 23.5 degrees South (Tropic of Capricorn).

Three horizontal orange bars labeled "Sunlight Beam" enter from the right, representing sunlight:

- The top sunlight beam fully covers the North Pole and the region around 23.5°N, showing that the Arctic is in continuous sunlight—experiencing 24 hours of daylight.
- The middle beam strikes the Equator directly, indicating the highest solar energy concentration in that region.
- The bottom beam misses the South Pole, leaving it in shadow. This shows the Antarctic is in continuous darkness, experiencing 24 hours of night.

This diagram illustrates how Earth's axial tilt affects the distribution of sunlight at the June solstice, causing one hemisphere to experience continuous daylight while the opposite hemisphere has continuous darkness.

Figure 1.1.8: Conditions in December

Diagram of Earth tilted on its axis to illustrate sunlight distribution during the December solstice. Earth is shown as a circle tilted to the left. Labels mark the North Pole (NP) at the top, the South Pole (SP) at the bottom, and the Equator across the middle. Two additional latitude lines are labeled: 23.5 degrees North (Tropic of Cancer) and 23.5 degrees South (Tropic of Capricorn).

Three orange horizontal bands labeled “Sunlight Beam” enter from the right, representing incoming solar radiation:

- The top sunlight beam does not reach the North Pole, indicating that the Arctic Circle is in full darkness, with 24 hours of night.
- The middle beam hits the Equator, showing balanced solar exposure at this latitude.
- The bottom beam directly hits the South Pole, demonstrating that the Antarctic Circle is fully illuminated, with 24 hours of daylight.

This diagram illustrates that at the December solstice, the Southern Hemisphere is tilted toward the Sun, resulting in summer and longer days. The Northern Hemisphere is tilted away from the Sun, experiencing winter and shorter days, including polar night conditions near the Arctic Circle.

Figure 1.2.1: Average monthly temperature in Iquitos, Peru

The image is a line graph showing the average monthly temperature in Iquitos, Peru across the 12 months of the year. The chart displays temperature in both degrees Fahrenheit (°F) and degrees Celsius (°C) on the vertical axis. The horizontal axis shows the months labeled numerically from 01 (January) to 12 (December). A red line with circular markers represents the monthly average temperature. A light red shaded band surrounds the line, indicating the typical temperature range (variation around the average).

Axes and Scale

Horizontal Axis (X-axis)

- Labeled: “Month of the year.”
- Months shown numerically from 01 to 12

Vertical Axis (Y-axis)

Two temperature scales appear on the left:

- Celsius (°C) scale ranging from 0°C to 40°C
- Fahrenheit (°F) scale ranging from 32°F to 104°F
- Tick marks appear at regular 5°C (approximately 9°F) intervals.

Temperature Pattern Throughout the Year

The graph shows very little seasonal variation. Temperatures remain consistently warm year-round. Approximate monthly averages:

- January–March: Around 26°C (79°F)
- April–May: Slight gradual decrease toward 25°C (77°F)
- June–July: Lowest point of the year, approximately 24–25°C (75–77°F)
- August–October: Gradual increase back to about 26–27°C (79–81°F)
- November–December: Slight decrease but remains near 26°C (79°F)

Range (Shaded Area)

The light red shaded region around the line suggests modest variability in temperatures:

- Upper range appears close to 29–30°C (84–86°F)
- Lower range appears around 22–23°C (72–73°F)
- The total annual variation in average temperature is small—approximately 2–3°C (3–5°F).

Key Takeaways

- Iquitos has a tropical climate with consistently high temperatures year-round.
- There is no pronounced winter or summer season.
- The warmest months appear around September–October.
- The coolest months appear around June–July.
- Overall annual temperature variation is minimal.

Figure 1.2.2 Average monthly temperature in San Jose, CA

The image is a line graph showing the average monthly temperature in San Jose, California, over the course of 1 year. The horizontal axis displays the months, numbered from 01 (January) to 12 (December). The vertical axis shows temperature in both degrees Celsius (°C) and degrees Fahrenheit (°F). A red line with circular markers represents the average monthly temperature. A light red-shaded band around the line indicates the typical temperature range (the variation around the monthly average).

Axes and Scale

Horizontal Axis (X-axis)

- Labeled: “Month of the year.”
- Months shown numerically from 01 through 12

Vertical Axis (Y-axis)

Two temperature scales appear on the left:

- Celsius (°C) scale from 0°C to 30°C
- Fahrenheit (°F) scale from 32°F to 86°F

Tick marks appear at regular 5°C (approximately 9°F) intervals.

Monthly Temperature Pattern

The graph shows a clear seasonal variation typical of a Mediterranean climate. Approximate monthly averages:

- January: About 10°C (50°F)
- February: About 11°C (52°F)
- March: About 13°C (55°F)
- April: About 14°C (57°F)
- May: About 16°C (61°F)
- June: About 18°C (64°F)
- July: About 20°C (68°F)
- August: About 20°C (68°F)
- September: About 21°C (70°F) (warmest month)
- October: About 17–18°C (63–64°F)
- November: About 13°C (55°F)
- December: About 10°C (50°F)

Seasonal Trends

- Temperatures gradually increase from winter through late summer.
- The warmest period occurs in July through September.
- Temperatures decline steadily in autumn.
- Winter months (December–February) are the coolest but remain mild compared to colder continental climates.

- The annual variation between the winter and late-summer averages is approximately 10–11°C (18–20°F).

Temperature Range (Shaded Area)

The light red shaded band indicates variability:

- Winter temperatures range roughly from 6–15°C (43–59°F).
- Summer temperatures range roughly from 15–28°C (59–82°F).
- The shaded band is widest during summer months, indicating greater daily variation.

Figure 1.2.3 Average monthly temperature in Tromsø, Norway

The image is a line graph showing the average monthly temperature in Tromsø, Norway, across the 12 months of the year. The horizontal axis displays months, numbered from 01 (January) to 12 (December). The vertical axis shows temperature in both degrees Celsius (°C) and degrees Fahrenheit (°F). A red line with circular markers represents the monthly average temperature. A light red shaded band around the line indicates typical variability around each monthly average. A thin horizontal black line across the graph marks 0°C (32°F), clearly indicating the freezing point of water.

Axes and Scale

Horizontal Axis (X-axis)

- Labeled: “Month of the year.”
- Months shown numerically from 01 to 12

Vertical Axis (Y-axis)

Two temperature scales appear on the left:

- Celsius (°C) scale from approximately –20°C to 20°C
- Fahrenheit (°F) scale from approximately –4°F to 68°F

Tick marks appear at regular 5°C (9°F) intervals.

Monthly Temperature Pattern

The graph shows strong seasonal variation typical of a high-latitude subarctic climate. Approximate monthly averages:

- January: About –10°C (14°F)
- February: About –9°C (16°F)
- March: About –6°C (21°F)
- April: About –2°C (28°F)
- May: About 3°C (37°F)
- June: About 8°C (46°F)
- July: About 12°C (54°F) (warmest month)
- August: About 11°C (52°F)
- September: About 7°C (45°F)
- October: About 0°C (32°F)
- November: About –6°C (21°F)
- December: About –9°C (16°F)

Seasonal Trends

- Temperatures remain below freezing from approximately October through April.

- The coldest months are January and February.
- Temperatures gradually rise in spring, crossing above freezing in May.
- The warmest period is short, centered around July.
- Temperatures decline rapidly after September, dropping below freezing again in October.
- The total annual temperature range is approximately 22°C (40°F) between winter minimum and summer maximum.

Temperature Range (Shaded Area)

The light red shaded band indicates variability around the monthly average:

- Winter ranges extend lower, suggesting frequent very cold days.
- Summer variability is narrower but still cooler than in temperate or tropical regions.
- Even in peak summer, average temperatures remain relatively mild.

Figure 1.2.4: The Climate Zones on Earth

The image is a labeled illustration of Earth as a three-dimensional globe, centered on the Americas. Several major lines of latitude are drawn across the globe and labeled. These lines divide the Earth into three main climate zones in each hemisphere: Arctic (polar), Temperate, and Tropical zones. The oceans are colored blue, and the continents are shown in light green. The background is black.

Labeled Lines of Latitude

Five key latitude lines are shown:

Arctic Circle (67° North)

- Drawn near the top of the globe.
- Encircles the high northern latitudes.
- Marks the southern boundary of the Arctic Zone.

Tropic of Cancer (23° North)

- Drawn in yellow.
- Located north of the Equator.
- Marks the northern boundary of the Tropical Zone.

Equator (0° Latitude)

- Drawn in red.
- Runs horizontally across the center of the globe.
- Divides Earth into the Northern and Southern Hemispheres.

Tropic of Capricorn (23° South)

- Drawn in yellow.
- Located south of the Equator.
- Marks the southern boundary of the Tropical Zone.

Antarctic Circle (67° South)

- Drawn near the bottom of the globe.
- Marks the northern boundary of the Antarctic (southern polar) Zone.

Climate Zones Identified

The globe is divided into horizontal bands:

1. Arctic Zone

- Located north of the Arctic Circle (67° N).
- Labeled near the top of the globe.
- Characterized by very cold temperatures and polar conditions.

2. Northern Temperate Zone

- Located between the Arctic Circle (67° N) and the Tropic of Cancer (23° N).
- Characterized by moderate seasonal variation.

3. Tropical Zone

- Located between the Tropic of Cancer (23° N) and the Tropic of Capricorn (23° S).
- Crosses the Equator.
- Characterized by warm temperatures year-round.
- Labeled on both sides of the globe.

4. Southern Temperate Zone

- Located between the Tropic of Capricorn (23° S) and the Antarctic Circle (67° S).
- Also characterized by moderate seasonal variation.

5. Antarctic (Southern Arctic) Zone

- Located south of the Antarctic Circle (67° S).
- Characterized by polar conditions and very cold temperatures.

Figure 1.3.1 A map of the world's rainforests

The image is a global map showing the distribution of tropical rainforests. The continents are displayed in light gray, and rainforest regions are highlighted in dark green. Several dashed horizontal lines mark key lines of latitude: 66.3° North, 23.5° North, the Equator, 23.5° South, and 66.3° South. The map emphasizes that tropical rainforests are concentrated near the Equator, within the band between the Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S).

Latitude Markers

Five dashed horizontal latitude lines are labeled:

- 66.3° N (Arctic Circle)
- 23.5° N (Tropic of Cancer)
- Equator (0°)
- 23.5° S (Tropic of Capricorn)
- 66.3° S (Antarctic Circle)

The rainforest regions appear almost entirely between 23.5° N and 23.5° S.

Major Rainforest Regions Highlighted

1. South America (Amazon Basin)

- The largest continuous dark green area appears in northern South America.
- Covers much of Brazil and extends into Peru, Colombia, Venezuela, Ecuador, Bolivia, and surrounding countries.

- Centered on the Equator.
- This represents the Amazon Rainforest, the largest tropical rainforest in the world.

2. Central America

- A narrow band of green runs through southern Mexico and into Central American countries such as Guatemala, Costa Rica, and Panama.
- Connects northward from the Amazon region.

3. Central and West Africa

- A large dark green region appears around the Equator in central Africa.
- Covers parts of the Democratic Republic of the Congo, Republic of the Congo, Gabon, Cameroon, and neighboring countries.
- Represents the Congo Basin rainforest.

4. Southeast Asia

- Extensive green areas appear in:
  - Southern India and Sri Lanka
  - Mainland Southeast Asia
  - The Malay Peninsula
  - Indonesia
  - The Philippines
  - Papua New Guinea

This region is part of the third major global concentration of tropical rainforest.

5. Madagascar

- A smaller green area appears along Madagascar's eastern coast, off the southeast coast of Africa.

Figure 1.3.2 A map of the world's deserts

The image is a global map showing the distribution of the world’s major desert regions. Continents are displayed in light gray with subtle shading. Desert areas are highlighted in bright orange. Dashed horizontal lines mark important latitudes: 66.3° North, 23.5° North (Tropic of Cancer), the Equator, 23.5° South (Tropic of Capricorn), and 66.3° South. The map shows that most deserts occur near 23.5° North and 23.5° South, though some extend into higher latitudes.

Latitude Reference Lines

Five dashed lines appear across the map:

- 66.3° N (Arctic Circle)
- 23.5° N (Tropic of Cancer)
- Equator (0°)
- 23.5° S (Tropic of Capricorn)
- 66.3° S (Antarctic Circle)

Most desert regions cluster near the Tropics rather than near the Equator.

Major Desert Regions Highlighted

North America

- Southwestern United States and northern Mexico (including areas such as the Mojave, Sonoran, and Chihuahuan deserts).
- Located near and just north of 23.5° N.

South America

- A narrow strip along the west coast (the Atacama Desert in Chile and Peru).
- A large desert region in southern Argentina (Patagonian Desert), extending farther south than most tropical deserts.

Africa

- A vast continuous region across North Africa, representing the Sahara Desert, centered around 23.5° N.
- Smaller desert areas in southwestern Africa (the Namib Desert) and southern Africa (the Kalahari region).

Middle East and North Africa

- The Arabian Peninsula extends eastward from the Sahara across Saudi Arabia and surrounding regions.

Central and East Asia

- A large desert region in Mongolia and northern China (Gobi Desert).
- Additional arid regions extend westward into Central Asia.

Australia

- A broad desert region across central Australia, centered near 23.5° S.

Figure 1.3.3 A Map of Global Ocean Currents

The image is a world map in the Robinson projection showing the major global ocean currents. Landmasses are shaded light tan, oceans are light blue-gray, and currents are represented by directional arrows.

- Warm currents are shown in red arrows.
- Cold currents are shown in blue arrows.
- Some neutral or connecting flows appear in black.
- Latitude reference lines are shown at approximately 60°, 30°, 0° (Equator), −30°, and −60°.
- A legend at the bottom indicates red for warm currents and blue for cold currents.

Major Currents by Ocean Basin

Atlantic Ocean

Warm Currents (Red):

- Gulf Stream: Flows northward along the eastern United States, then northeast toward Europe.
- Brazil Current: Flows southward along the east coast of South America.
- North Atlantic Drift: Extension of the Gulf Stream moving toward northwestern Europe.
- Norwegian Current: Continues warm water into the Arctic region.

Cold Currents (Blue):

- Labrador Current: Flows southward from the Arctic along eastern Canada.
- Canary Current: Flows southward along northwest Africa.
- Benguela Current: Flows northward along southwest Africa.

The Atlantic shows a large clockwise circulation (gyre) in the Northern Hemisphere and a counterclockwise circulation in the Southern Hemisphere.

Pacific Ocean

Warm Currents (Red):

- Kuroshio Current: Flows northward along the east coast of Japan.
- East Australia Current: Flows southward along eastern Australia.
- North Pacific Drift: Moves eastward across the northern Pacific.

Cold Currents (Blue):

- California Current: Flows southward along the west coast of North America.
- Peru (Humboldt) Current: Flows northward along the west coast of South America.
- Oyashio Current: Flows southward from the Arctic toward Japan.
- West Australia Current: Flows northward along Western Australia.

The Pacific also shows circular gyres:

- Clockwise in the Northern Hemisphere
- Counterclockwise in the Southern Hemisphere

Indian Ocean

Warm Currents:

- Mozambique Current and related flows moving southward along southeast Africa.
- South Equatorial flows across the basin.

Cold Currents:

- West Australia Current along Western Australia.

The Indian Ocean circulation reverses seasonally in parts due to monsoon winds (not explicitly labeled but implied by current structure).

Equatorial Currents

Across all three major oceans:

- North Equatorial Current flows westward just north of the Equator.
- South Equatorial Current flows westward just south of the Equator.
- Equatorial Countercurrent flows eastward between them.

These currents form part of the tropical circulation system.

Southern Ocean

- The Antarctic Circumpolar Current flows continuously eastward around Antarctica.
- The Antarctic Subpolar Current also circles Antarctica.

These currents connect the Atlantic, Pacific, and Indian Oceans.

Figure 1.3.4 The Rain Shadow Effect

The image is a cross-sectional diagram illustrating the rain shadow effect. It shows a body of water on the left, a mountain in the center, and dry land on the right. Arrows indicate air movement, and text at the top reads: “Rising Air Cools and Condenses.” The diagram demonstrates how mountains affect precipitation patterns by causing moist air to rise, cool, and lose moisture before descending as dry air on the opposite side.

Left Side: Ocean and Moist Air (Windward Side)

- A blue body of water appears on the far left.
- Arrows point from the ocean toward the mountain, indicating moist air moving inland.
- As the air reaches the mountain slope, arrows curve upward, indicating that the air is being forced to rise.
- Blue dots within the rising air represent water vapor and condensation.
- A large gray cloud forms above the mountain slope.
- The text “Rising Air Cools and Condenses” appears above the cloud, indicating that as air rises, it cools and water vapor condenses into clouds and precipitation.
- This side of the mountain is called the windward side, where precipitation occurs.

Mountain Peak

- The mountain is shown in tan color.
- The upper portion of the peak has a small white area, possibly representing snow.
- The cloud sits above the windward slope near the peak.

Right Side: Dry Descending Air (Leeward Side)

- On the right side of the mountain, arrows point downward.
- There are no blue dots or clouds on this side.
- The land appears dry, devoid of vegetation or water.
- The absence of precipitation indicates dry conditions.
- This side of the mountain is called the leeward side, also known as the rain shadow region.

This map depicts the average annual precipitation across parts of Northern California, including the San Francisco Bay Area, based on data collected from 1900 to 1960. The geographic region extends from the coastline near San Francisco and Santa Cruz inland to Livermore, Tracy, and parts of the Central Valley.

Figure 1.3.5 Annual Precipitation over the San Francisco Bay Area

This map depicts the average annual precipitation across parts of Northern California, including the San Francisco Bay Area, based on data collected from 1900 to 1960. The geographic region extends from the coastline near San Francisco and Santa Cruz inland to Livermore, Tracy, and parts of the Central Valley.

Map Overview:

- City names such as San Francisco, Oakland, San Jose, Fremont, Sunnyvale, Santa Cruz, and Livermore are labeled on the map for spatial reference.
- The base map uses colored contours to indicate zones of average annual precipitation in inches.
- The map legend on the right categorizes precipitation into 13 ranges, from 3–4 inches up to 125 inches per year.

Precipitation Ranges and Patterns:

The color-coded contour regions represent the following precipitation ranges (in inches):

- 3–4
- 5–6
- 7–8
- 9–10
- 11–15
- 16–20
- 21–25
- 26–30
- 31–50
- 51–125

Key patterns:

- Lowest precipitation areas (3–10 inches per year) are concentrated in valleys and interior lowlands, especially near San Jose, Fremont, and parts of the East Bay.
- Moderate precipitation zones (15–25 inches) appear in much of the San Mateo Peninsula, Redwood City, and parts of the inland hills near Livermore and Concord.
- Higher precipitation zones (over 30 inches) are found along the coastal mountains, including the Santa Cruz Mountains west of San Jose and near Santa Cruz and parts of the coastal Pacific slope.
- A small area near Big Basin or the Santa Cruz Mountains may reach over 50 inches per year.

Figure 1.3.6: Topography of the San Francisco Bay Area

This is a topographic map of central coastal California, focusing on the San Francisco Bay Area and adjacent terrain. The map uses shaded relief to represent elevation and terrain texture, but does not include contour lines, colors, or elevation labels beyond land shading.

Geographic Scope:

- Several prominent cities are labeled, including San Francisco (located in the northwest corner of the map, near the ocean), San Jose (in the center of the map, inland from the bay), Santa Cruz (in the southwest portion of the map, near the coast), and the Pacific Ocean to the west.
- The San Francisco Bay is visible, extending eastward and splitting into multiple channels.

Topographic Features:

- The Santa Clara Valley, where San Jose is located, is surrounded by mountainous terrain.
- The Santa Cruz Mountains lie west of San Jose and extend southward toward Santa Cruz.
- The Diablo Range lies to the east of the Santa Clara Valley.
- The elevated terrain is represented by darker-shaded areas that form ridges and valleys.
- Lowland valleys and plains are shown in lighter shading and are mainly located around San Jose and east of San Francisco Bay.

This page titled 2.4: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

3: RECORDS OF CLIMATE HISTORY

Introduction

Have you ever wondered what the "normal" weather for your hometown or location was, or how that normal was determined? With a little bit of observation and experience, it's pretty easy to identify basic climate patterns once you've lived somewhere for a while. For example, in most of California, it only rains in Fall/Winter and is dry in the summertime. Meanwhile, for most of Texas, it can rain during any month of the year, as shown in Figure 3.1. However, as Earth continues to warm, even local climate patterns are shifting, and climate scientists need access to long-term climate data for individual locations to get a clearer picture of how climate change is being felt locally.

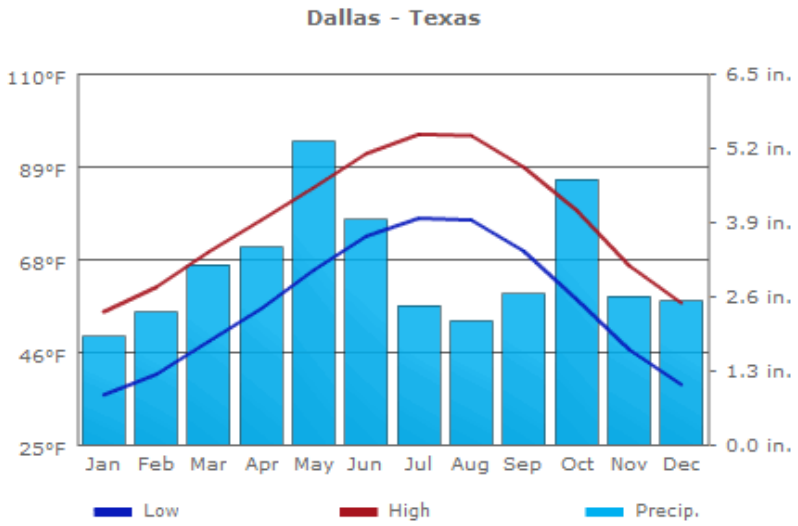


Figure 3.1: Climate averages for Dallas, Texas, showing monthly averages for high temperature, low temperature, and precipitation. (CC-BY 3.0; Soleado44 via Wikimedia Commons). Details from the figure are provided in Table 2.1.

Table 2.1: Average monthly temperatures (°F) and precipitation (in) for Dallas, Texas.

Month	Low (°F)	High (°F)	Precip. (in.)
Jan	36	56	1.9
Feb	41	62	2.3
Mar	48	69	3.2
Apr	55	77	3.5
May	64	85	5.3
Jun	73	92	3.9
Jul	77	96	2.4
Aug	76	96	2.2
Sep	69	88	2.6
Oct	58	78	4.6
Nov	47	66	2.5
Dec	38	57	2.5

In this investigation, we will access and review data and reports from the National Centers for Environmental Information (NCEI), the agency responsible for collecting and archiving Climate Data. While there are other agencies worldwide, for this investigation, we will focus on the United States, specifically the San Francisco Bay Area.

Learning Objectives

- Be able to investigate a location's temperature and precipitation patterns, and how they are changing.
- Be able to access climate records and extremes for a location.

Navigational Note

Investigation 2 has 21 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

3.1: Climate Data

3.2: Local Climate Data

3.3: Annual Climate

This page titled 3: Records of Climate History is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

3.1: Climate Data

Climate At A Glance

Numerous weather and climate data, including observations of temperature, wind, air pressure, and precipitation, make up the climate record, and climatologists are particularly interested in these variables to describe a location's climate. In the United States, Climatologists can access the NCEI Climate at a Glance (CAG) website to access and analyze real-time or near-real-time recorded data. You can access the CAG website: Climate At A Glance. For many of the activities we'll do in this investigation, the data and any plots will be given to you, but it is still a worthwhile skill to explore the CAG website and pull up climate data for a location.

To do so, do the following:

1. Go to the Climate At A Glance website.
2. In the tabs at the top, click "Nation," then under "Time Series," click "Launch."
3. The National Time Series page has five drop-down menus near the top that let you change settings for the parameter (variable), time scale, month, start year, and end year.
    1. Under Timescale, click the dropdown menu, select "12 months," then under month, select "December."
    2. You shouldn't need to change anything else. Before proceeding, make sure the parameter is set to "Average Temperature" and that the start and end years are 1895 and 2026, respectively. This will give you annual temperature averages for the United States from 1895 to 2026.
4. Under the "Base Period" and "Trend" menus, click on both the "display base period" and "display trend" checkboxes.
5. Hit Plot. You should now see a time series of Annual Average Temperatures for the United States for the 12-month period ending in December.

Questions based on above procedure

Let's start answering some questions based on this plot:

1. The 20th-century (1901-2000) temperature average (mean) for the United States was approximately:
    a. 51.09°F
    b. 49.37°F
    c. 52.01°F
    d. 53.36°F

The blue trend line shows how temperatures are trending over time. Trend lines are useful for identifying a discernible trend in the data. When a line slopes upwards as it moves right, that indicates a warming trend; when it slopes downwards, a cooling trend.

2. Average temperature data from the United States show that temperatures are experiencing a _____ trend.
    a. warming
    b. no
    c. cooling
3. This indicates that, if the trend were to continue, we could expect temperatures in the United States to _____ in the next several decades.
    a. level off
    b. begin falling
    c. keep rising
4. Hover your cursor over the time series to see individual years (which will appear as a vertical line in the time series with an average temperature at the bottom of the line). You could also scroll down and view the data presented in the table below the chart. The last time an individual year was BELOW the 20th century average was:
    a. 1976
    b. 1996
    c. 1989
    d. 2020

Now let's look at the US Precipitation data.

- Scroll back up to the top of the page, where the drop-down menus were.
- Under the dropdown menu next to "Parameter," select "Precipitation."
- Keep Everything else the same. Hit "Plot."

Now you should see a time series with an average, trend, and individual years for precipitation in inches and millimeters. Scrolling down further, you can see the same data in table form.

5. The 20th average precipitation for the United States is _____ inches.
   a. 30.37"
   b. 28.74"
   c. 31.39"
   d. 29.92"
6. Based on the per-decade trend, the United States is, on average, becoming:
   a. Wetter
   b. Drier
   c. Neither Wetter or Drier.
7. Based on your analysis of the last two charts, the United States is, on average, becoming:
   a. Colder and drier
   b. Colder and wetter
   c. Warmer and drier
   d. Warmer and wetter

The NCEI CAG website also contains data for individual regions and even cities. Let's examine California specifically.

- Scroll back up to the top of the page, where you can see the "National Time Series" title. Above that, there should be a menu with options such as "Global," "Nation," "Region," "State," etc. Hover over "State" and select "Statewide Time Series."
- You'll see a page similar to the National Time Series page, but with an extra box for State.
- Select "Average Temperature" as your parameter, "12-Month" as your time scale, 1895 and 2025 as your start/end times respectively, and California as your State. Then press "Plot".
- Make sure you click the "display base period" and "display trend" checkboxes again.

You should now see a very similar time series to what you saw for the United States, but now for California.

8. The 20th-century average temperature for California is a bit warmer than the United States average (makes sense since California is in one of the warmer climates of the country), with an average of:
   a. 57.4°F
   b. 59.37°F
   c. 55.32°F
   d. 56.18°F
9. Look at the trend line and the calculated trend, which you can see in the upper-right of the graph. The plotted trend line and the calculated trend show that California is:
   a. Getting cooler
   b. Not changing much
   c. Getting warmer.
10. Now scroll up to the dropdown menus again and change the parameter to "Precipitation" and click "Plot." Based on the Time series for average precipitation, California's wettest year was:
    a. 1998
    b. 2015
    c. 2023
    d. 1983
11. Based on the plotted and calculated trend, California is getting:
    a. Drier
    b. Wetter
    c. Experiencing little to no change in average precipitation

This page titled 3.1: Climate Data is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

3.2: Local Climate Data

Daily Local Climate Data

Have you ever watched a weather report and heard about the “normal” and “record” high and low temperatures for a particular day? If you haven’t, watch an evening news show one night, and watch a weather report. Meteorologists use “normal” and “record” data to compare current conditions to both averages and extremes, providing viewers with a sense of what kind of weather to expect. Before we jump into accessing and analyzing these data, let’s briefly cover the definitions of “normal” and “record.”

Normal weather conditions are based on the *30-year average*, typically reevaluated at the end of each decade. The purpose for using a 30 year average is to allow the average to change as a location’s climate changes (i.e. if it’s getting warmer in a city, the city’s “normal” temperature should be increasing… however, if we are basing that normal off of 140 years of data, recent observations may/usually are cancelled out by earlier observations) while also maintaining a statistically acceptable average (if you ever take a statistics class, you’ll likely learn that in order to assume that data follows a normal distribution, you need to have a minimum of 30 pieces of data… so having 30 years of temperature data satisfies that requirement). So, in short, we use a 30-year average to assume a normal distribution while preventing substantially older data from cancelling out newer data.

A **Record** weather condition represents the biggest extreme a location has experienced for a particular date. Records are based on all-time data rather than 30 years (since we are not taking an average, a record low from 100 years ago does not negate a record high from last year). The most common records shown are record high temperature, record low temperature, and record precipitation, but records for “coldest high” and “warmest low” temperatures are also available.

Accessing Normals and Records Data

As with the climatic data on the previous page, the normals and records data are easily accessible to anyone. This data is held and analyzed by the National Weather Service (because meteorologists use it as part of daily weather forecasts and reports, it makes more sense for NWS to house it than NCEI, which houses data used for longer-term analysis). You can access it by following these steps:

- Go to the National Weather Service Organisation page, which will take you to the NWS organisation page, which will show you a map with links to all of the NWS Weather Offices (local forecasts are managed by local offices as opposed to one central office).
- For this assignment, click on “San Francisco”, but if you want to look at other localities, you can do that by clicking on other stations. This will take you to San Francisco’s NOWData page, which can be used to access data from various Bay Area Cities.
- In the "NOWData – NOAA Online Weather Data" box, you should see four columns: Location, Product, Options, and View
  - Under Location, select San Francisco AP, CA – which is SFO Airport
  - Under Product, select “Daily Almanac”
  - Under Options, change the date to September 10th, 2022
  - Under View, press “Go”

The information you should be able to see is shown in Table 3.2.1, containing substantial data for normals and records.

Table 3.2.1: Almanac for San Francisco International AP, CA
September 10, 2022

Daily Data	Observed	Normal	Record Highest	Record Lowest
Max Temperature	79	75	94 in 1979	63 in 1989
Min Temperature	60	56	64 in 1997	49 in 1947
Avg Temperature	69.5	65.5	76.5 in 2017	58.0 in 1948
Precipitation	0.00	0.00	T in 1997	0.00 in 2025
Snowfall	M	M	0.0 in 2019	0.0 in 2019

Snow Depth	M	-	0 in 2019	0 in 2019
HDD (base 65)	0	1	7 in 1948	0 in 2025
CDD (base 65)	5	2	12 in 2017	0 in 2024
Month-to-Date Summary	**Observed**	**Normal**	**Record Highest**	**Record Lowest**
Avg Max Temperature	83.5	74.7	85.6 in 1984	66.4 in 1962
Avg Min Temperature	60.4	56.2	64.3 in 2017	50.9 in 1948
Avg Temperature	72.0	65.5	74.7 in 2017	59.2 in 1962
Total Precipitation	0.00	0.01	0.26 in 1978	0.00 in 2024
Total Snowfall	M	M	0.0 in 2019	0.0 in 2019
Max Snow Depth	M	-	0 in 2019	0 in 2019
Total HDD (base 65)	4	14	56 in 1962	0 in 2023
Total CDD (base 65)	76	19	98 in 2017	0 in 2018
Year-to-Date Summary	**Observed**	**Normal**	**Record Highest**	**Record Lowest**
Avg Max Temperature	68.1	67.1	69.5 in 2014	61.2 in 1949
Avg Min Temperature	51.6	50.8	53.8 in 2014	45.6 in 1955
Avg Temperature	59.9	58.9	61.6 in 2014	54.3 in 1949
Total Precipitation	1.90	12.61	30.22 in 1958	0.04 in 1945
Total Snowfall (since July 1)	M	M	0.0 in 2019	0.0 in 2019
Max Snow Depth (since July 1)	M	-	0 in 2019	0 in 2019
Total HDD (since July 1)	65	117	347 in 1955	8 in 2015
Total CDD (since Jan 1)	229	128	276 in 2014	8 in 1953

Table 2.2.2: Period of Record for Table 2.2.1

Measurement	Start Date	End Date
Max Temperature	1945-07-01	2026-04-19
Min Temperature	1945-07-01	2026-04-19
Precipitation	1945-07-01	2026-04-19
Snowfall	1945-07-01	2020-05-25
Snow Depth	1948-01-01	2020-03-09

12. On September 10, 2022, San Francisco reported a maximum temperature of 79°F, which was _____ the normal temperature for the day.
    a. Above
    b. Below
    c. Equal to
13. For the same day, the record highest Maximum temperature was:
    a. 64°F
    b. 60°F
    c. 94°F
    d. 76.5°F
14. Going to the Month-to-Date summary, the month of September 2022, at least as of September 10th, 2022, has been _____ (Hint: Compare Observed Average Max/Min to Normal Average Max/Min):
    a. Substantially Warmer than Normal
    b. About equal to Normal

    c. Substantially Cooler than Normal
15. Meanwhile, reported precipitation for September 10th was:
    a. Substantially Wetter than Normal
    b. About Equal to Normal
    c. Substantially Drier than Normal.
16. Written Question: Pick another city of your choice (you could either stay in the Bay Area, or if would like to go back to another location's weather office, you may do that), and pick a date of your choice (you can choose your birthday, favorite holiday, wedding day, or whatever you'd like), and then view the Almanac for that date and city you chose. Report the following (in the answer sheet provided by your instructor):
    1. Date and Location you chose.
    2. Max Temperature and if it was above or below normal.
    3. Min Temperature and if it was above or below normal.
    4. What the record Highest Maximum and Lowest Minimum were.
    5. Was there any precipitation on that day, and was it above/below normal?

Example: For April 16, 1998 in Long Beach California.

1. April 16, 1998, Long Beach (Area), California
2. Maximum Temperature was 71°F which was slightly below normal.
3. Minimum Temperature was 49°F which was below normal
4. Record Highest Maximum was set in 1999 at 89°F, and Lowest Minimum was 39°F in 1967.
5. There was no precipitation, which was slightly below the normal of 0.02" (note: April is the very tail end of the rainy season, so it's not abnormal to have dry days... but still being in the rainy season, it's also not uncommon for some rain... hence an average of 0.02").

This page titled 3.2: Local Climate Data is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

3.3: Annual Climate

Annual Climate Data Summaries

Finally, in addition to providing almanacs and keeping track of normals and records, The National Center for Environmental Information (NCEI) provides annual summaries of a location's weather and climatological comparison for about 275 locations (since this is a significantly more manual and human-involved process than storing and archiving almanac data, NCEI only does it for a small number of locations in comparison to total available weather stations). To access this Local Climatological Data (LCD), do the following:

1. Go to Annual Climate Data Summaries website.
2. Under "where," type "San Francisco, CA, USA"
3. Under "when," select "2020, 01, 01"
4. Finally, select "Download" under "SAN FRANCISCO DOWNTOWN, CA US (2020-01-01T00:00:00 "Annual")... you will then be provided a .pdf file that will contain the Local Climatological Data report for San Francisco in 2020.

Questions based on above procedure

17. For San Francisco, the warmest day of the year had a temperature of approximately 100°F during which month?
    a. April
    b. July
    c. September
    d. October
18. Oddly enough, The months with the warmest temperatures were _____ in 2020 which is very abnormal compared to other cities which typically experience their warmest months in June and July.
    a. April and May
    b. February and March
    c. August, September and October

This occurs because the months of June-August tend to experience substantial fog due to other climate factors such as Coastal Upwelling (we'll investigate that in a future investigation)

19. In 2020, the wettest day of the year saw about 1.25" of rain in which month?
    a. January
    b. March
    c. May
    d. December

Scroll to the next page of the document, which provides a complete Meteorological summary for San Francisco in 2020.

20. The warmest month of the year (using Mean Daily Maximum) was _____.
    a. May
    b. August
    c. September
    d. October
21. Scroll to the Precipitation Row on the same page, and look at the YEAR column. The top number is the total precipitation for San Francisco in 2020... this number is _____ than San Francisco's Normal annual rainfall of 23.65", indicating that 2020 was a _____ rain year.
    a. Well above; Particularly Wet
    b. Well below; Particularly Dry
    c. About Average; About Average

This investigation provides just a taste of the many data sources we employ in diagnosing current anthropogenic climate change. While we only looked at a few locations and instances, a bit of pursuing would show that much of the United States is on a warming trend (as seen by the increase in national average temperature) while changes in precipitation tend to be more regionally

dependent (the west has been getting drier while the north and east are getting a bit wetter). But how do we know that these trends are concerning? The answer to that is to compare current trends to trends observed over thousands of years... while we only have recorded climate data that goes back to the late 19th century, we can use other sources (such as paeloclimate proxies) to look further into the past... we'll do that in the next investigation.

This page titled 3.3: Annual Climate is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4: HEAT AND THE GREENHOUSE EFFECT

Introduction

Outside on a sunny day, you can feel the sun's energy on your skin. You can feel it as *heat*. Standing under the shade of a tree that blocks the sun's rays makes a significant difference in temperature. It also lowers your risk of sunburn and makes you feel much cooler. But the Sun is very far away from the Earth, where we are (Figure 4.1). The closest the Earth gets to the Sun is approximately 93 million miles. How does the sun's energy reach so far? What does the Earth do with all this energy? And how does it affect our climate? In this investigation, we'll explore the different types of heat transfer, their mechanisms, and then focus on electromagnetic radiation and its role in heating the Earth.



Figure 4.1: The Sun provides the Earth with most of its energy. (CC BY 2.0; Edmund Garman via Flickr).

Learning Objectives

- To discern one type of heat transfer from another.
- To identify the relationship between an object's temperature and the type and amount of radiation it emits.
- Distinguish the roles of the angle of insolation and the length of day in determining seasonal temperature changes.

Navigational Note

Investigation 3 has 21 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

4.1: Heat Transfer

4.2: Radiation

4.3: Selective Absorbers and Greenhouse Gases

4.4: Atmospheric Carbon Dioxide measurements

4.5: The Greenhouse Effect

4.6: Accessible Descriptions

This page titled 4: Heat and the Greenhouse Effect is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4.1: Heat Transfer

Types of Heat Transfer

Heat is energy that travels between two objects due to differences in their temperature. Imagine you're cooking a pizza in the oven: you put a cold pizza in a warm oven, and heat from the air inside the oven transfers to your pizza, thus cooking it. This example demonstrates the fundamental facts of heat transfer:

- Heat travels from a warm object to a cold object.
- Once the two objects have the same temperature (i.e., thermal equilibrium), heat transfer ceases.

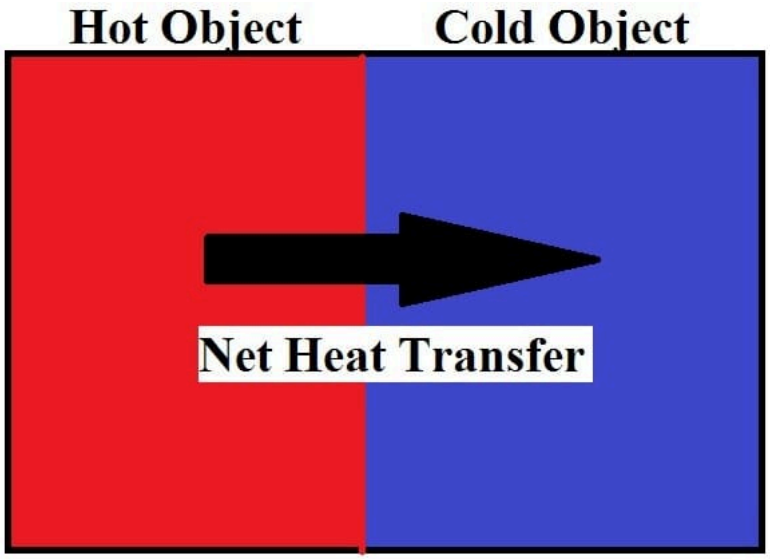


Figure 4.1.1: The net direction heat travels is from a warm object to a cold object. The figure indicates heat transfer from a "Hot Object" in red to a "Cold Object" in blue, and this process is shown via a black arrow with the words "Net Heat Transfer" (CC BY 4.0; Alicia Mullens)

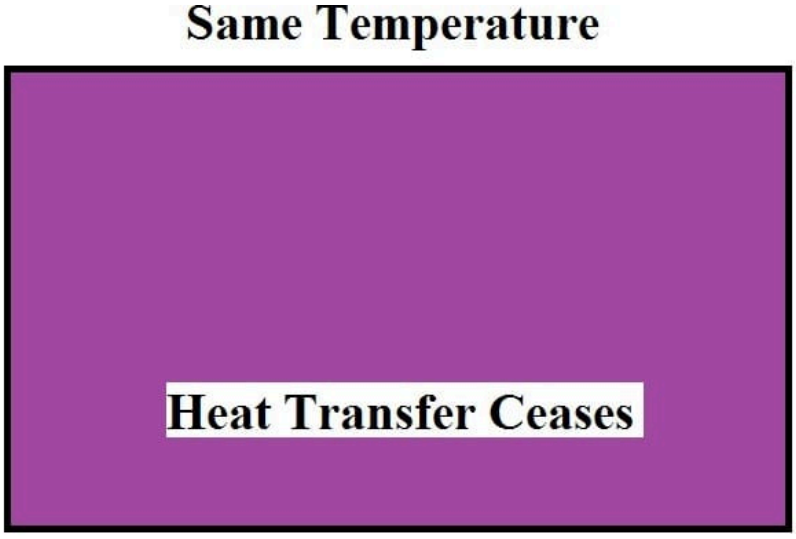


Figure 4.1.2: Once everything has the same temperature, net heat transfer ceases. (CC BY 4.0; Alicia Mullens)

Figures 4.1.1 and 4.1.2 illustrate the general nature of heat transfer. When two objects of different temperatures are next to one another in Figure 4.1.1, heat travels from the hot object to the cold object until the two objects have the same temperature in

Figure 4.1.2. There are three primary ways that heat can travel between the warm object and the cold object.

- Conduction: The transfer of heat through direct contact/via an intermediate object.
- Convection: The vertical transfer of heat through a fluid.
- Radiation: The transfer of heat through waves of electromagnetic energy called photons.

An example of the three main types of heat transfer is provided in Figure 4.1.3. When roasting a marshmallow at a bonfire, heat can travel from the fire's flame through the skewer to the person holding the skewer. This is **Conduction**, where the metal skewer acts as an intermediate object that allows heat from the flame to transfer to the person's hand. Wearing a thick glove or using a wooden-handled skewer can insulate the hand from heat transfer. Air itself is a poor conductor. However, when air comes into direct contact with the flame, it heats up, becomes less dense than the surrounding air, and rises. This, in turn, forces the cooler air surrounding the warm air to sink toward the flame, where it is heated. This transfer of heat via warm air rising and cold air sinking is called **Convection**. This distributes heat throughout the atmosphere and is key to warming our atmosphere. However, heat can sometimes travel horizontally as well. Warm ocean currents travel horizontally from the equator to the poles, transporting warm water to cooler regions of the Earth. This horizontal physical transport of a fluid and its stored heat from one place to another is called **Advection**. Since convection contributes to most of the heat transfer on our planet, advection isn't considered a primary mode of heat transfer, but a secondary one. Finally, the heat radiated by the flame is called radiation. If you've ever been near a warm object, such as a flame or a heater, and felt heat without touching it or being directly above it, the heat you experienced is radiation. **Radiation** is the transfer of heat through electromagnetic particles, known as photons. The benefit of radiation is that, unlike conduction, which requires either direct contact or an intermediate object, and convection, which requires a fluid, radiation can travel through nothing. Radiation can travel through various media, such as water, air, and glass, as well as through space, known as a vacuum.

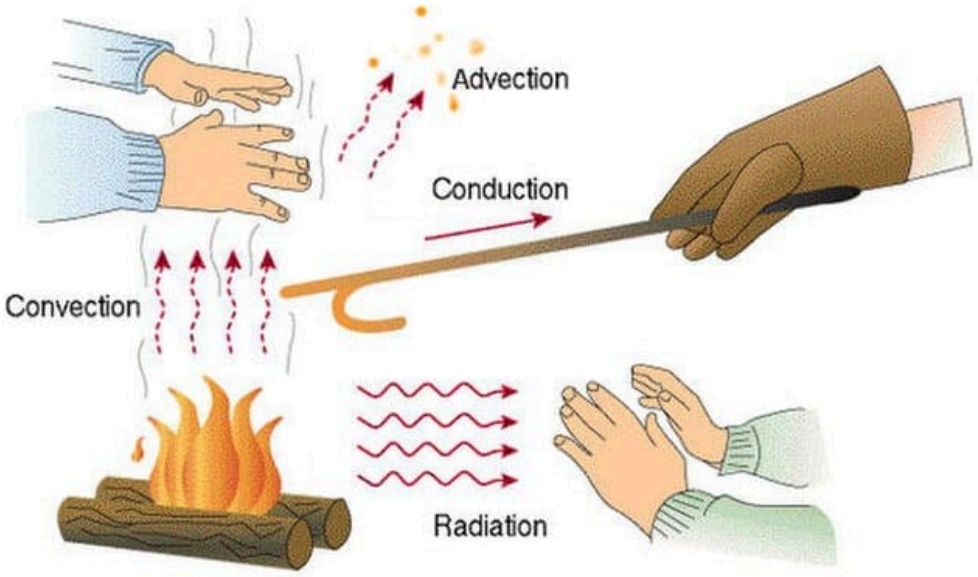


Figure 4.1.3: Different types of heat transfer processes (CC BY 4.0; Cmglee Kmecfiunit via Wikimedia Commons). Alternative description of the image.

Based on this information, let's try to answer the following questions:

1. Provide and describe an example of how each type of heat transfer is present in your everyday life (not counting boiling a pot of water). Please provide one example for each type of heat transfer (conduction, convection, and radiation), and explain how it is an example of that type of heat transfer.

2. When you step out in the sun and feel warmth, the sun is heating you via _____.
   a. conduction
   b. convection
   c. radiation

This page titled 4.1: Heat Transfer is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4.2: Radiation

What is radiation?

Radiation is how the Sun heats the Earth. The Sun, being a large and hot object, radiates a massive amount of energy that makes an 8-minute, 92,000,000-mile journey to Earth. Meteorologists must have a keen understanding of radiation. You would be surprised how much radiation is surrounding you right now. As a society, we often equate radiation with nuclear disasters, gamma rays, Homer Simpson, and so on. However, the light that brightens your home at night, the Wi-Fi signal you receive on your phone, and the radio signal that brings your favorite radio station to you are all examples of radiation. However, they are all very different types of radiation. Therefore, we need to understand what determines the type of radiation a photon contains. There is one key property that defines this: The radiation's wavelength (the Greek symbol λ, or lambda, is often used to denote wavelength). If you visualize a beam of radiation as a wave, the wavelength is the distance between successive peaks (as shown in Figure 4.2.1). The wavelength determines two other key properties of radiation: Energy and Frequency. Both are inversely proportional to the wavelength. This means that as the wavelength of a beam of radiation increases, both its frequency (f) and its energy (E) decrease. Therefore, longer-wavelength radiation is low-energy and typically harmless.

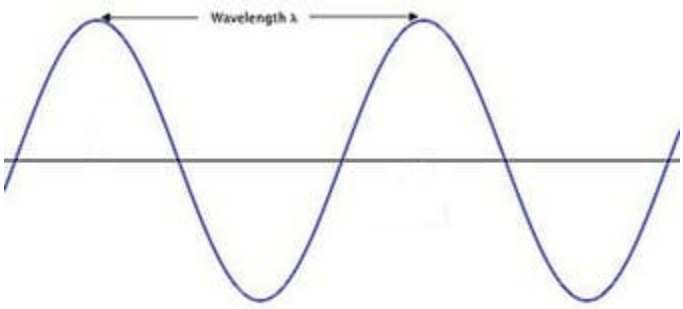


Figure 4.2.1: The wavelength is the distance between two consecutive peaks of an Electromagnetic Wave. (CC BY 4.0; Alicia Mullens)

The Electromagnetic Spectrum

The Electromagnetic Spectrum (Figure 4.2.2) shows the relationship between the wavelength, frequency, and energy of a category of radiation. AM Radio Waves have wavelengths of tens or even hundreds of meters, are extremely low-energy, and thus pass through things harmlessly. On the other hand, as the wavelength shortens, the type of radiation changes to FM Radio Waves, TV Waves, Microwaves, Infrared Waves, and so on, with each type becoming more energetic as the wavelength decreases.

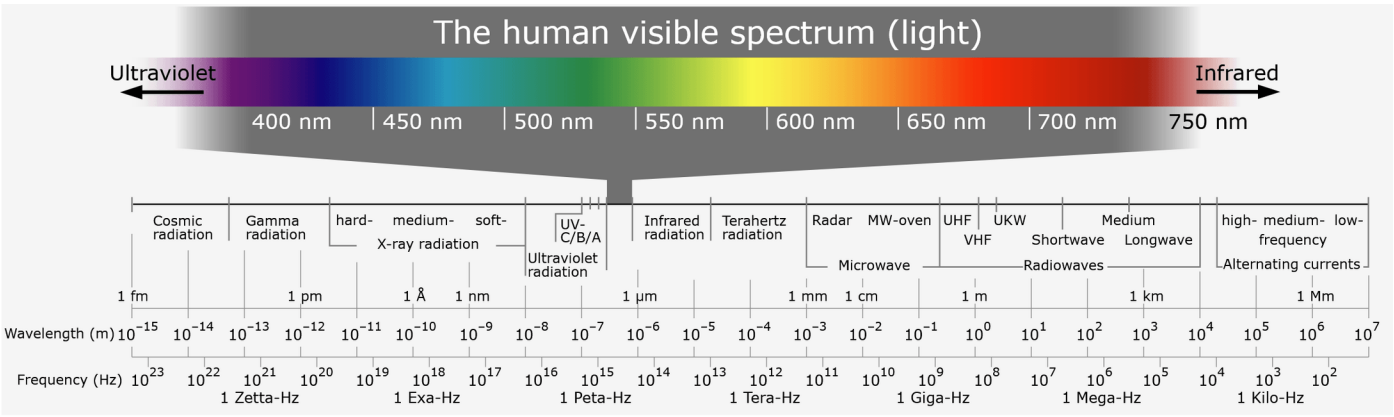


Figure 4.2.2: The Electromagnetic Spectrum. (CC BY 4.0; Horst Frank via Wikimedia Commons). Alternative description of image

Table 4.2.1 provides a more detailed description of the types of radiation, their wavelength ranges, and the corresponding types.

Table 4.2.1 *The Electromagnetic Spectrum explained*

Region	Wavelength Range (m)	Frequency Range (Hz)	Explanation
Cosmic Radiation	≈ 10^{-15}	≈ 10^{23}	Extremely high-energy radia
Gamma Radiation	10^{-14} – 10^{-12}	10^{22} – 10^{20}	High-frequency radiation fro
Hard X-ray	10^{-12} – 10^{-11}	10^{20} – 10^{19}	Shorter-wavelength, higher-
Medium X-ray	10^{-11} – 10^{-10}	10^{19} – 10^{18}	Intermediate energy X-rays
Soft X-ray	10^{-10} – 10^{-9}	10^{18} – 10^{17}	Lower-energy X-rays have gr
Ultraviolet (UV-C/B/A)	10^{-9} – 4×10^{-7}	10^{17} – 10^{15}	Non-visible UV light is just s
Visible Light	4×10^{-7} – 7.5×10^{-7}	10^{15} – 10^{14}	The portion of the spectrum
Infrared Radiation	7.5×10^{-7} – 10^{-4}	10^{14} – 10^{12}	Emitted by warm objects; us
Terahertz Radiation	10^{-4} – 10^{-3}	10^{12} – 10^{11}	Bridges microwave and infra
Radar	10^{-3} – 10^{-2}	10^{11} – 10^{10}	Used in detection systems f
Microwave (MW Oven)	10^{-2} – 10^{-1}	10^{10} – 10^{9}	Used for cooking, telecomm
Radio – UHF	10^{-1} – 1	10^{9} – 10^{8}	Ultra High Frequency; used i
Radio – VHF	1 – 10	10^{8} – 10^{7}	Very High Frequency; used i
Radio – UKW	10 – 100	10^{7} – 10^{6}	Ultra-shortwave radio; overla
Radio – Shortwave	100 – 1000	10^{6} – 10^{5}	Used for long-distance radic
Radio – Medium Wave	1 km	10^{5} – 10^{4}	AM radio broadcast frequen

Region	Wavelength Range (m)	Frequency Range (Hz)	Explanation
Radio – Longwave	10 km	10^4 – 10^3	Long-distance, low-frequenc
Low-Frequency (AC)	10^3 – 10^7	10^3 – $10^{\square 3}$	Alternating current; used in

3. Based on the visible light portion of the EM spectrum, _____ light has the shortest wavelength while _____ light has the longest wavelength.
   a. Red; Violet
   b. Yellow; Violet
   c. Violet; Red
   d. Blue; Green

4. Thus, recalling the relationship between wavelength and energy, the most energetic color is _____, while the least energetic color is _____.
   a. Red; Violet
   b. Yellow; Violet
   c. Violet; Red
   d. Blue; Green

Because radiation waves can become so short, we must introduce two new units into our toolbox: The nanometer (1 nm = 0.000000001 m) and the micrometer (1 µm = 0.000001 m). 1000 nm = 1 µm. There are a few key facts and laws of the electromagnetic spectrum that you need to know before we can thoroughly investigate how radiation affects our weather:

Fact and Law

Fact: Every object with a temperature above Absolute Zero (0 K) emits radiation! Yes, that includes everything around you, and you as well! We jokingly call this "Oprah's Law" (Everybody emits radiation!), but it's important to note that it's a fact, not a law.

Stefan-Boltzmann Law: The warmer an object is, the more radiation the object emits. This is called the Stefan-Boltzmann law, and the equation for it is given as:

$$E = \sigma T^4 \tag{4.2.1}$$

Where E is the total amount of energy, T is the object's temperature, in Kelvin, and σ is called the Stefan-Boltzmann Constant, and σ = 5.670373 x 10^{-8} $Wm^{-2}K^{-4}$. Don't worry about the equation; focus on the idea that Warmer Objects Emit More Radiation.

Wein's Law: The warmer an object is, the shorter the wavelength it emits. This is called Wein's Law (pronounced Vein's law), and the equation for it is:

$$\lambda_m = \frac{2898(\mu m K^{-1})}{T(K)}$$

Where λ_m is the wavelength (in micrometers) most emitted by an object, and T is the temperature in Kelvin. To convert a wavelength from micrometers to nanometers, multiply by 1000. Thus, not only is the amount of radiation emitted by an object dependent on the temperature of the object, but so is the type of radiation.

Let's answer the following questions based on these laws.

5. Based on the Stefan-Boltzmann Law, the Sun (T = 6000K) emits _____ radiation than the Earth (T = 290 K).
   a. more

   b. less

6. Using the equation for Wien's Law, the wavelength most emitted by the Sun (T = 6000K) is approximately:
   a. 48.3 µm
   b. 483 µm
   c. 0.483 µm
7. Converted to nanometers (multiply your answer to question 6 by 1000), the wavelength of radiation emitted by the Sun is approximately:
   a. 48,300 nm
   b. 483,000 nm
   c. 483 nm
8. According to the Electromagnetic Spectrum, the radiation most emitted by the Sun is in the form of:
   a. Infrared rays (741 nm-1 mm)
   b. Visible Light (400-740 nm)
   c. Ultraviolet Rays (10 nm-399 nm).
9. On the other hand, using the equation for Wein's Law, the Earth, with a temperature of approximately 290 K emits radiation primarily as _____.
   a. Infrared Rays
   b. Microwaves
   c. Gamma Rays
10. Thus, the _____ emits Shorter-Wave radiation (we'll call this Shortwave Radiation from now on). In contrast, the _____ emits Longer-Wave radiation (we'll call this Longwave Radiation from now on).
   a. Earth; Sun
   b. Sun; Earth

Now that we have a baseline understanding of the types of radiation emitted by the Earth and the Sun, we can discuss how they affect our atmosphere. Once Solar radiation, which extends beyond the wavelength calculated above, reaches the top of the atmosphere, several processes can occur. Radiation that enters the top of the atmosphere can either be:

- Reflected by clouds
- Reflected/Scattered by the Atmosphere
- Reflected by Earth's Surface (Land and Ocean)
- Absorbed by the Atmosphere
- Absorbed by the Earth's surface (Land and Ocean)

All of these factors significantly affect the amount of heat the Earth receives and, thus, its temperature.

This page titled 4.2: Radiation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4.3: Selective Absorbers and Greenhouse Gases

Absorption by the atmosphere

Most of the key gases in the atmosphere are called Selective Absorbers, meaning they are entirely transparent to some wavelengths of radiation while completely absorbent (i.e., opaque) to others. This is particularly crucial when considering Greenhouse Gases, which are widely regarded as the primary drivers of global warming.

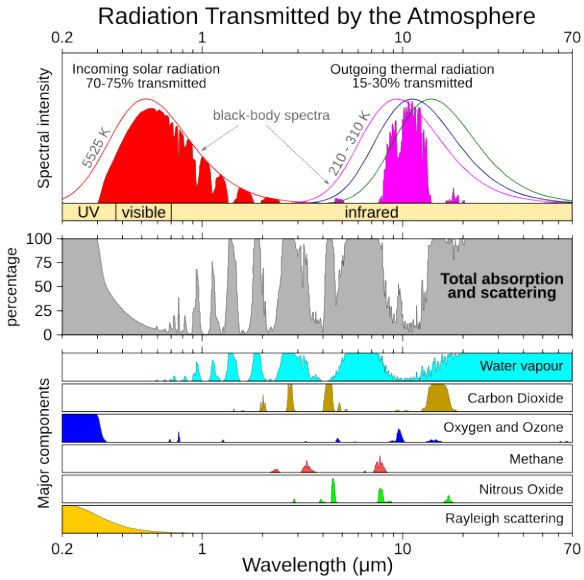


Figure 4.3.1: The Absorption Spectrum of the Atmosphere. (Public domain; Wikkiwonkk via Wikimedia Commons). Alternative description of the image.

To understand which gases absorb which wavelengths of radiation, we must examine the absorption spectrum in Figure 4.3.1 . Here's how to read this figure: There are eight panels, each with the same “x” axis (wavelength) and “y” axis (% of radiation absorbed or scattered by gases). Wherever you see a grey area in the second panel, it represents absorption happening at that wavelength. Meanwhile, for panels 3-7, the amount of colored area represents the percentage absorbed. For example, Oxygen and Ozone absorb almost 100% of radiation between 0.2 and 0.3 μm (200-300 nm). These wavelengths fall within the ultraviolet range. This is reasonable because the ozone layer absorbs ultraviolet radiation, thereby protecting us from its effects. It can also be assumed that radiation not absorbed by these gases passes right through them. The bottom panel represents Rayleigh Scattering, which we won't cover here.

11. The second panel in Figure 4.3.1 shows total absorption and scattering, which represents the total absorption from all of the gases of the atmosphere. According to the figure, most visible light is _____ by the atmosphere.
    a. absorbed
    b. not absorbed

12. However, with a few exceptions, many wavelengths with values above 0.7 μm are mostly _____ by gases in the atmosphere.
    a. absorbed
    b. not absorbed

Gases that are mostly transparent to shortwave radiation (visible Light and shorter wavelengths... 0.7 μm and less) but absorb longwave radiation (Infrared radiation, mostly above 0.7 μm) are called Greenhouse Gases. These gases play a crucial role in keeping Earth warm by allowing shortwave radiation to heat the Earth while preventing longwave radiation from escaping to space.

13. According to the Absorption Spectrum, which of these gases are greenhouse gases?
    a. Water Vapor (H_2O)
    b. Methane (CH_4)

c. Carbon Dioxide (CO_2)
d. Nitrous Oxide (NO_2)
e. All of these

14. Except for a massive spike in absorption of radiation near 10 μm, the atmosphere is mainly transparent to wavelengths between _____. This is called the Atmospheric Window.
    a. 1 and 100 μm
    b. 5 and 20 μm
    c. 7 and 12 μm

This page titled 4.3: Selective Absorbers and Greenhouse Gases is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4.4: Atmospheric Carbon Dioxide measurements

The Keeling Curve

While there are numerous greenhouse gases present in the atmosphere, with all of them contributing somewhat to Earth's Greenhouse Effect, by far the most influential and concerning greenhouse gas is Carbon Dioxide (we'll explore why in more depth when we explore Radiative Forcing). Since the mid-1800's, approximately the same time as the Industrial Revolution, which resulted in significant advancements in the quality of life across many developed countries, Carbon Dioxide has seen a notable rise, as seen in Figure 4.4.1.

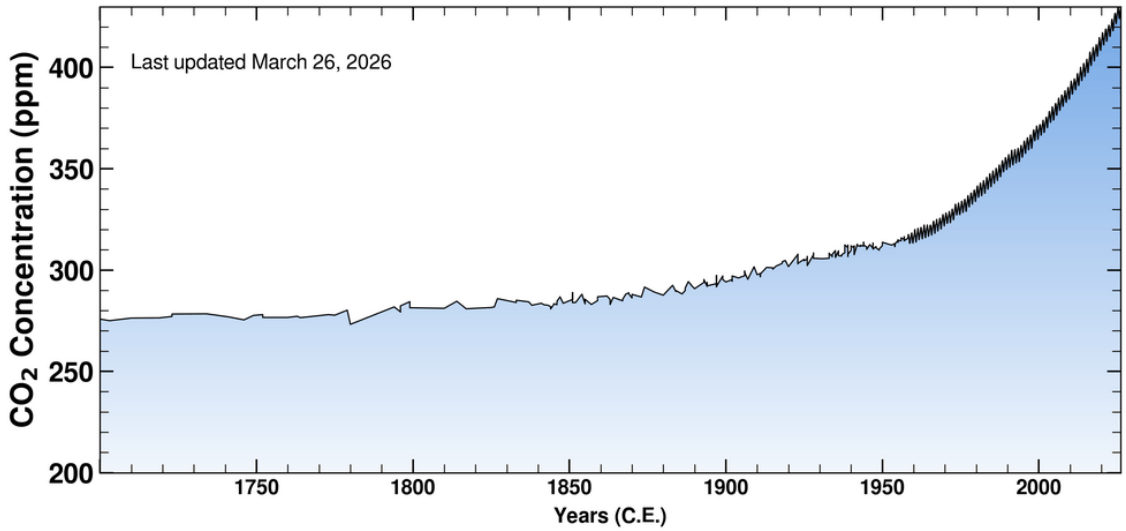


Figure 4.4.1: Carbon Dioxide concentrations in the atmosphere since 1700. (CC BY 4.0; Ralph Keeling via Scripps Institution of Oceanography)
Alternative description of the image.

Figure 4.4.1 shows Carbon Dioxide concentrations in the atmosphere since 1700. However, since 1958, Carbon Dioxide concentrations have been directly measured and monitored at the Mauna Loa Observatory on the Big Island of Hawaii. Today, a graph of these remarkable measurements versus time is known as the **Keeling Curve**, and it is shown in Figure 4.4.2. On the curve, the unit for Carbon Dioxide concentrations is parts per million (ppm), which is the average number of carbon dioxide molecules in a sample of 1,000,000 molecules of atmospheric air. It was named after the monitoring station's founder, David Keeling, who showed a steady increase in atmospheric Carbon Dioxide since 1958. Prior to 1958, ice core data were used to estimate atmospheric Carbon Dioxide concentrations, as shown in Figure 4.4.1.

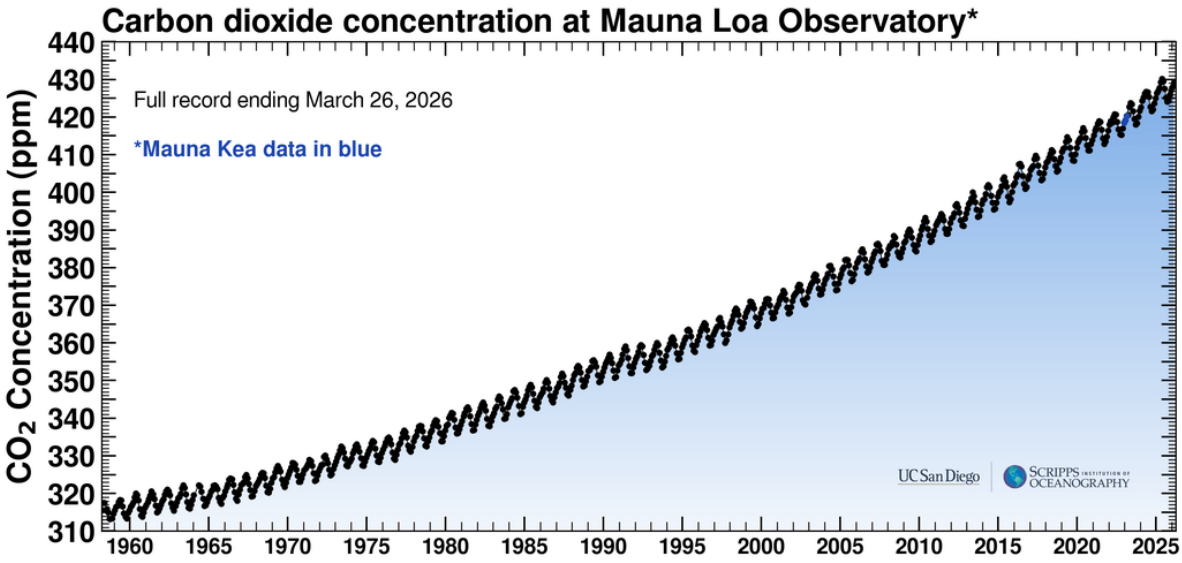


Figure 4.4.2: Carbon Dioxide concentrations in the atmosphere measured by the Keeling Curve since 1958. (CC BY 4.0; Ralph Keeling via Scripps Institution of Oceanography) Alternative description of the image.

Based on this information, let's try to answer the following questions:

15. Based on Figure 4.4.1, Carbon Dioxide concentrations were generally stable from 1700 until approximately 1850. During this time, they had a concentration of approximately:
    a. 210 ppm
    b. 280 ppm
    c. 315 ppm
    d. 420 ppm
16. On the other hand, based on Figure 4.4.2, the current Carbon Dioxide concentrations are approximately: (CO_2 concentration in 2025-2026)
    a. 315 ppm
    b. 295 ppm
    c. 395 ppm
    d. 430 ppm
17. Also based on Figure 4.4.2, while there is some variation in annual Carbon Dioxide concentrations (the zig-zags in the curve), the overall trend in the concentrations is:
    a. decreasing
    b. leveling off
    c. increasing

This page titled 4.4: Atmospheric Carbon Dioxide measurements is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4.5: The Greenhouse Effect

Greenhouse Gases

So, how do greenhouse gases affect Earth's temperatures? Greenhouse gases absorb some of the outgoing longwave radiation emitted by the Earth. This increases their temperature, and in turn they emit longwave radiation back towards the Earth, keeping us warm. However, as greenhouse gas concentrations in the atmosphere increase, that effect is amplified. For a more precise estimate, we can consult simplified climate models to investigate this effect. A simplified model is available from the University of Colorado, which you can find on PHET interactive simulations page. This allows us to modify the model to observe how greenhouse gas concentrations in our atmosphere affect our temperature. This includes examining Earth's temperatures prior to the Industrial Revolution! For the rest of this investigation, we'll examine this model and answer the following questions.

- Go to the PHET interactive simulations page.
- On the home screen, select “Waves”. If you select “Photons,” you’ll still get the same results. But don’t select “Layer Model”, since that will be used in a future activity.
- To answer the next three questions, we'll adjust the "Greenhouse Gas Concentration" slider on the right-hand side of the page.

18. Let’s get rid of greenhouse gases altogether. If it’s not already selected, click the “by concentration” radio button in the “Greenhouse Gas Concentration” area to activate the slider. Move it all the way down to “None”. Then select the “Start Sunlight” button. As the model plays, it shows changes in the surface temperature (in Celsius). A Thermometer is shown at the bottom-left of the animation. After about a minute, the temperature will stabilize. This represents the Earth's estimated surface temperature. In a world without any greenhouse gases, the estimated surface temperature of Earth would be approximately:
    a. -18°C
    b. -2°C
    c. 0°C
    d. 4°C

19. Now select the “Reset All” button (at the bottom right of the screen) to refresh the model. Let’s set the greenhouse gas concentrations to the maximum level (“Lots”), select the “Start Sunlight” button, and give the model a minute or two to adjust. The estimated surface temperature of Earth would be approximately:
    a. 25.8°C
    b. 15.1°C
    c. 17.4°C
    d. 31.2°C

20. Now, let’s examine Earth's temperature during the pre-industrial period. First, select the “Reset All” button to refresh the model. There are two buttons at the bottom of the Greenhouse Gas Concentrations area. We have been using “By Concentration,” which has a slider. Now we will select the “Time Period” button, which looks like a calendar. This lets you select greenhouse gas levels for several time periods. Select the button to activate this mode, then choose the year “1750” (if it is not already selected). Select the “Start Sunlight” button to run the model. After a minute of the model playing, the temperature stabilizes at approximately:
    a. 17.4°C
    b. 13.6°C
    c. 14.9°C
    d. 11.2°C

21. Finally, select 2020 and run the model again. As the model is running, the temperature _____ from the 1750 level.
    a. increased
    b. decreased

As you can see in the model, greenhouse gases have a significant impact on the climate. You can play around with the model a little bit to see how changes in cloud cover would affect Earth’s temperature. We will revisit this model in future investigations and delve deeper into climate models.

This page titled 4.5: The Greenhouse Effect is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

4.6: Accessible Descriptions

Figure 3.1.3 Different Types of Heat Transfers

An educational diagram illustrating four methods of heat transfer: conduction, convection, radiation, and advection. A fire is at the center of the image.

- Convection is shown as upward motion of warm air from the fire toward a pair of hands held above it, indicating heat transfer through the movement of heated air.
- Radiation is shown by wavy lines traveling directly from the fire to another pair of hands held at a distance in front of it, representing direct heat transfer via electromagnetic radiation.
- Conduction is depicted by a person holding a metal rod in their hand, with the opposite end placed in or near the fire. This shows heat traveling through the solid rod from the hot end to the hand.
- Advection is represented by particles or dots moving horizontally away from the heated air, symbolizing horizontal heat transfer through bulk fluid motion.

The diagram is designed to clarify how thermal energy moves in different ways depending on the medium and mechanism.

Figure 3.2.2 The Electromagnetic Spectrum

A labeled diagram of the electromagnetic spectrum focusing on the range of human-visible light. The visible spectrum is positioned between ultraviolet and infrared regions. The top section marks visible wavelengths in nanometers, ranging from 400 to 750 nm. Below it, a horizontal scale shows corresponding electromagnetic categories—such as ultraviolet radiation, infrared radiation, microwaves, and radio waves—with their associated wavelength values (from 1 femtometer to 10 megameters) and frequency values (from 10^{24} Hz to 10^{4} Hz). Key divisions like cosmic radiation, gamma rays, X-rays, radar, and alternating currents are labeled accordingly.

This diagram illustrates the full electromagnetic spectrum, highlighting the visible portion, which spans wavelengths from approximately 400 to 750 nanometers. The spectrum is organized from left to right by increasing wavelength and decreasing frequency.

To the left of visible light are shorter wavelengths and higher frequencies, representing high-energy radiation. This includes cosmic radiation (starting at about 1 femtometer), gamma rays, and various types of X-rays (hard, medium, and soft). These radiations are mostly invisible and hazardous to biological tissue.

Immediately before the visible spectrum is ultraviolet radiation, divided into UV-C, UV-B, and UV-A types. The visible spectrum lies in the middle of the chart and spans 400 to 750 nanometers. This is the only portion of electromagnetic radiation detectable by the human eye.

To the right of visible light, the wavelengths grow longer, and frequencies drop. This includes infrared radiation, followed by terahertz radiation and microwaves, which are commonly used in communication and cooking appliances.

Beyond these lie radio waves, organized into bands such as ultra-high frequency (UHF), very high frequency (VHF), and others, including shortwave, medium wave, and longwave. At the far right are low-frequency alternating currents with extremely long wavelengths, used in electrical power systems.

The diagram also includes logarithmic scales along the bottom:

- Wavelength, measured in meters, ranges from 10^{-15} meters to 10^{7} meters.
- Frequency, measured in hertz (Hz), ranges from 10^{23} Hz to 10^{3} Hz.

This spectrum provides a comparative view of how electromagnetic radiation types are distributed by wavelength and frequency, with the visible portion emphasized for reference. More details regarding the exact wavelengths within the spectrum are provided in Table 3.2.1.

Figure 3.3.1: Absorption Spectrum

A scientific diagram titled "Atmospheric Transmission" shows how much electromagnetic radiation is absorbed or scattered by Earth's atmosphere at different wavelengths. The horizontal axis is labeled with wavelength in micrometers and nanometers, ranging logarithmically from approximately 10^{-3} micrometers (gamma rays) to 10^{6} micrometers (radio waves). Major sections along the wavelength axis are labeled as gamma rays, X-rays, ultraviolet, visible, infrared, and radio waves. The vertical axis represents the percentage of atmospheric absorption and/or scattering, from 0% to 100%.

Table 4.6.1: Atmospheric transmission versus wavelength

Wavelength Region	Approx. Wavelength (µm)	Solar Radiation (5525 K)	Earth Thermal Radiation (210–310 K)	Atmospheric Transmission	Dominant Absorbers / Scatterers
Ultraviolet (UV)	0.2–0.4	Present	Negligible	Very low	Ozone, oxygen, Rayleigh scattering
Visible	0.4–0.7	Peak emission	Negligible	Very high (most transmitted)	Minimal absorption
Near Infrared	0.7–3	Moderate	Very low	Variable; many absorption bands	Water vapor, CO_2, O_2, O_3
Mid Infrared	3–8	Very low	Significant	Mostly absorbed except windows	Water vapor, CO_2, CH_4, N_2O
Atmospheric Window	~8–13	Very low	Strong emission	High transmission	Relatively little absorption
Far Infrared	>13–70	Negligible	Declining thermal emission	Mostly absorbed	Water vapor, CO_2

The figure also shows different components such as water vapor, carbon dioxide, oxygen/ozone, methane, and nitrous oxide absorbing different wavelengths of light. A list of the components and their corresponding wavelengths is shown in Table 3.6.2.

Table 4.6.2: Atmospheric absorption components and their contributions

Atmospheric Component	Principal Absorption Regions (Approx. µm)	Relative Contribution
Water Vapor (H_2O)	0.9, 1.1, 1.4, 1.9, 2.7, 5–8, >17	Dominant absorber over much of the infrared
Carbon Dioxide (CO_2)	2.0, 2.7, 4.3, 15	Strong infrared absorption
Oxygen (O_2)	0.76	Narrow absorption band
Ozone (O_3)	UV (<0.35), 9.6	Strong UV absorption and IR band near 9.6 µm
Methane (CH_4)	3.3, 7.7	Moderate infrared absorption
Nitrous Oxide (N_2O)	4.5, 7.8	Moderate infrared absorption
Rayleigh Scattering	Strongest below ~0.5	Scattering decreases rapidly with increasing wavelength

The top panel compares black-body spectra of the Sun (5525 K) and Earth (210–310 K). The peak wavelengths of these curves are shown in Table 3.6.3.

Figure 4.6.1: Blackbody curves and their peak wavelengths.

Temperature	Peak Emission Region	Approximate Peak Wavelength (µm)
5525 K (Sun)	Visible	~0.52

Temperature	Peak Emission Region	Approximate Peak Wavelength (μm)
310 K	Infrared	~9.3
260 K	Infrared	~11.1
210 K	Infrared	~13.8

Figure 3.4.1: Carbon Dioxide concentrations in the atmosphere since 1700

A line graph shows the change in atmospheric carbon dioxide (CO_2) concentration over time. The horizontal axis is labeled “Years (C.E.)” and spans from roughly 1700 to the early 2020s. The vertical axis is labeled “CO_2 Concentration (ppm)” and ranges from about 200 to 420 parts per million.

A black line traces the data, with a light blue shaded area beneath it. From 1700 through the mid-1800s, the line is relatively flat, fluctuating slightly around 270–285 ppm. From the late 1800s to about 1950, the line rises gradually to just over 310 ppm. After 1950, the increase becomes steeper and more pronounced, with small, regular up-and-down oscillations visible along the line. The values climb rapidly from around 315 ppm in 1960 to over 410 ppm by the early 2020s.

Text in the upper left reads “Last updated March 26, 2026.”

Key takeaway: CO_2 levels remained fairly stable for about 150 years, then began increasing gradually, followed by a sharp acceleration in the second half of the 20th century through the present.

Figure 3.4.2: The Keeling Curve

This image is a line graph titled “Carbon dioxide concentration at Mauna Loa Observatory.” It shows measurements of atmospheric carbon dioxide (CO_2) concentration over time from approximately 1958 through March 2026. The graph is commonly known as the Keeling Curve, one of the most important long-term records of atmospheric carbon dioxide.

Chart Structure

Horizontal Axis (X-Axis)

- Represents time, beginning around 1958 and extending through 2026.
- Major tick marks are shown at roughly five-year intervals.

Vertical Axis (Y-Axis)

- Represents CO_2 concentration in parts per million (ppm).
- Values range from approximately 310 ppm to 440 ppm.

Data Display

- The data appear as a black line with small points.
- The area beneath the curve is shaded light blue.
- A note indicates that Mauna Kea data are shown in blue when used to supplement the record.
- The graph notes that the record extends through March 26, 2026.

Overall Trend

The graph shows a strong long-term increase in atmospheric carbon dioxide concentration over nearly seven decades.

- In the late 1950s, concentrations were approximately 315 ppm.
- By the mid-1980s, concentrations reached about 345 ppm.

- Around 2000, levels are approximately 370 ppm.
- By 2010, concentrations exceeded 390 ppm.
- Around 2020, values rise above 410 ppm.
- By early 2026, concentrations approach 430 ppm.

The overall pattern is an upward-sloping curve that becomes progressively steeper over time, indicating that atmospheric CO_2 is increasing at an accelerating rate.

Seasonal Oscillations

Superimposed on the long-term rise is a repeating annual zigzag pattern.

Each year:

- CO_2 concentrations rise to a peak.
- Then decline slightly.
- Then rise again the following year.

These seasonal fluctuations typically range from 5 to 10 ppm.

The oscillations occur because:

- Plants in the Northern Hemisphere absorb large amounts of carbon dioxide during the growing season (spring and summer), thereby lowering atmospheric concentrations.
- During fall and winter, plant growth slows and decomposition releases carbon dioxide back into the atmosphere, causing concentrations to increase.

This creates the characteristic sawtooth appearance of the curve.

Key Numerical Changes

Approximate values shown on the graph:

Year	CO_2 Concentration
1958	315 ppm
1970	325 ppm
1980	338 ppm
1990	355 ppm
2000	370 ppm
2010	390 ppm
2020	415 ppm
2026	430 ppm

Overall increase:

- About 115 ppm higher than the initial measurements.
- Represents an increase of roughly 36% compared with 1958 levels.

This page titled 4.6: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

5: EARTH'S ENERGY BUDGET

Introduction

Have you ever wondered why the warmest time of day is in the mid-afternoon instead of at noon when the sun is highest in the sky? Or why are evenings warm, even though the sun is almost setting? Both of those questions deal with the concept of Earth's energy budget, namely the balance between incoming solar (shortwave) radiation and outgoing terrestrial (longwave) radiation. The Sun does not heat the Earth evenly. It heats the tropical regions much more than the polar regions. Figure 5.1 shows how the Earth's spherical nature changes the angle that sunlight makes with the surface.

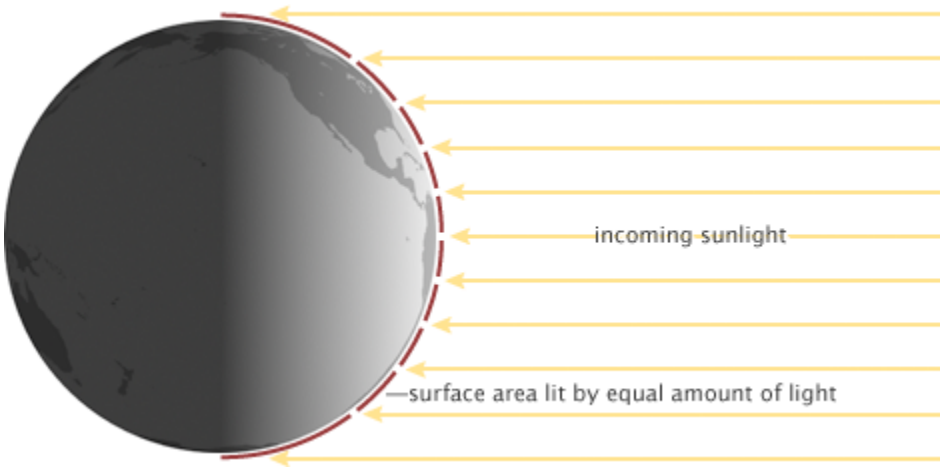


Figure 5.1: Schematic of Sunlight hitting the surface of the Earth. (Public Domain; Robert Simmons via Wikimedia Commons)

In climate science, the concept of Earth's energy budget is crucial because it is the very alteration of that budget, through the introduction of excess greenhouse gases into the atmosphere, that has raised Earth's temperature. In this investigation, we will explore the major components of Earth's energy budget, what affects it, and how excess greenhouse gases have influenced it.

Learning Objectives

- Explore and quantify the key components of Earth's energy budget.
- Describe how the imbalance in Earth's energy budget, both daily and seasonally, affects temperature.
- Identify ways that humans have impacted the energy budget.

Navigational Note

Investigation 4 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

5.1: Energy Balance
5.2: Global Energy Balance
5.3: Energy Budget and Climate Change
5.4: Other factors affecting Earth's Energy Budget
5.5: Accessible Descriptions

This page titled 5: Earth's Energy Budget is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

5.1: Energy Balance

A Balanced Budget

In Investigation 3, we introduced the concepts of Heat, Radiation, and Absorption. Recall that radiation is either absorbed, reflected, or scattered by Earth's surface/atmosphere. What is reflected either returns to space, is absorbed by other materials, or is scattered in the atmosphere, producing the beautiful colors we see. We'll investigate this breakdown a bit more in this investigation, but for the sake of simplicity, we can say that approximately 70% of the sunlight that reaches Earth's atmosphere is absorbed by the Earth (51% by Land/Ocean/Surface, and 19% by the Atmosphere and Clouds) and 30% is either reflected or scattered by Earth (20% is reflected by clouds and the atmosphere, 4% by land/ocean/surface, and 6% is scattered by atmospheric molecules, producing colors).

All the energy that the Earth absorbs increases its temperature above absolute zero (0 K). According to the Law of Conservation of Energy, energy cannot be created or destroyed, but can be transferred from one form of energy to another. Thus, the energy absorbed by the Earth is converted into other forms of heat, such as conduction, convection, radiation, and latent heat exchanges. We'll briefly cover those later in this investigation. While the energy budget sounds complicated, you can think about it like a checking account, and you can think about your budget as two main components: Income and Spending.

A **balanced budget** is achieved when your income and your spending are equal. In this case, what goes in equals what comes out, and the amount of money in your account ends up staying the same. When income is higher than spending, meaning you are earning more money than you are losing, the amount of money in your account should go up. When income is less than spending, meaning you spend more money than you make, the amount of money in your bank account should go down ☹.

Now let's apply that same concept to temperature:

1. When incoming solar radiation equals the amount of radiation lost by Earth, Earth's temperature should:
    a. Increase
    b. Decrease
    c. Remain the Same.

Well, let's throw our budget out of balance. Figure 5.1.1 is a 24-hour graph of incoming (yellow line) vs. outgoing (blue line) radiation and temperature (red line).

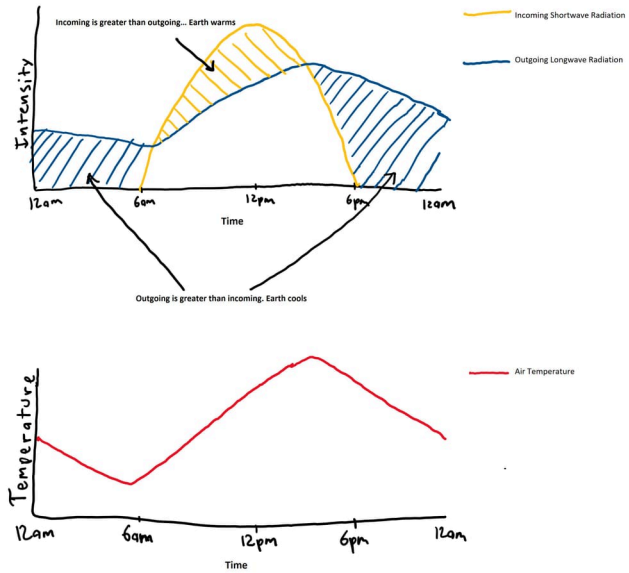


Figure 5.1.1: Daily radiation balance and air temperature, highlighting warming when energy in exceeds out and cooling otherwise. (Public Domain; Alicia Mullens). Alternative Description of Image.

From just after sunrise (6 am) until mid-afternoon, incoming solar radiation is larger than outgoing radiation (the blue line). During this time, more heat is going in than coming out. Just like the checking account example before question 1.

2. When incoming solar radiation is greater than outgoing radiation, Earth's temperature should:
   a. Increase
   b. Decrease
   c. Stay the same

Notice that the warmest time of day, i.e., when the red temperature line is at its peak, occurs a few hours after noon, i.e., when the sun is at its highest in the sky. This is called Temperature Lag. This is because, even though solar radiation declines after noon, it remains greater than outgoing radiation for some time. However, as the Earth continues to warm, it also emits more radiation (as per the Stefan-Boltzmann law from Investigation 3). In the afternoon, incoming radiation begins to decline while outgoing radiation continues to increase. Eventually, the two equal one another, and balance is achieved again. At this moment, the temperature stops rising and levels off, and it is the warmest time of the day. So if you've ever wondered why it's warmer at 3 or 4 pm than it was at noon, it's because Earth remains in an energy surplus until later in the afternoon.

3. Now let's go past mid-afternoon. At this point, the sun is lower on the horizon, and the amount of incoming solar radiation is less than the amount leaving Earth. At this point, the air temperature should:
   a. Increase
   b. Decrease
   c. Stay the same

If you've ever noticed, especially on those long, sunny summer days, it feels cooler later in the evening (around sunset) than it did earlier in the afternoon. This is because, even though there is still sunlight coming in, it is now much less than the radiation escaping Earth. Once it is nighttime, no sunlight is heating the Earth anymore. But the Earth continues to emit radiation. It is important to note that this is *not* because of "heat left over from the day." If the sun never rose again, Earth would still continue emitting radiation for a long period of time because it would still have a temperature above 0 K. So at night, Earth continues cooling until the next morning, when the Sun rises, and the cycle begins all over again.

A quick review before we continue on:

- When incoming heat is greater than outgoing heat, Earth warms
- When incoming heat is less than outgoing heat, Earth cools
- When incoming heat is equal to outgoing heat, Earth's temperature remains the same.

Energy Balance and Seasons

Let's apply this same concept to understand our seasons. But before we do, we need to know two important dates for the Northern Hemisphere (these two dates are the opposite for the Southern Hemisphere):

Winter Solstice: December 21st. On this day, the Sun is the furthest south of the equator, and the amount of incoming solar radiation in the Northern Hemisphere is at its lowest.
Summer Solstice: June 21st. On this day, the Sun is the furthest north of the equator, and the amount of incoming solar radiation in the Northern Hemisphere is at its highest.

4. Applying the same logic from questions 2-3 (namely, the warmest time of day is a few hours after the sun is at its peak), the warmest time of the year should be:
   a. Before June 21st
   b. Exactly on June 21st
   c. After June 21st

Let's check our answer. Figure 5.1.2 shows a map of the average warmest day of the year for the continental United States.

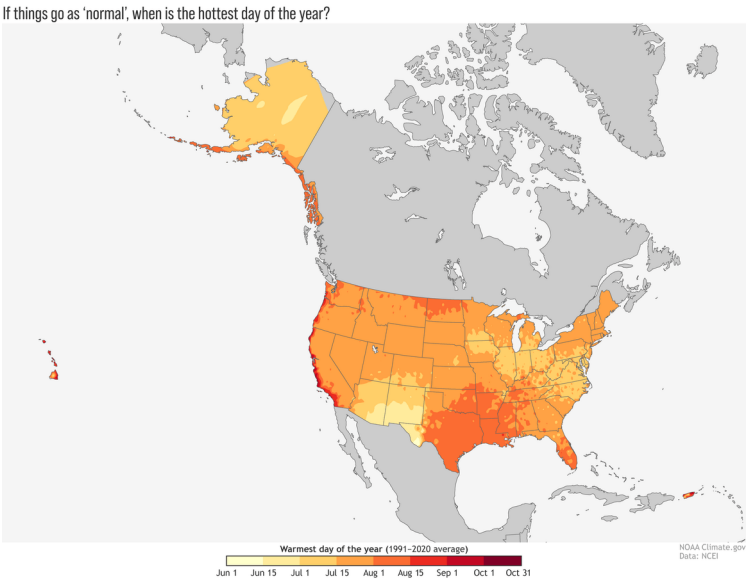


Figure 5.1.2: Map of the average warmest day of the year for the United States, including Alaska and Hawaii. (Public Domain; NOAA via Climate.gov). Alternative Description of Image.

5. With the exception of Southern Arizona, New Mexico, and western Texas, most of the continental United States has an average warmest day of the year:
   a. Before June 21st
   b. Exactly on June 21st
   c. After June 21st
6. This _____ the hypothesis made in question 4.
   a. Can Confirm
   b. Cannot Confirm

This page titled 5.1: Energy Balance is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

5.2: Global Energy Balance

Energy Balance applied globally

In Investigation 1.1, we learned how the Angle of Insolation plays a vital role in determining how much energy is incident upon the Earth. The Earth's tilt results in different regions of the Earth absorbing differing amounts of solar radiation. Figure 5.2.1 shows the average incoming and outgoing radiation for each latitude.

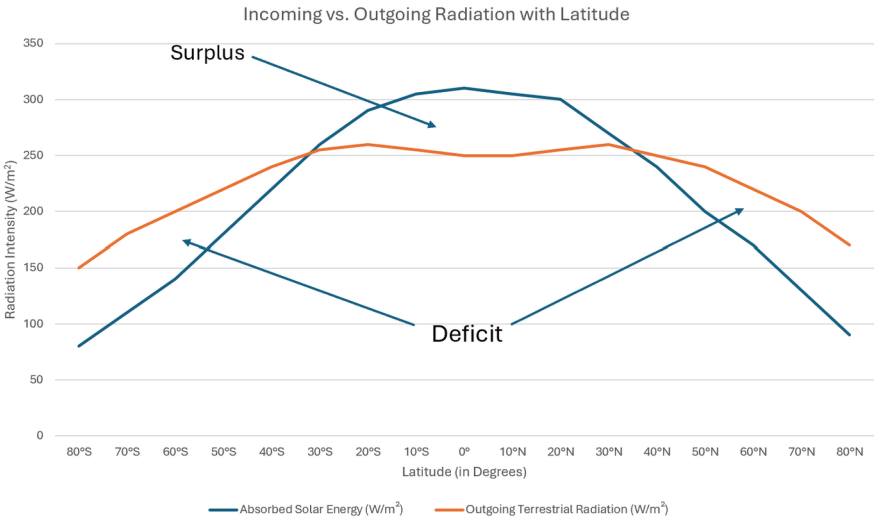


Figure 5.2.1: Zonally (latitude) averaged incoming (blue) versus outgoing (orange) radiation. (Public Domain; Alicia Mullens). Alternative Description of Image.

7. From the Equator (latitude 0) to approximately 38°N/S, incoming solar radiation (blue) is greater than outgoing radiation (orange). In theory, temperatures at these locations should:
   a. Increase
   b. Decrease
   c. Not change
8. Meanwhile, from approximately 38°N/S poleward (towards the edges of this chart), incoming solar radiation (blue) is less than outgoing radiation (orange). Here, temperatures at these locations should:
   a. Increase
   b. Decrease
   c. Stay the same

Since there is an excess of heat near the equator and a deficit near the poles, natural processes (like weather) redistribute that heat surplus towards the poles, while bringing cooler air down towards the equator. These processes are what give us our most extreme weather. However, as the climate changes, the difference in temperatures between the equator and the poles will change too, causing this weather machine to shift in ways we can't fully predict.

This page titled 5.2: Global Energy Balance is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

5.3: Energy Budget and Climate Change

Earth's Energy Budget

So far, we have explored the concept of Earth's energy budget applied to daily, seasonal, and global heat and temperature variations, and have concluded that, in an energy surplus, a location should warm, whereas in an energy deficit, it should cool. We can now apply that same concept to the science behind climate change. Figure 5.3.1 presents a more detailed and holistic view of Earth's energy budget.

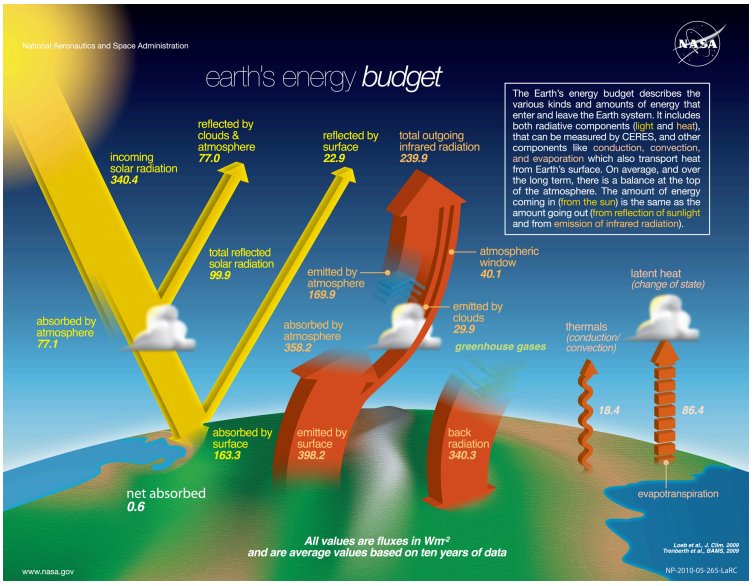


Figure 5.3.1: Earth's detailed energy budget. (Public Domain; NASA via Wikimedia Commons). Alternative Description of Image.

The figure may look overwhelming, but let's take it step-by-step. The yellow numbers represent incoming solar radiation, while the orange numbers represent radiation/heat emitted by Earth. Let's focus on the top of the Earth's Atmosphere, where energy either enters (incoming) or leaves (reflected or outgoing) the Earth system. The units for radiation are Watts per Square Meter (W/m^2), i.e., how many watts flow through a square meter. These numbers are determined by direct measurements and analysis by the Intergovernmental Panel on Climate Change (IPCC).

9. Based on Figure 5.3.1, the amount of incoming solar radiation equals approximately _____ W/m2
   a. 163.3
   b. 398.2
   c. 340.4
   d. 239.9
10. Meanwhile, the total amount of radiation leaving Earth can be found by adding the three items at the top of the diagram (namely, reflected by clouds/atmosphere, reflected by the surface, and total outgoing infrared radiation). This total is:
   a. Equal to the amount coming in
   b. Greater than the amount coming in
   c. Less than the amount coming in
11. Therefore, Earth's temperature should:
   a. Stay the same
   b. Increase
   c. Decrease
12. While there is some year-to-year variation, Earth's average temperature has been trending upward since records began in 1880. This _____ the conclusion you made in question 11.
   a. Confirms.
   b. Does not confirm.

So far, we have covered heat, radiation, temperature, absorption, and energy balance. However, the reflectivity of Earth, along with what is present in the atmosphere at a given time (i.e., clouds), can also have a significant impact on Earth's Energy Budget.

This page titled 5.3: Energy Budget and Climate Change is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

5.4: Other factors affecting Earth’s Energy Budget

Reflection by Clouds and Earth's Surface - Albedo

Radiation that isn’t absorbed by the atmosphere is either absorbed by the surface of the earth, reflected by the surface of the earth, or reflected by clouds. With the exception of some surface covers, which we will cover below, the Earth’s surface absorbs almost 100% of the radiation that reaches it. However, many objects both in the atmosphere and on Earth’s surface are good reflectors of sunlight. Every object has a property called Albedo that represents the percentage of sunlight it reflects. While you can measure albedo by calculating the ratio of sunlight reflecting off an object to sunlight hitting the object, you can actually estimate the albedo simply by looking at how dark/light colored the object is. If you’ve ever worn a dark-colored t-shirt, or driven in a car with dark interiors, you probably know that dark objects don’t reflect much of the sunlight that hits them... and thus have a low albedo. Objects with a low albedo absorb the radiation instead, causing them to heat up. On the other hand, if you’ve ever gone skiing and been snow-blinded, or had a bad sunburn, you probably know that light-colored objects have higher albedos, thus reflecting sunlight and keeping them cool. A simple guide to albedo is found in Figure 5.4.1.

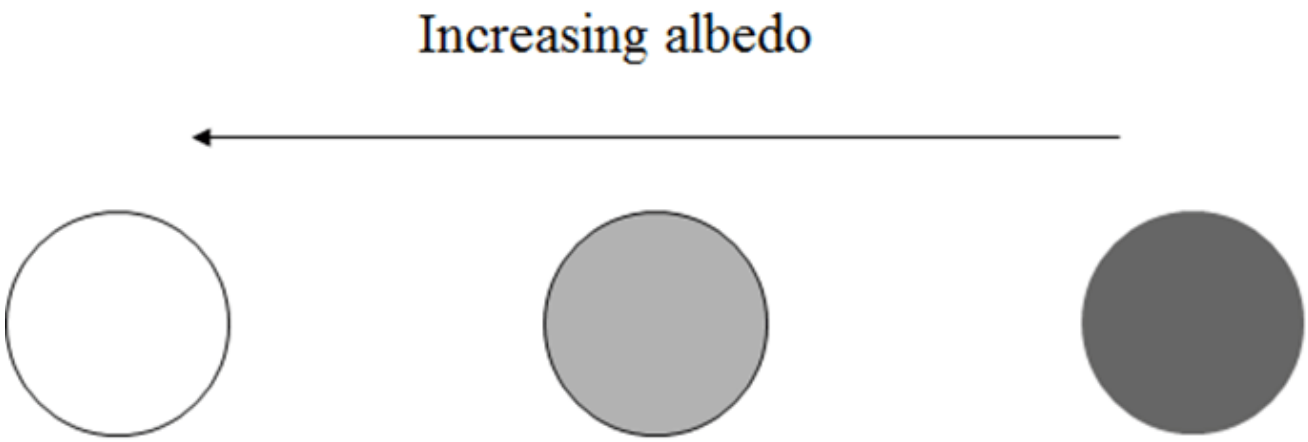


Figure 5.4.1: Relationship between Albedo and Darkness. Lighter colors have a high albedo while darker colors have a low albedo (CC BY 4.0; Alicia Mullens)

Simply put, the lighter an object's color is, the higher the albedo. Let's put this to the test. Figure 5.4.2 is a typical snow-covered mountainside and Figure 5.4.3 is a typical building in an urban area.



Figure 5.4.2: A snow capped mountain (Public Domain; Wikimedia Commons)



Figure 5.4.3: Dark buildings and street typical of an urban area. (CC-BY-SA 2.0; Wikimedia Commons)

We know that objects that reflect sunlight are cooler, while objects that absorb sunlight are warmer. The phenomenon covered above is called the **Urban Heat Island Effect.**

13. Ice and Snow, as shown in Figure 5.4.2, would likely have a _____ albedo.
    a. high
    b. middle
    c. low
14. On the other hand, urban areas, as shown in Figure 5.4.3, most likely have a _____ albedo.
    a. high
    b. low
15. As a result, urban areas should absorb _____ radiation than non-urban areas.
    a. more
    b. less
16. Meanwhile, ice-covered areas should absorb _____ radiation than other areas.
    a. more
    b. less
17. Therefore, urban areas are likely to be _____ than ice-covered locations.

a. warmer
b. colder

Ice-Albedo Feedback

A particularly concerning consequence of Earth warming is the melting of Earth's ice. As air temperatures continue to rise, the edges of ice sheets (especially in the Northern Hemisphere, where the ice sheet is floating above warmer water, and is therefore more vulnerable to melting) begin to melt. We can see the dramatic effects of this at NASA's Images of Change website, which features the Northern Polar Ice Cap in 1984 vs 2012.

18. Ice Coverage in 2012 (slide the "curtain" all the way to the right) was significantly _____ than in 1984 (slide the "curtain all the way to the left).
    a. Less
    b. More
    c. About the Same

What's concerning about this is that ice has a very high albedo while ocean and land have a very low albedo (Ocean has between 5-10% and Land between 20-30%). So by ice melting, higher albedo surfaces are replaced with lower albedo surfaces.

19. Suppose Earth Warms, and Ice Melts. Earth's Average Albedo would:
    a. Increase
    b. Decrease
20. Therefore, Earth would _____ more solar radiation.
    a. Absorb
    b. Reflect
21. The result is that Earth would:
    a. Continue to Warm
    b. Begin to Cool
    c. Not experience a change in temperature

The scenario mentioned in the past three questions is is what is called a **Positive Feedback Loop**. In this nightmare scenario, the initial change (Earth warming) is amplified by further processes (such as ice melting). Thankfully there are also **Negative Feedback Loops**, which can include changes in cloud cover that could counteract such warming. We will investigate that next.

Clouds and Radiation

The last topic we'll cover in this investigation is in regards to cloud cover and temperature. You can usually observe that typical clouds are a bright white, meaning they reflect most of the sunlight that hit them, keeping Earth cool during the day time. This is called the **Cloud Albedo Effect**. However, what is often times not thought of is the insulating properties of clouds; Clouds have a large amount of water vapor, and are thus can absorb much of the longwave radiation escaping Earth. This keeps Earth Warm at night (when there is no incoming sunlight, thus the Albedo Effect has no effect). This is called the **Cloud Greenhouse Effect**. Figure 4.4.4 is a visualization of these two effects.

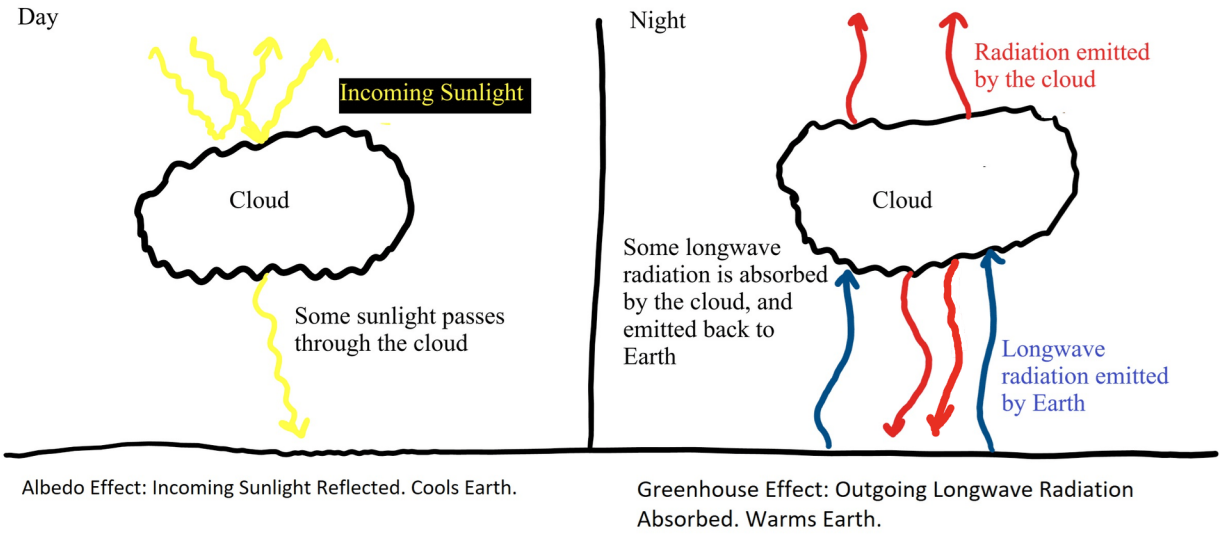


Figure 5.4.4: Cloud Albedo and Greenhouse Effects. (Public Domain; Alicia Mullens). Alternative Description of Image.

Let's consider weather conditions at a location on a cloudy vs. sunny day, and investigate these effects. Table 4.4.1 is data taken from San Jose International Airport on Tuesday, April 16th (A cloudy/rainy day) and Wednesday, April 17th (A clear day).

Table 5.4.1: Conditions for April 16th and 17th, 2023 at San Jose International Airport

Date	April 16th (Cloudy)	April 17th (Clear)
High (°F)	66.9°F	73.9°F
Low (°F)	48.9°F	46.9°F

22. Based on the data above, we could expect that the temperature range (difference between high and low temperature) for a day would be _____ on Cloudy days than on Clear days.
    a. Lower
    b. Higher

However, the presence of Clouds could come with a bad side effect. There are two types of clouds: High Clouds and Low Clouds.



Figure 5.4.5: Cirrus Clouds are a type of High Cloud (Public Domain, NOAA via Wikimedia Commons)



Figure 5.4.6: Cumulus and Stratus clouds are types of low clouds. (Public Domain; NOAA via National Weather Service)

23. High Clouds are typically thin and transparent (Figure 4.4.5)... they are poor reflectors of sunlight, but are excellent absorbers of outgoing radiation... in essence, high clouds could increase the amount of radiation trapped near the surface of the Earth. This could _____ Earth.
    a. Warm
    b. Cool
    c. Neither Warm nor Cool.
24. Meanwhile, Low Clouds are very thick (Figure 4.4.6), and made up of trillions of liquid droplets that are excellent reflectors of sunlight... hence they do a good job of preventing solar radiation from reaching the surface of the Earth. This could _____ Earth.
    a. Warm
    b. Cool
    c. Neither Warm nor Cool.
25. As a result, the future effect of clouds on Earth's temperature _____ on what types of clouds become more common in a warmer world.
    a. Depends

b. Does Not Depend.

In a future investigation, we'll examine the role of Climate Change on Earth's Water Cycle, and investigate the impacts this could have on cloud formation. There is major uncertainty in the role of clouds in climate change, but there is at least some hope that additional clouds could counteract some warming.

This page titled 5.4: Other factors affecting Earth's Energy Budget is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

5.5: Accessible Descriptions

Figure 4.1.1: Energy Balance and Temperature

Two related graphs show how daily energy balance connects to changes in air temperature over a 24-hour period.

The first graph presents radiation intensity over time. It compares incoming solar radiation, which increases during the day and is absent at night, with outgoing terrestrial radiation, which occurs continuously. Periods when incoming energy is greater than outgoing correspond to warming, while periods when outgoing energy exceeds incoming correspond to cooling.

The second graph shows air temperature over the same time period. Temperature decreases during the night to a minimum in the early morning, rises during the day to a peak later in the day, and then decreases again at night.

The combined message is that changes in temperature follow the balance between incoming and outgoing energy, with a delay between peak energy input and peak temperature.

Figure 4.1.2: Warmest day of the year

Map of North America showing the average timing of the hottest day of the year based on 1991–2020 data. It includes the United States, Canada, Alaska, and Hawaii, with land areas categorized by date. In most regions, the hottest day occurs after the summer solstice, reflecting a seasonal lag between peak solar energy and peak temperature. Many inland areas reach maximum heat in mid-summer, while coastal, higher latitude, and some southern regions peak later, extending into late summer or early fall. Alaska generally shows earlier peak dates than much of the contiguous United States. A legend indicates dates ranging from early June through late October, and the title asks when the hottest day typically occurs under normal conditions.

Figure 4.2.1: Incoming vs. Outgoing radiation with Latitude

Line graph titled “Incoming vs. Outgoing Radiation with Latitude” showing how absorbed solar energy and outgoing terrestrial radiation vary from high southern latitudes through the equator to high northern latitudes. Absorbed solar energy increases from low values at high latitudes to a maximum near the equator, then decreases again toward the opposite pole. Outgoing terrestrial radiation changes more gradually, with values that are relatively higher than absorbed energy at high latitudes and closer to or slightly lower than absorbed energy in low latitudes. The graph identifies an energy surplus in tropical regions where absorbed energy exceeds outgoing radiation, and an energy deficit in higher latitudes where outgoing radiation exceeds absorbed energy. The two values are equal to each other at approximately 38 degrees N/S. Axes are labeled latitude in degrees and radiation intensity in watts per square meter, and a legend distinguishes the two variables.

Figure 4.3.1: Earth's Energy Budget

Infographic titled “Earth’s energy budget” showing the flows and balance of energy entering, moving through, and leaving the Earth system, with values in watts per square meter based on multi-year averages. Incoming solar radiation is about 340.4 W/m². Of this, roughly 99.9 W/m² is reflected back to space, including about 77.0 by clouds and the atmosphere and 22.9 by the surface. The remaining energy is absorbed, with about 77.1 W/m² absorbed by the atmosphere and 163.3 W/m² absorbed by the surface.

The surface releases energy upward primarily as infrared radiation, about 398.2 W/m². The atmosphere absorbs a large portion of this energy, about 358.2 W/m², and re-emits it both upward and downward. Upward emissions include about 169.9 W/m² from the atmosphere and 29.9 W/m² from clouds, with about 40.1 W/m² escaping directly to space through an atmospheric window, contributing to a total outgoing infrared radiation of about 239.9 W/m². Downward emission from the atmosphere back to the surface, often associated with greenhouse gases, is about 340.3 W/m².

Additional energy transfers from the surface to the atmosphere occur through latent heat from evaporation and transpiration, about 86.4 W/m², and through thermals (conduction and convection), about 18.4 W/m². The diagram indicates a small net energy gain of about 0.6 W/m², showing that incoming and outgoing energy are nearly balanced over time. A text box explains that the energy budget includes both radiative processes and non-radiative processes such as conduction, convection, and evaporation,

and that, on average, energy entering the system is approximately equal to energy leaving it.

Figure 4.4.4: Albedo and Greenhouse effects of clouds.

*]:pointer-events-auto R6Vx5W_threadScrollVars scroll-mb-[calc(var(--scroll-root-safe-area-inset-bottom,0px)+var(--thread-response-height))] scroll-mt-(--header-height)" data-scroll-anchor="false" data-testid="conversation-turn-31" data-turn="user" data-turn-id="81e043fd-2375-46cc-bfef-cecc73c57bb7" dir="auto">
Diagram comparing how clouds affect Earth's energy during daytime and nighttime.
*]:pointer-events-auto [content-visibility:auto] supports-[content-visibility:auto]:[contain-intrinsic-size:auto_100lvh] R6Vx5W_threadScrollVars scroll-mb-[calc(var(--scroll-root-safe-area-inset-bottom,0px)+var(--thread-response-height))] scroll-mt-[calc(var(--header-height)+min(200px,max(70px,20svh)))]" data-scroll-anchor="false" data-testid="conversation-turn-32" data-turn="assistant" data-turn-id="request-WEB:e170c146-d340-43eb-bfb5-81e76e9eec8f-15" dir="auto">

In the daytime, incoming sunlight interacts with a cloud, with part of the energy reflected away and part passing through to the surface. This reflection reduces the amount of energy reaching the surface and contributes to cooling, illustrating the albedo effect.

In the nighttime portion, energy emitted from Earth's surface as longwave radiation rises toward the cloud. The cloud absorbs some of this energy and then emits energy both away from Earth and back toward the surface. The energy returned toward the surface reduces heat loss and contributes to warming, illustrating the greenhouse effect.

Text in the diagram explains that reflection of incoming sunlight leads to cooling during the day, while absorption and re-emission of outgoing longwave radiation leads to warming at night.

This page titled 5.5: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

6: WATER AND THE CLIMATE

Introduction

Up to this point in the class, we've primarily focused our attention on the Atmosphere – Earth's Air. It contains the important gases that make life possible on Earth which provide us with oxygen to breathe and fresh drinking water. However, it would be highly inaccurate to claim that the state of the atmosphere – weather (short term) and climate (long term) is dependent only on the atmosphere itself. Instead, the atmosphere constantly influences and is influenced by other major components of the Earth System. We can appreciate this fact by observing a picture of the Earth from space, as shown in Figure 6.1.



Figure 6.1: The famous Blue Marble photograph taken during the Apollo 17 mission. (Public Domain; Harrison Schmitt via NASA) Alternative description of the image.

As we investigate Figure 6.1, we realize that in addition to the atmosphere, there are four other major components of the Earth System: The Geosphere (Land), the hydrosphere (water), the biosphere (life), and the cryosphere (ice).

1. Based on this information, identify one example of each of the components of the Earth (biosphere, hydrosphere, etc) visible in Figure 5.1.

In the next few labs, we will attempt to understand how the components of the Earth System interact. We will cover topics including the Carbon Cycle, Topography, Land Surface Processes, Ecosystems, and the role of Geophysical calamities, such as Volcanic Eruptions, on the climate. For this investigation, we are going to focus on the Hydrosphere – Earth's Water and its impacts on Climate.

Learning Objectives

- Define the phase change of water and how it is a part of the Water Cycle on Earth.
- Examine the effect of latent heat exchange during phase change.
- Compare the effect of warm and cold ocean currents on a region's temperatures.

Navigational Note

Investigation 5 has 21 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

6.1: The Water Cycle
6.2: Ocean-Atmosphere Interaction
6.3: Accessible Descriptions

This page titled 6: Water and the Climate is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

6.1: The Water Cycle

Phase Changes

Water is considered one of the most important, if not the most important, ingredients for life as we know it. When NASA scientists and astrobiologists evaluate a planet's ability to sustain life, one of the main criteria is the presence of water. Here on Earth, temperatures are at the perfect range (approximately -129°F to +134°F based on record low/high temperatures) for water to exist naturally in all three of its phases – Liquid, Solid, and Gas. In fact, not only are those temperatures ideal for water to exist in all three phases, but they are also ideal for water to undergo transitions between each of the phases in processes called **Phase Changes**. These phase changes are the most important for sustaining life on Earth. Without water's ability to readily change phases, we'd never get rain/snow, we wouldn't have rivers/lakes/streams, and any water not present in the oceans would eventually drain into the ocean, leaving us without any fresh water sources. Figure 6.1.1 is an extremely simplistic, but useful diagram of Earth's water cycle, including important phase changes and processes.

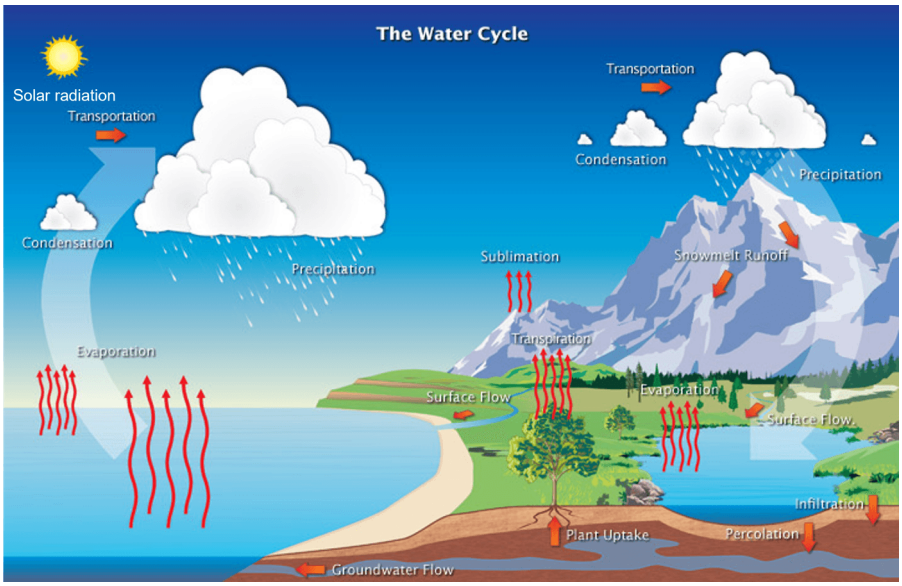


Figure 6.1.1: The Water Cycle on Earth. (Public Domain; NWS Jetstream via NOAA) Alternative description of the image.

The primary driving mechanism of the water cycle is heat, which "pulls" water from Earth's surface into the atmosphere.

2. The main source of heat for various processes on Earth is: (hint: which of these three is shown on Figure 6.1.1?)
   a. Heat from the Earth's core
   b. Solar radiation from the Sun
   c. Metabolism from plants and animals

Without this mechanism, there would be no water cycle on the Earth. Heat is absorbed by water as it **evaporates** (changes from liquid to gas) and rises in the atmosphere. As water in the form of water vapor (gas) travels through the atmosphere, it loses some of that heat in the form of sensible heat exchanges (such as conduction or convection) and then **condenses** (changes from gas to liquid) into liquid cloud droplets (note: if the temperature of the air surrounding the liquid water is below freezing, the water can freeze into ice becoming ice and snow). Once these liquid droplets grow large enough, they fall out of the cloud as **precipitation** (ice can also fall as precipitation). This precipitation then reaches the Earth's surface, where it either collects into ice caps and glaciers, is absorbed by the ground through infiltration, is consumed by plants and animals, or runs off back to the ocean. Other phase changes, such as **sublimation** (ice to gas), **deposition** (gas to ice), and **melting** (ice to liquid), also regularly occur on Earth, as shown in Figure 6.1.2 and are essential components of the Water Cycle.

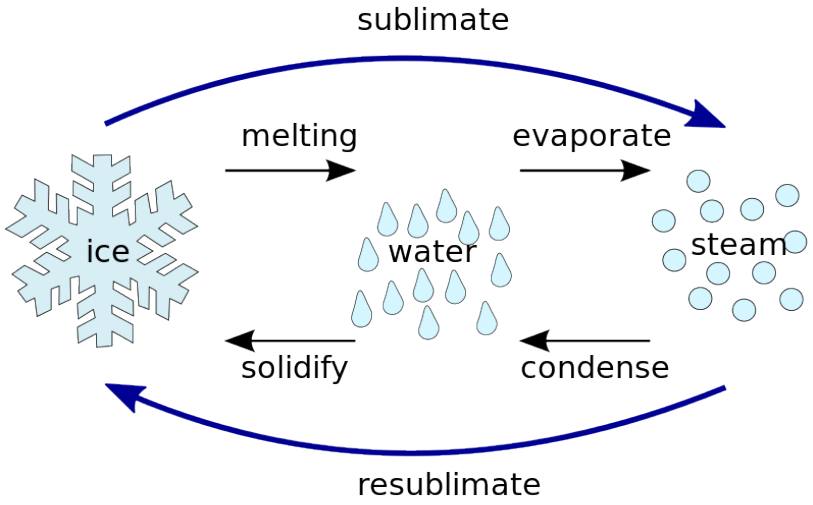


Figure 6.1.2: Phase changes of water. Melting, evaporation, and sublimation are considered cooling processes because they take heat from the environment. Condensation, freezing, and deposition are considered warming processes because, during the phase change, energy is released into the environment. (CC BY-SA 3.0; Synkizz via Wikimedia Commons). Alternative description of the image.

Latent Heat

While the transport of water is critical to Earth's climate, the water cycle's equally important, if not more important, role is the transport of heat. The primary reason for this is what is known as **latent heat**. Latent Heat is the heat that is exchanged between water and its surroundings as it changes phases. For water to remain in a given phase, it must have a certain amount of energy stored in its chemical and molecular bonds. When it undergoes a phase change, it releases heat from those bonds as water condenses, freezes, or deposits, which is known as "moving down a phase" from a higher-energy to a lower-energy phase. Water absorbs heat into those bonds when it melts, evaporates, or sublimates, which is known as "moving up a phase" from a lower-energy to a higher-energy phase.

Important: Before we move on, let's review these definitions and their importance:

- **Phase Change:** When water transitions from one phase to another.
- **Order of Phases** (from lowest to highest): Solid (Ice), Liquid, Gas (Vapor). Ice has the lowest energy, while gas has the highest.
- **Moving "Up" a Phase:** When water transitions from a lower phase to a higher phase... melting, evaporation, and sublimation. Water absorbs heat from its surroundings as it changes phase, cooling those surroundings.
- **Moving "Down" a Phase:** When water transitions from a higher phase to a lower phase... freezing, condensation, and deposition. Water releases heat into its surroundings as it changes phase, warming them.

This is why you feel cold when you step out of the shower. The drier air outside the shower causes water on your skin to evaporate. For water to evaporate, it must absorb heat from its surroundings, including the air and your skin. Thus, the water droplets evaporating from your skin make you feel colder. During hot summer days, your body sweats to cool itself. Heat is absorbed by the beads of sweat on your skin as they evaporate, cooling you down. Let's now use this concept to further understand Figure 6.1.1.

3. Water absorbs heat as it evaporates and rises into the atmosphere. As it condenses, it _____ heat into/from the surrounding atmosphere _____ the atmosphere.
   a. absorbs; cooling
   b. absorbs; heating
   c. releases; cooling
   d. releases; heating

This exchange is crucial in the formation of storm systems, wind patterns, and the overall function of the atmosphere. Table 6.1.1

shows the latent heat (L) exchanged by water as it changes phase at 0°C and Standard Atmospheric Pressure.

Table 6.1.1: Latent heat absorbed or released during phase change at 0 °C.

Phase Change	Latent Heat (Calories/gram)
Fusion (melting/freezing)	80
Vaporization (evaporating/condensing)	597
Sublimation (ice to gas, or gas to ice)	677

4. When one gram of ice melts, it absorbs _____ calories of heat from the atmosphere. When one gram of liquid water freezes, it releases _____ calories of heat into the atmosphere
   a. absorbs; cooling
   b. absorbs; heating
   c. releases; cooling
   d. releases; heating

Here's a cool little experiment you can do at home. You need a pot, ice water (preferably 50% ice and 50% liquid water), a stove, and a thermometer. Put the ice water in the pot and stir it with the thermometer. If you measure the water's temperature after stirring, it should be approximately 0°C (32°F), the freezing/melting point of water. Now, put the pot with ice water on the stove and turn on the heat. Set a timer and measure the water temperature every minute. You'll notice that as long as there is ice in the pot, the water's temperature will not rise significantly, remaining near 0°C. This is because any heat added to the ice-liquid water "system" is instantly used to melt the ice. Once all the ice melts, the temperature will rise quickly until the water reaches approximately 100°C (212°F), the boiling point of water. If you continue to apply heat, the water's temperature will not keep rising once it starts boiling. Any additional heat added instantly goes towards evaporation.

5. Based on Table 6.1.1, it takes _____heat to evaporate water than it does to melt water.
   a. significantly more
   b. significantly less
   c. the same amount of

6. Thus, when water in the atmosphere condenses, it releases _____ heat than it absorbed when it evaporated.
   a. more
   b. less
   c. the same amount of

7. Suppose water sublimates, going directly from ice to gas. It would absorb _____ calories per gram, which is _____ the sum of the latent heats of fusion (melting) and vaporization (evaporation).
   a. 80; less than
   b. 597; less than
   c. 677; the same as

Because of latent heat exchanges, water becomes an important mechanism for transporting heat throughout the atmosphere. An example of this is the Rain Shadow Effect, which was briefly covered in Investigation 1. Liquid water absorbs energy from the sun over the ocean, causing it to evaporate. This evaporated water vapor is blown onshore by the wind, forming a relatively cool sea breeze. As this moist air moves over land, it rises up hillsides where it cools and condenses into rain, releasing latent heat in the process. Eventually, the air reaches the top of the hillside and begins to travel down the other side, warming as it sinks. By the time the air reaches the bottom of the hill, it has regained the warmth it lost on the way up, plus the latent heat released by water vapor as it condensed/rained out on the other side of the hill. Table 6.1.2 shows the average July temperature for Santa Cruz, on the windward side (side facing the ocean) of the Santa Cruz Mountains, and San Jose on the leeward side (side facing away from the ocean) of those mountains.

Table 6.1.2: Average July high temperature for Santa Cruz and San Jose, CA.

City	Average July High (°F)
Santa Cruz	74
San Jose	82

8. San Jose, on the leeward side of the Santa Cruz mountains has a _____ average high temperature in July than Santa Cruz. This _____ the idea that as air rises over a hillside, it gains latent heat released by water that condenses on the windward side of the hill.
   a. warmer; confirms
   b. cooler; cannot confirm

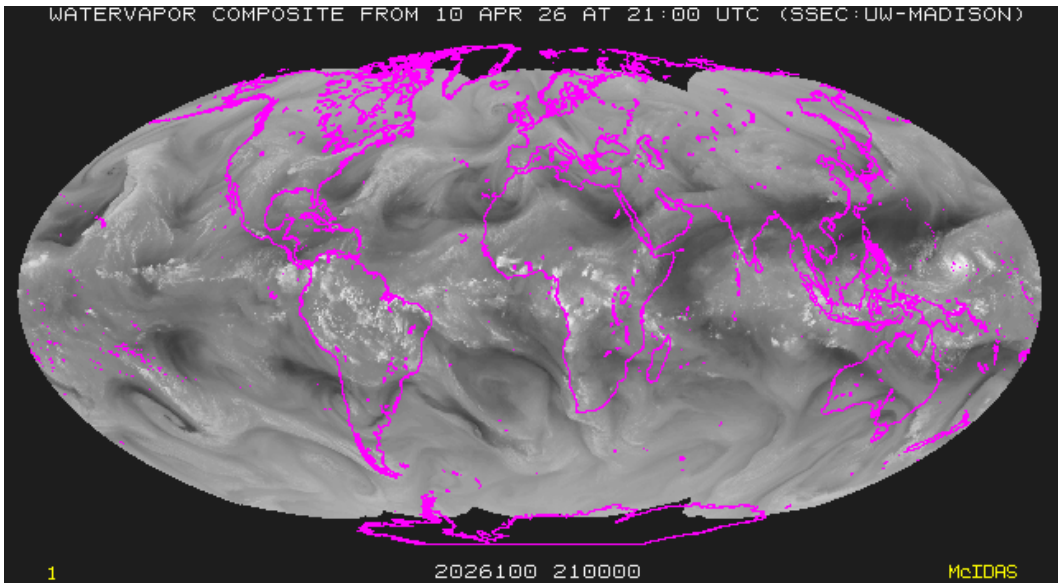


Figure 6.1.3: Satellite composite water vapor image. (CC BY-NC 4.0; Space Science and Engineering Center via University of Wisconsin-Madison) Alternative description of the image.

Because of global wind patterns, which will be investigated in a future investigation, there are places on Earth where more water evaporates than precipitates (making those places drier) and other places where more water precipitates than evaporates (making those places wetter). Figure 6.1.3 is a satellite-derived water vapor imagery map, which shows the presence of water vapor in the atmosphere. Black represents an area with dry air; the "milky" grey color represents air with at least some water vapor; and brighter white spots represent areas of clouds and precipitation. Let's answer the following questions based on this information.

9. Based on Figure 6.1.3, water vapor is present, at least to some degree: (i.e., there's some grey shading):
   a. Across most of the world
   b. Across very little of the world

10. However, clouds and precipitation (bright white regions) are present:
   a. Across only a few parts of the world
   b. Across the entire world

This suggests that while water vapor is a component of the atmosphere almost everywhere on Earth, not every place receives precipitation. As discovered in Investigation 1, there are numerous rainforests (where precipitation is bountiful) and deserts (where precipitation is scarce) on Earth. Global weather patterns, differential heating from the Sun, and surface vegetation all play a role in where precipitation falls/doesn't fall on Earth.

This page titled 6.1: The Water Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

6.2: Ocean-Atmosphere Interaction

How Water Influences the Climate

From water vapor in the air, let's now discuss the role of liquid water on the Earth. As we know, nearly 71% of the Earth's surface is covered by water. Our oceans are considered to be a tremendous reservoir of heat. Ocean currents distribute heat across the planet from areas of abundant sunlight and high heat (the equator) to areas of little sunlight and low heat (the poles). Ocean currents also play a crucial role in moderating the temperature of neighboring landmasses. Both of these topics were briefly covered in Investigation 1, but let's investigate them further. Figure 6.2.1 is a map of global ocean currents, with arrows showing the direction of motion and warm, blue, and black arrows showing warm, cold, and neutral currents. Based on this information, let's answer the following questions.

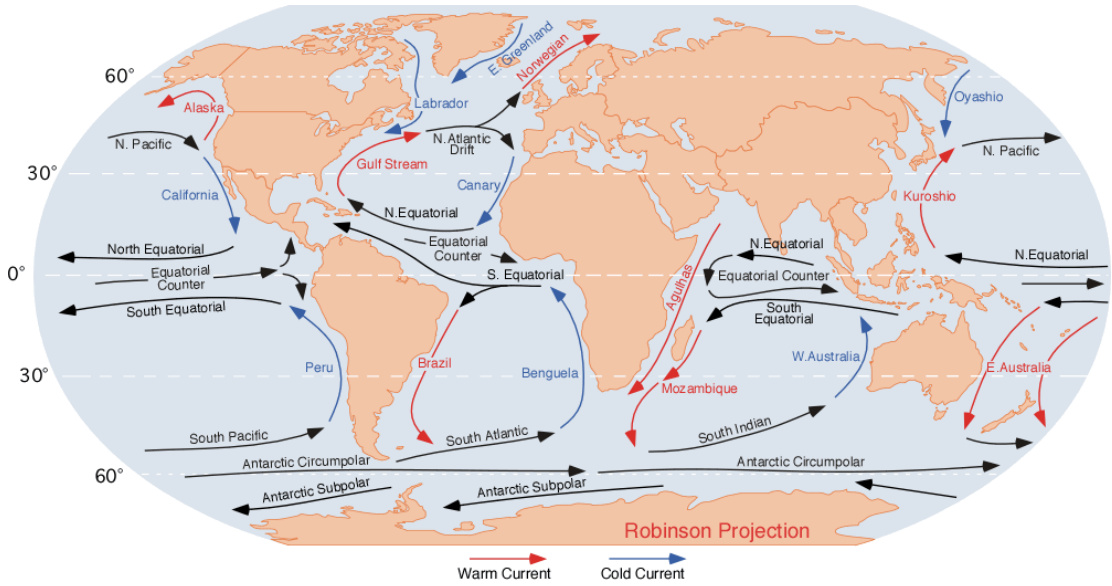


Figure 6.2.1: A map of global ocean currents. (Public Domain; Dr. Michael Pidwirny via Wikimedia Commons) Alternative description of the image.

11. Cold ocean currents, such as the California and Canary currents, carry cold water from:
    a. Tropical latitudes
    b. Polar latitudes
    c. both latitudes

12. Meanwhile, warm ocean currents, such as the Gulf Stream and the Kuroshio currents, carry warm water from:
    a. Tropical latitudes
    b. Polar latitudes
    c. both latitudes

Let's focus on the United States to examine how these ocean currents impact our climate. Figure 6.2.2 shows the average monthly high temperatures for San Francisco, California, and Richmond, Virginia. Both cities are at 37.5°N, so they receive the same amount of sunlight. However, San Francisco is on the U.S. West Coast, near the cold California Current, while Richmond is on the East Coast, near the warm Gulf Stream.

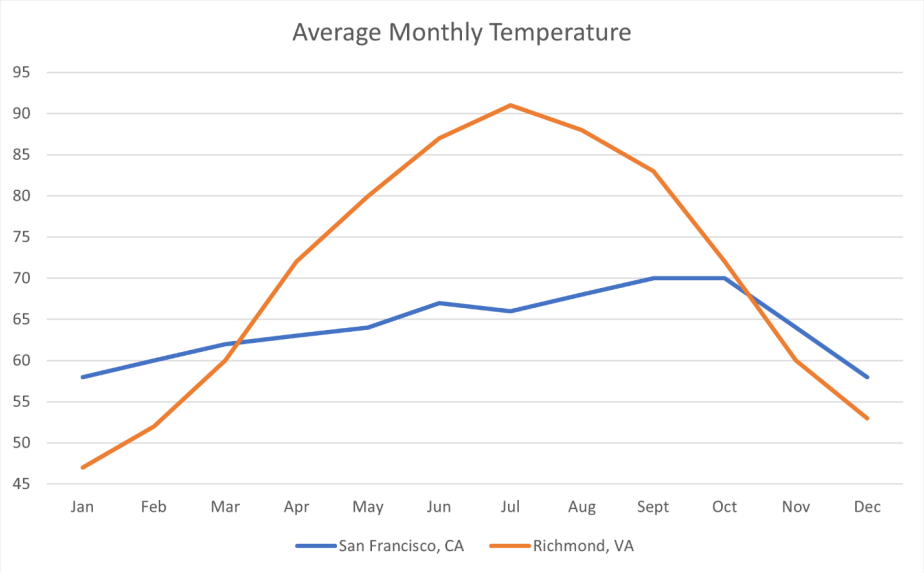


Figure 6.2.2: Average Monthly Temperatures for San Francisco, CA, in blue and Richmond, VA, in orange. (CC-BY-NC 4.0; Alicia Mullens)
Alternative description of the image.

13. Richmond, VA, next to the warm Gulf Stream, has _____ temperatures for most of the year (from approximately March to October), compared to San Francisco.
    a. much colder
    b. much warmer
    c. about the same

14. This is _____ due to the heat provided by the Gulf Stream to Richmond, VA.:
    a. Tropical latitudes
    b. Polar latitudes
    c. both latitudes

Specific Heat

While this holds true for Spring/Summer/Fall months, you'll notice that in late Fall and Winter, the relationship between San Francisco and Richmond is different. Let's investigate why that is. Imagine a warm, sunny day on the beach. You decide to get up from your beach towel and walk towards the ocean water. As you do so, you have to walk through brutally hot sand, but when you get to the water, you notice it's much cooler. If you stayed at the beach all day and into the evening, you'd notice the opposite... the sand is cold at night while the ocean water is fairly warm. The reason for this is **specific heat,** which is the amount of heat required to raise the temperature of 1 kilogram of an object by 1°C. Table 3 presents sensible heat values for various surface cover types on Earth.

Table 6.2.1: Specific heat capacity of various surfaces.

Object	Specific Heat (J/kg°C)
Water	4182
Soil (wet, avg)	1480
Soil (dry, avg)	800
Concrete	880

15. Table 6.2.1 suggests that, for 1 kg of water to warm by 1 °C, it would need to absorb 4182 Joules of heat. This amount of heat is _____ the amount needed to warm soil and concrete.
    a. about the same as
    b. larger than
    c. smaller than

Let's further examine the effects of this heat. Suppose we have 1 kg of liquid water and 1 kg of dry soil, both at 20°C. Suppose we now add 10,000 Joules of heat to both the liquid water and the dry soil (each receives 10,000 joules of heat). We could calculate their new temperature using the following formula:

$$\text{New Temperature} = 20°C + (10000 \div \text{Specific Heat}).$$

For e.g., (for wet soil) New Temperature = 20°C + (10000/1480)

$$= 20°C + 6.76°C = 26.76°C$$

16. Let's do the same for water. Adding 10,000 Joules of heat to 1 kg of water at 20°C will result in a new water temperature of:
    a. 22.39°C
    b. 17.61°C
    c. 32.5°C
    d. 07.5°C

17. On the other hand, adding 10,000 Joules of heat to 1 kg of dry soil at 20°C will result in a new dry soil temperature of:
    a. 22.39°C
    b. 17.61°C
    c. 32.5°C
    d. 07.5°C

In summary, water warms more slowly than land does because of water's specific heat. The opposite is true: water cools much more slowly than land. So during the warm months of the year, inland locations become significantly warmer than areas near the ocean. Let's illustrate this by comparing Long Beach, California (near the ocean), to Dallas, Texas (far inland), as shown in Figure 6.2.3.

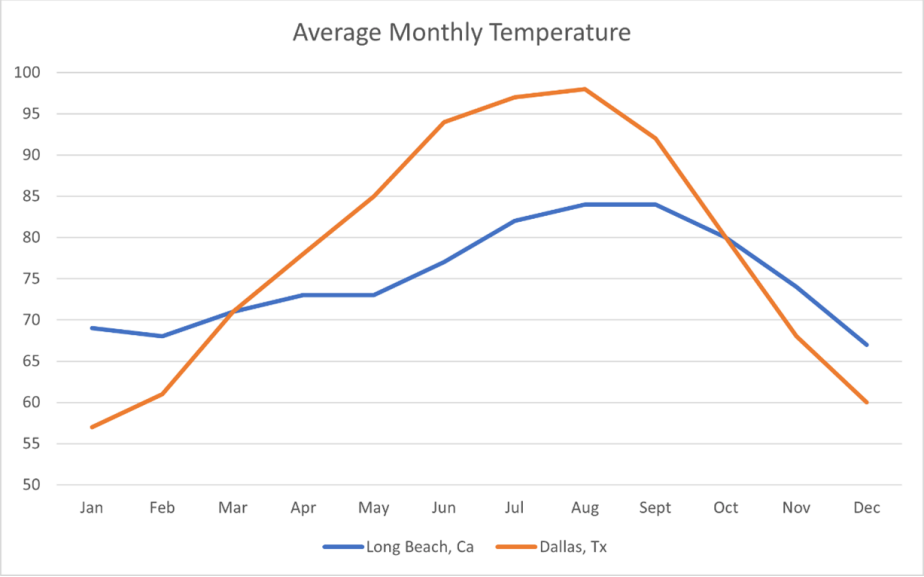


Figure 6.2.3: Average Monthly Temperature for Long Beach, CA, in blue and Dallas, TX, in orange. (CC-BY-NC 4.0; Alicia Mullens) Alternative description of the image.

18. Dallas, which is much further inland than Long Beach, has a _____ yearly temperature range (difference between winter cold and summer warm) than Long Beach.
    a. much smaller
    b. much larger
    c. about the same

19. This _____ that cities closer to the ocean experience lower seasonal temperature variations than inland locations.
    a. confirms
    b. cannot confirm

So how does this relate to San Francisco vs. Richmond in Figure 6.2.2? During winter, the prevailing wind at latitude 37.5°N blows from West-to-East. The Pacific Ocean is to the west of San Francisco, meaning that the wind blows over the Pacific Ocean before reaching San Francisco. Thus, San Francisco doesn't get very cold in the winter months because the Pacific Ocean moderates temperatures.

20. Meanwhile, Richmond is on the East Coast of the United States, meaning that prevailing winds coming from the west are coming from over _____.
    a. land
    b. ocean

21. Therefore, although next to a warm body of water, Richmond's winter temperatures are mostly influenced by the _____ air coming from the west. (hint: How was Dallas' winter temperature compared to Long Beach)?
    a. warm
    b. cold

During summer, the jet stream (which drives the prevailing west-to-east winds) moves northward. This weakens the influence of cool continental air over Richmond and allows for more south- and southwesterly winds. These bring in warm, humid air from the Atlantic Ocean and the Gulf Stream, resulting in warmer and more humid summers.

This page titled 6.2: Ocean-Atmosphere Interaction is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

6.3: Accessible Descriptions

Figure 5.1: The Blue Marble

A full-disk color photograph of Earth as seen from space against the black background of space. The entire sunlit hemisphere of the planet is visible, with Africa centered in the image and the Indian Ocean occupying much of the right half. The photograph is commonly known as the "Blue Marble." The globe fills most of the image and is nearly circular. The surrounding background is completely black, with no visible stars.

The visible continents include:

- Africa occupies the center of the image. The Sahara Desert dominates northern Africa with light tan and reddish-brown colors. Central Africa appears darker green and brown beneath extensive white cloud cover. Southern Africa narrows toward the Cape of Good Hope.
- The Arabian Peninsula is visible northeast of Africa as a large tan landmass. The Red Sea forms a narrow blue strip separating northeastern Africa from the Arabian Peninsula.
- Madagascar appears as a large island off the southeastern coast of Africa.
- Portions of southern Europe and southwestern Asia are visible near the upper edge of the globe, although they are partly obscured by the curvature of Earth.

The oceans are a deep blue:

- The Indian Ocean occupies much of the right side of the image.
- The South Atlantic Ocean lies to the left of Africa.
- The Southern Ocean surrounds Antarctica near the bottom of the globe.

White clouds cover large portions of both land and ocean:

- A broad band of broken clouds stretches across central equatorial Africa.
- Numerous long, curved cloud bands spiral across the Southern Hemisphere oceans. Several of these form large comma-shaped weather systems characteristic of mid-latitude cyclones.
- Smaller cloud clusters are scattered across the tropical Indian Ocean and South Atlantic.
- Thin streaks of cloud trace atmospheric circulation over the oceans.

Near the bottom of the globe, Antarctica appears bright white due to its extensive ice and snow cover. Much of the continent is partially hidden by the curvature of Earth and overlying clouds, but its broad ice-covered surface forms a bright white cap along the southern edge of the planet. The image shows the contrast between Earth's major surface features:

- Blue oceans cover most of the visible hemisphere.
- Brown and tan deserts dominate northern Africa and the Arabian Peninsula.
- Darker vegetated regions appear across central and southern Africa.
- Bright white clouds and polar ice provide strong contrast against both land and sea.

Figure 5.1.1 The Water Cycle

A colorful, labeled diagram titled “The Water Cycle” shows how water moves through the environment in a continuous loop. The scene is divided into three main areas: a large body of water on the left, land with vegetation and a river in the center, and mountains on the right.

- At the top left, a bright yellow sun labeled “solar radiation” shines over a blue ocean or lake. Red upward arrows rising from the water indicate evaporation, where liquid water turns into vapor and rises into the air. A large curved arrow shows this vapor moving upward into clouds.
- In the upper middle and right portions, white clouds are labeled condensation, indicating that water vapor cools and forms cloud droplets. Orange arrows labeled “transportation” show wind moving the clouds from left to right across the sky.
- On the right side, above a mountain range, clouds release precipitation, shown as white streaks falling downward as rain or

snow. On the mountain slopes, arrows labeled snowmelt runoff show melting snow flowing downhill.
- At ground level, water moves across the land as surface flow, shown by arrows following a river that runs from the mountains toward a lake or ocean. Some of this water seeps into the soil (infiltration) and moves deeper underground through percolation. Beneath the surface, a horizontal arrow labeled groundwater flow shows water moving through underground layers.
- Vegetation in the center of the image includes a tree with roots extending into the soil. An upward arrow labeled plant uptake shows water being absorbed by roots. Additional red upward arrows above plants indicate transpiration, where plants release water vapor back into the atmosphere. Near the mountains, red upward arrows labeled sublimation indicate that ice and snow turn directly into vapor without first becoming liquid.

Overall, arrows throughout the diagram connect these processes, illustrating a continuous cycle: water evaporates, condenses into clouds, is transported by wind, falls as precipitation, and returns to bodies of water through runoff, infiltration, and groundwater flow before repeating the cycle.

Figure 5.1.2 Phase Changes of Water

A simple diagram illustrates changes between the three states of water: solid, liquid, and gas.

- On the left, a large white snowflake icon labeled “ice” represents the solid state. In the center, a cluster of light-blue water droplet shapes represents liquid water. On the right, a group of small, light-blue circles represents water vapor (gas).
- Two large curved blue arrows connect the three states in a loop. The top arrow curves from the ice (left) across the top of the image to the gas (right), indicating a transition directly from solid to gas (sublimation). The bottom arrow curves from the gas (right) back to the ice (left), indicating the reverse process (deposition).
- Although not explicitly labeled, the central liquid state lies between the solid and gas states, visually suggesting the typical transitions: melting (solid to liquid), freezing (liquid to solid), evaporation (liquid to gas), and condensation (gas to liquid).

Overall, the diagram shows that water can move between solid, liquid, and gas states, including both direct transitions and those that pass through the liquid phase.

Figure 5.1.3 Global Water Vapor Concentrations

A global map shows the distribution of atmospheric water vapor across Earth using a flattened, oval (world) projection. The continents are outlined in bright magenta, while the oceans and atmosphere are displayed in shades of gray.

- The background is black, with the Earth centered as a wide oval. North and South America appear on the left side of the oval, Europe and Africa near the center, and Asia and Australia on the right. Antarctica stretches along the bottom edge. Coastlines and land boundaries are highlighted in magenta, making the continents' shapes clearly visible against the grayscale background.
- Across the entire map, swirling patterns in varying shades of gray represent the concentration and movement of water vapor in the atmosphere. Lighter gray and white areas indicate higher moisture concentrations, forming cloud-like bands and spirals, especially over tropical regions and across large ocean areas. Darker gray regions indicate drier air, commonly seen over deserts or certain ocean regions.
- Long, curved streaks and spiral formations suggest large-scale weather systems, such as storm tracks and atmospheric circulation. Bands of moisture are visible near the equator, while more fragmented, swirling structures appear in mid-latitude regions.
- At the top of the image, small text reads “water vapor composite,” with a specific date and time (April 26 at 21:00 UTC). Additional small text and numbers appear along the bottom edge, likely indicating timestamps or data-source information.

Overall, the image visualizes global atmospheric moisture patterns at a specific moment in time, highlighting how water vapor is distributed and transported around the planet.

Figure 5.2.1 Global Ocean Currents Map

This image is a world map in a Robinson projection, showing the major ocean currents worldwide. Landmasses are shaded in light tan, while oceans are light blue-gray. The map includes latitude lines at approximately 60° North, 30° North, the Equator (0°), 30° South, and 60° South.

Ocean currents are illustrated using arrows:

- Red arrows indicate warm currents
- Blue arrows indicate cold currents
- Black arrows indicate general surface current flow directions

Overall Pattern

The map highlights large circular current systems, called gyres, in the Atlantic, Pacific, and Indian Oceans. These gyres rotate:

- Clockwise in the Northern Hemisphere
- Counterclockwise in the Southern Hemisphere

There is also a continuous eastward current encircling Antarctica called the Antarctic Circumpolar Current.

Atlantic Ocean Currents

In the North Atlantic:

- The Gulf Stream (warm, red) flows northeast from the southeastern United States toward Europe.
- The North Atlantic Drift continues this flow toward northwestern Europe.
- The Norwegian Current carries warm water further north.
- The Labrador Current (cold, blue) flows south along the eastern coast of Canada.
- The Canary Current (cold) flows south along the northwest coast of Africa.
- Near the equator, the North Equatorial Current flows westward, while the Equatorial Countercurrent flows eastward.

In the South Atlantic:

- The Brazil Current (warm) flows south along the eastern coast of South America.
- The Benguela Current (cold) flows north along the southwest coast of Africa.
- The South Equatorial Current flows westward.
- The gyre closes with eastward flow in the Southern Ocean.

Pacific Ocean Currents

In the North Pacific:

- The Kuroshio Current (warm) flows north along the coast of Japan.
- The Oyashio Current (cold) flows south from the Bering Sea.
- The California Current (cold) flows south along the U.S. West Coast.
- The North Pacific Current flows eastward across the ocean.
- The North Equatorial Current flows westward, with an eastward Equatorial Countercurrent.

In the South Pacific:

- The East Australian Current (warm) flows south along Australia's east coast.
- The Peru (Humboldt) Current (cold) flows north along South America's west coast.
- The South Equatorial Current flows westward.
- These currents form a counterclockwise gyre.

Indian Ocean Currents

- The Agulhas Current (warm) flows south along the southeast coast of Africa.
- The Mozambique Current (warm) flows south through the Mozambique Channel.
- The West Australian Current (cold) flows north along Western Australia.
- The South Equatorial Current flows westward.
- A seasonal North Equatorial Countercurrent flows eastward near the equator.

Southern Ocean

- The Antarctic Circumpolar Current flows continuously from west to east around Antarctica.
- Just north of it, the Antarctic Subpolar Current flows in the opposite direction (east to west).

Figure 5.2.2 Average monthly temperatures for San Francisco, CA, and Richmond, VA

This image is a line chart titled “Average Monthly Temperature.” It compares average temperatures across all twelve months for two cities: San Francisco, California, and Richmond, Virginia.

Chart Structure

- The horizontal (x) axis shows months from January through December.
- The vertical (y) axis shows temperature values ranging approximately from 45°F to 95°F.
- Two lines represent the cities:
  - Blue line: San Francisco, CA
  - Orange line: Richmond, VA
- A legend at the bottom identifies these lines by color and city.

San Francisco Temperature Pattern (Blue Line)

San Francisco shows mild, stable temperatures year-round:

- Starts at about 58°F in January
- Gradually rises to around 67°F in June
- Slight dip in July (~66°F)
- Peaks at about 70°F in September and October
- Declines back to about 58°F in December

Overall, the variation is small, staying roughly between 58°F and 70°F throughout the year.

Richmond Temperature Pattern (Orange Line)

Richmond shows greater seasonal variation with hot summers and cool winters:

- Begins at about 47°F in January
- Gradually increases to 60°F in March
- Warms rapidly to 72°F in April and 80°F in May
- Peaks at approximately 91°F in July
- Slightly decreases to 88°F in August
- Drops to 83°F in September and 70°F in October
- Falls further to about 60°F in November and 53°F in December

Temperatures range widely, from about 47°F to 91°F.

Figure 5.2.3 Average monthly temperatures for Long Beach, CA, and Dallas, TX

This image is a line chart titled “Average Monthly Temperature.” It compares the average monthly temperatures for Long Beach, California and Dallas, Texas across the full year.

Chart Structure

- The horizontal (x) axis lists the months from January through December.
- The vertical (y) axis shows temperature values ranging approximately from 50°F to 100°F.
- Two lines represent the cities:
  - Blue line: Long Beach, CA
  - Orange line: Dallas, TX
- A legend at the bottom identifies each line by color and city.

Long Beach Temperature Pattern (Blue Line)

Long Beach shows a mild coastal climate with moderate seasonal variation:

- Starts around 69°F in January
- Slight dip to about 68°F in February
- Gradually rises to 73°F in April and May
- Continues warming to about 77°F in June
- Peaks around 82°F in July and 84°F in August and September
- Declines to 80°F in October, 74°F in November, and 67°F in December

Temperatures remain within a relatively narrow range of about 67°F to 84°F.

Dallas Temperature Pattern (Orange Line)

Dallas shows a continental climate with hot summers and cooler winters:

- Begins near 57°F in January
- Increases steadily to 61°F in February and 71°F in March
- Continues rising to 78°F in April and 85°F in May
- Climbs sharply to 94°F in June
- Peaks around 97°F in July and 98°F in August
- Drops to 92°F in September
- Falls significantly to 80°F in October, 68°F in November, and 60°F in December

Temperatures vary widely, from about 57°F to 98°F.

This page titled 6.3: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

7: THE CARBON CYCLE

Introduction

While water undoubtedly has significant impacts on Earth's Climate, the number one culprit of our current Climate Change crisis is Carbon. Specifically, in two forms: Carbon Dioxide (CO_2) and Methane (CH_4). Both of these gases are greenhouse gases, which are gases that, while mostly transparent to incoming shortwave radiation, are highly absorbent to outgoing longwave radiation, resulting in additional heat being trapped in the Earth System. While there are numerous other greenhouse gases, Carbon Dioxide and Methane have by far the greatest impacts and are therefore of importance to climate scientists.



Figure 7.1: Black Carbon is one of many forms that Carbon takes on as it moves throughout the Earth System. (Public Domain; FK1950 via Wikimedia Commons)

It's important to understand that while both Carbon Dioxide and Methane have anthropogenic sources, they are both important components of the Earth System and regularly cycle through its various components. In fact, it's those natural cycles that have been altered by human activity that are the chief cause of excess Carbon in the atmosphere and subsequent warming. In this investigation, we will examine the Carbon Cycle and a few ways humans have altered it.

Objectives

- Identify key Carbon sources, reservoirs, and sinks in the Earth System
- Differentiate the short-term Carbon Cycle from the long-term Carbon Cycle
- Investigate how humans have disrupted the Carbon Cycle

Navigational Note

Investigation 6 has 22 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

7.1: Components of the Carbon Cycle

7.2: Ocean Acidification and Short Term Carbon Cycle

7.3: Long Term Carbon Cycle
7.4: Accessible Descriptions

This page titled 7: The Carbon Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

7.1: Components of the Carbon Cycle

What is Carbon?

Before we begin to look at the Carbon Cycle in-depth, let's very quickly cover a few important facts about Carbon:

- Carbon is the fourth most abundant element in the Universe
- Carbon is essential to all living things... we are "carbon-based" lifeforms... in fact, all life on Earth is carbon-based.
  - Proteins, Fats, and Carbohydrates are all carbon-based as well.
  - By mass, Humans are approximately 19% Carbon
- Carbon is "conserved" on Earth, meaning that the total amount of Carbon on Earth doesn't change appreciably.
  - Rather, Carbon transitions from one component of the Earth System to another.
  - These processes, and the numerous things that contain carbon on Earth, are a part of the Carbon Cycle
- Carbon can be found everywhere... here are just a few examples:
  - Food: Proteins, Fats, and Carbohydrates all contain carbon.
  - Beverages: Any "fizzy" beverage has been carbonated... pumped with Carbon Dioxide to create those pleasant little "bubbles."
  - Jewelry: A diamond is entirely carbon!
  - Plants and Animals: All living things have carbon.
  - Natural Gas: Mostly made up of Methane, with a small percentage of other hydrocarbons (such as butane and propane)

As mentioned above, Carbon on Earth is "conserved" meaning that its amount on Earth really doesn't change (yes, there are small amounts of planetary outgassing and incoming meteors and so on, but the contributions of those components to Earth's Carbon stockpile are negligible, even over a very long period of time). Instead, Carbon is continuously moving through various reservoirs, such as the human body, the deep ground, or the atmosphere. We call processes that add carbon to a reservoir "sources," and processes that remove carbon from a reservoir "sinks." We'll investigate these in the next section.

Carbon Sources, Reservoirs, and Sinks

Figure 7.1.1 provides an overview of the various components of the Carbon Cycle. It may feel overwhelming, but this is actually a fairly simplified picture of the Carbon Cycle. Numbers in white represent the amount of Carbon (in Gigatons, or billions of tons) in a reservoir; yellow numbers represent processes that exchange carbon between reservoirs; and red numbers represent excess carbon introduced into the system by human activities (such as burning fossil fuels and land-use change).

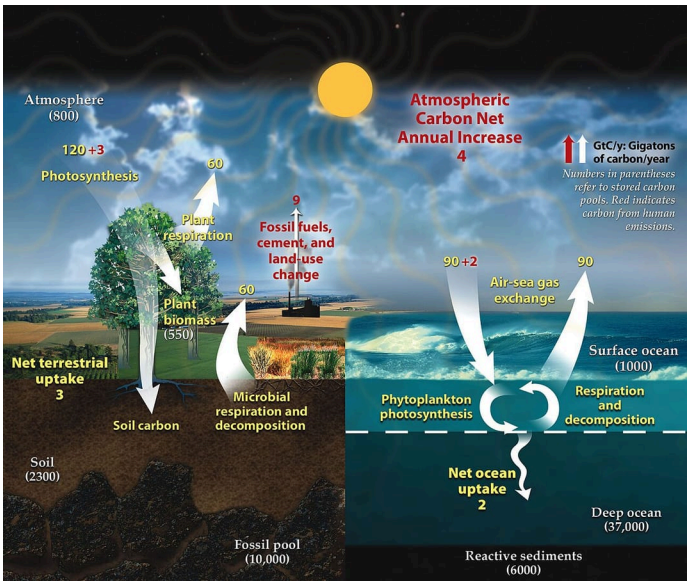


Figure 7.1.1: The Global Carbon Cycle and Estimated Values of Carbon Exchange. (Public Domain; U.S. Department of Energy via Wikimedia Commons). Alternative description of image.

1. The largest carbon reservoir, according to Figure 7.1.1 is:
   a. Soil
   b. Atmosphere
   c. Fossil Pool
   d. Deep Ocean
2. Photosynthesis, a commonly understood process of removing Carbon Dioxide from the atmosphere (these are called “carbon sinks”), removes approximately _____ gigatons of Carbon from the atmosphere in a given year (hint: include both the yellow natural number and the red anthropogenic number).
   a. 123
   b. 60
   c. 92
   d. 90

Plant biomass is itself a carbon reservoir, holding an annual average of 550 gigatons of Carbon. While photosynthesis is a carbon sink for the atmosphere (since it removes carbon from the atmosphere), photosynthesis is a “carbon source” for plant biomass (meaning that it adds carbon to the plant biomass). On the other hand, respiration by both plants and microbes (via respiration and decomposition) is one of the two key carbon sinks for plant biomass.

3. Combined, plant respiration and microbial respiration/decomposition account for _____ gigatons of Carbon being removed from plant biomass.
   a. 60
   b. 90
   c. 120
   d. 3
4. Since your answer for question 2 represents Biomass’ Carbon source while your answer for question 3 represents Biomass’ Carbon sink, the net amount of Carbon into biomass can be calculated by simply subtracting the amount removed by the sink from the amount added by the source. As a result, there is a net increase of approximately _____ gigatons of carbon in biomass.
   a. 3
   b. 6
   c. 9
   d. 12

This excess Carbon is absorbed into the ground, becoming part of Earth’s soil, and may eventually sink all the way into the fossil pool (which will take tens of thousands of years).

5. Written Question: Now consider the human body as a Carbon reservoir. Name one thing that adds Carbon to the human body

(source) and one thing that removes Carbon from the human body (sink). It's okay to use the internet to research your answer, but please put your answer in your own words and cite your source (note: AI-generated answers are unacceptable and will receive zero credit)

Another important component of the Carbon Cycle is the ocean. Because the deep ocean holds a vast amount of Earth's carbon, while the surface ocean is home to major sources of photosynthesis (such as phytoplankton), the ocean plays an important role in balancing Earth's Carbon processes. Unfortunately, as with plant biomass, there is a net increase in carbon being added to the ocean.

6. Of the 9 gigatons of carbon added to the atmosphere by Human activities, approximately _____ giga tons of that excess carbon is absorbed by the ocean:
   a. 1
   b. 2
   c. 3
   d. 4
7. Combining your answer from question 6 with your answer from question 4 (which showed the amount of excess carbon absorbed into the ground), natural processes are only capable of removing _____ gigaton's of the 9 gigatons added by human activities.
   a. 2
   b. 3
   c. 5
   d. 9

Unfortunately, the remaining Carbon is absorbed into the atmosphere, enhancing Earth's greenhouse effect.

This page titled 7.1: Components of the Carbon Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

7.2: Ocean Acidification and Short Term Carbon Cycle

Ocean Acidification

Before we delve into the impacts of greenhouse gases, let's stay in the ocean for just a few more moments. The excess carbon absorbed by the ocean does not come without consequences. Carbon is a very reactive element, and one of its favorite molecules to bond with is Water (H_2O), so when Carbon is absorbed into the ocean, it reacts with water. Since most of the excess carbon pumped into the atmosphere by human activities is in the form of Carbon Dioxide, most of the excess carbon absorbed by the ocean is also Carbon Dioxide. As a result, Carbon Dioxide and Water react to form a new compound, one that is familiar to anyone who has enjoyed a carbonated beverage before: Carbonic Acid. While this isn't a Chemistry class, we will share a brief chemical formula to explain how the reaction occurs.

$$CO_2 + H_2O = H_2CO_3 = +H + HCO_3$$

The left term is Carbon Dioxide added to Water; the middle term is Carbonic Acid, which then dissociates into the right term, bicarbonate and free hydrogen ions, which are the nasty little culprits in acidification. Figure 7.2.1 outlines the ocean acidification process a bit more:

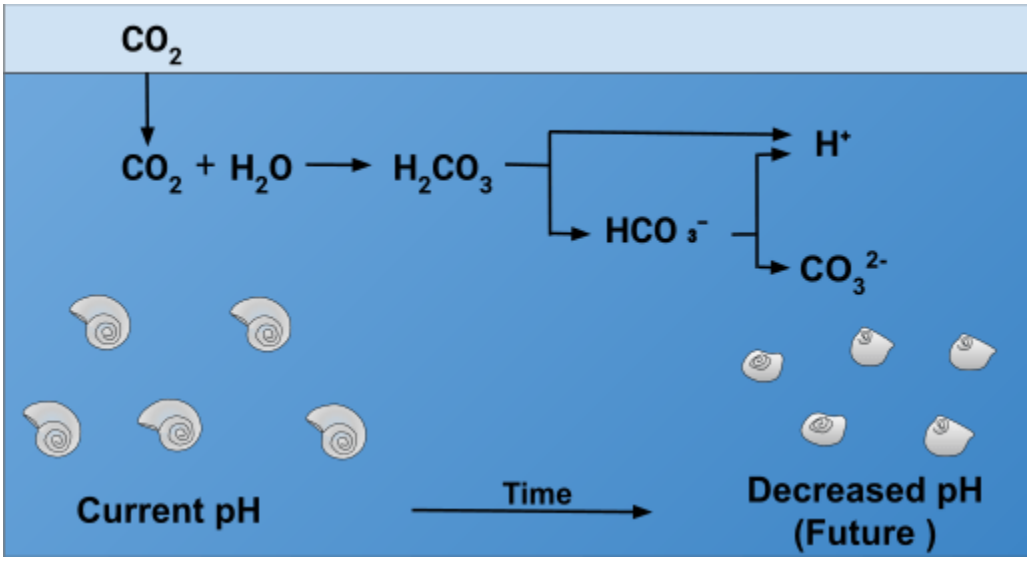


Figure 7.2.1: Effects of Ocean Acidification on Calcification. Note that in a decreased pH environment, calcium shells become deformed. (CC-BY-SA 4.0; Elizajans via Wikimedia Commons).

If you remember your high school chemistry class, the **pH scale** measures how acidic or alkaline a substance is. The scale ranges from 0 to 14. A pH of 7 is neutral. A pH less than 7 is acidic, and a pH greater than 7 is basic. Pure water is neutral, with a pH of 7.0. When chemicals are mixed with water, the mixture can become either acidic or alkaline to some extent. Vinegar and lemon juice are acidic substances, while laundry detergents and ammonia are alkaline. Figure 7.2.2 shows the change in pH of the world ocean since pre-industrial times (1770s).

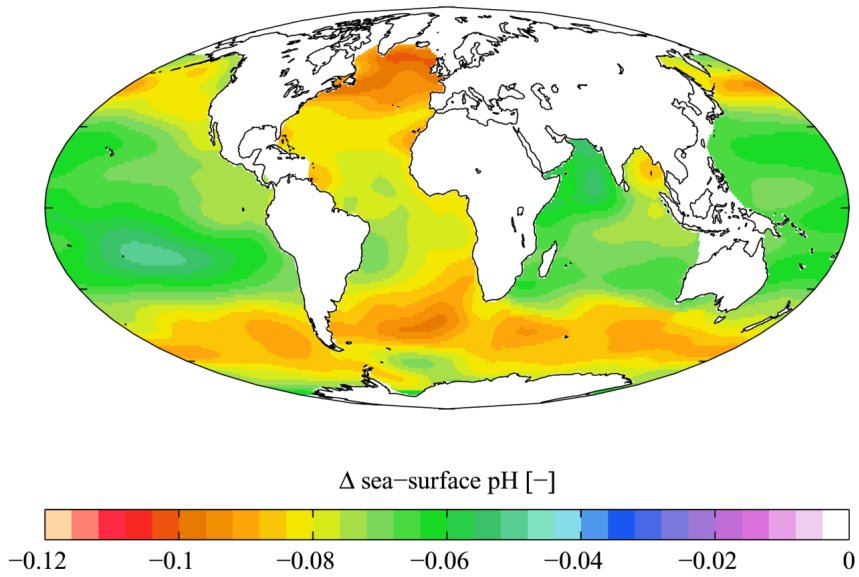


Figure 7.2.2: Change in average Ocean pH from the 1770s to the 1990s. (CC-BY-SA 3.0; Plumbago via Wikimedia Commons). Alternative Description of Image.

While Figure 7.2.2 shows the global pH distribution of our oceans, Figure 7.2.3 is a time series of global average pH from 1988 to 2021, based on data from the Aloha Station in Hawaii, and plotted by Our World In Data.

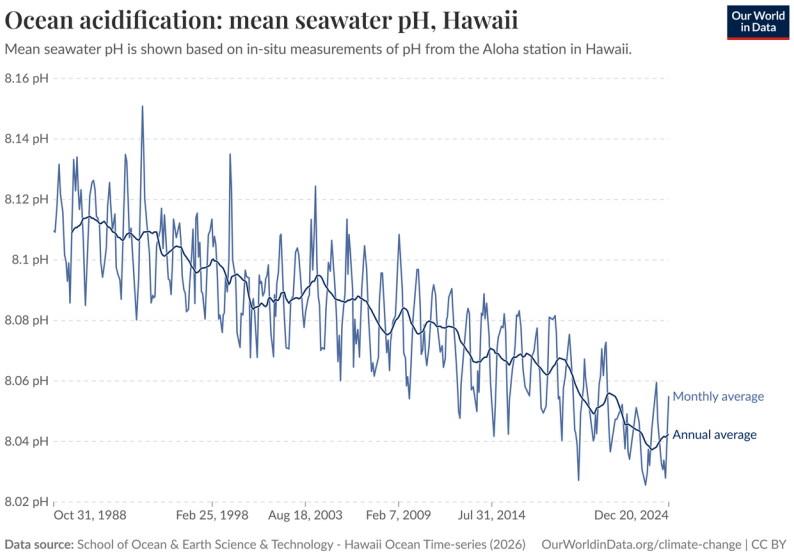


Figure 7.2.3: Time series of Mean seawater pH from 1988 to 2024. Data collected by the University of Hawaii and displayed by OurWorldInData.org (CC-BY 4.0; Ocean Acidification via Our World in Data). Alternative Description of Image.

8. From Figure 7.2.3, while there is a seasonal cycle (hence the jaggedness and “up and down” nature of the plot), the overall trend in global average pH (which can be found in the "Annual Average” line) is:
   a. Upward
   b. Downward
   c. Neither
9. This indicates that the ocean is becoming (note: higher values indicate a more basic substance while lower values indicate a more acidic substance):
   a. More Basic
   b. More Neutral
   c. More Acidic
10. However, Figure 7.2.2 makes it clear that not every location in the ocean is experiencing the same decline in pH. Rather, the _____ seem to be seeing the biggest change while the _____ is seeing the least amount of change. Note: The

Southern Ocean refers to the Southern Atlantic, Pacific, and Indian Oceans.

a. Equator; North Atlantic and Southern Ocean
b. North Atlantic; Southern Ocean
c. Equator; Southern Atlantic Only
d. North Atlantic and Southern Ocean; Equator

While these numbers and figures may seem relatively insignificant to us as humans, the truth is that many marine species (such as coral) are very sensitive to changes in the pH of the ocean, so even a slight change in either direction can significantly stress an ecosystem or, in the case of more significant changes, cause an ecosystem to collapse.

Short-Term Carbon Cycle

In Figure 7.2.3, you may notice a "jagged" shape to the "Monthly Average" line. This is due to seasonality; many natural systems exhibit seasonal variation, with levels of a particular variable higher in one season and lower in another. While there are many causes of the ocean's pH seasonality, one of the main causes would be Carbon Dioxide levels, which experience a similar but inverse (opposite) seasonality. This seasonality is part of the Short-Term Carbon Cycle: carbon exchanges that occur over relatively short time spans, i.e., seconds, minutes, hours, days, weeks, or months. Meanwhile, long-term chemical and geological processes often take millions of years. Figure 7.2.4 is CO_2 data taken from the Mauna Loa Observatory from the two-year period ending on May 27th, 2026.

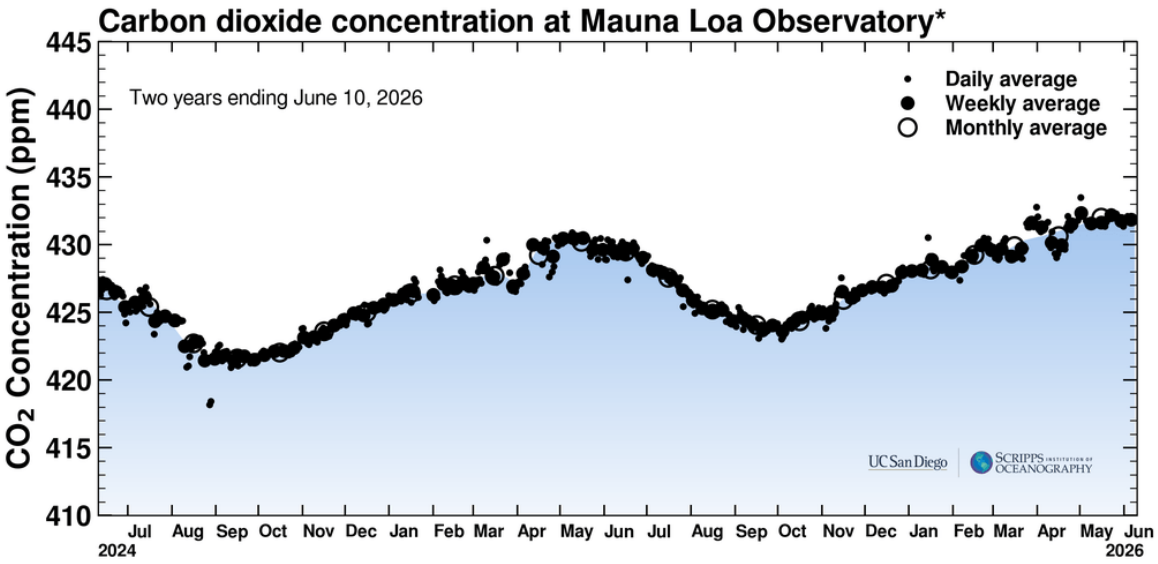


Figure 7.2.4: Carbon Dioxide Concentrations measured at the Mauna Loa Observatory for the two-year period ending on May 27th, 2026. (CC BY 4.0; Ralph Keeling via Scripps Institute of Oceanography). Alternative Description of Image.

11. While there may be some year-to-year variation, Carbon Dioxide concentrations tend to peak around May and reach their lowest annual levels in approximately:
    a. February/March
    b. September/October
    c. December/January
12. Based on the information above, Carbon Dioxide levels tend to increase during _____and decrease during _____.
    a. Fall/Winter; Summer
    b. Summer; Winter
    c. Spring; Fall/Winter

There is some lag between when photosynthetic activity wakes up/shuts down and when levels change, but in general, this is what happens:

- During warmer/brighter months, there is more sunlight, so vegetation can perform photosynthesis. As a result, there is more photosynthesis than respiration happening, and Carbon Dioxide Concentrations go down.
- During colder/darker months, there isn't enough sunlight for photosynthesis, so vegetation can't perform photosynthesis. As

a result, vegetation often hibernates during those months, consuming sugars produced during the prior growing season and releasing Carbon Dioxide back into the atmosphere (via respiration). This causes Carbon Dioxide concentrations to rise.

13. Despite the seasonality shown here, comparing CO_2 concentrations from May 2021 (the far left of the graph) to May 2023, you can still see that Carbon Dioxide concentrations are:
    a. Higher in 2023 than in 2021
    b. Lower in 2023 than in 2021
    c. Exactly the same in 2023 as in 2021
14. So even though there is a seasonality to Carbon Dioxide, the overall trend in Carbon Dioxide is:
    a. Upward
    b. Downward
    c. Neither

To figure out what's causing this, we need to investigate the Long-Term Carbon Cycle, which we will do in the next section.

This page titled 7.2: Ocean Acidification and Short Term Carbon Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

7.3: Long Term Carbon Cycle

The Long-Term Carbon Cycle

Has anyone ever told you “a good way to reduce your Carbon Footprint would be to breathe less?” If so, it’s okay to laugh out loud at the suggestion. The fact is that there are trillions of organisms right now, all performing respiration, including humans. But in general, these respirations don’t add CO_2 appreciably to the atmosphere because they are quickly counteracted by photosynthesis. In short, human respiration is a component of the short-term carbon cycle and doesn’t really cause any appreciable change. In fact, the short-term carbon cycle remains fairly stable because short-term processes, such as respiration, are well balanced by others, such as photosynthesis.

The real harm to the Earth System is occurring in the Long-Term Carbon Cycle. Unlike the short-term cycle (which consists of processes that operate on a seconds-minutes-days-months timescale), the long-term carbon cycle operates over millions of years! And yet, we can still see them in plain sight every day. Imagine a raindrop falling onto a hillside; you may not know this, but that raindrop consists of a very small amount of Carbonic Acid dissolved in the water. This carbonic acid chemically weathers that hillside, producing a small amount of sediment. Over many months/years, this sediment travels downhill into streams, which eventually enter the oceans, sink, and deposit on the ocean floor. This entire process already takes significantly longer than any short-term process. However, once the sediment is deposited on the ocean floor, it takes millions of years for it to subduct (sink) into the crust, melt into magma, and then erupt back to the surface of the Earth via a volcanic eruption. The Carbon Dioxide released by such volcanic eruptions then gets absorbed by rainfall and falls back to the ground as Carbonic Acid, restarting the cycle. This entire cycle is called the Geologic Leg of the Long-Term Carbon Cycle. Figure 7.3.1 is a diagram of the Geologic Leg of the Long-Term Carbon Cycle.

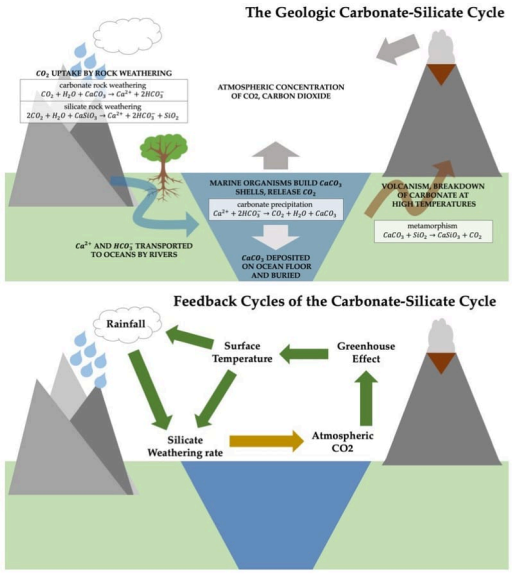


Figure 7.3.1: The Geologic Leg of the Long-Term Carbon Cycle and associated Feedback Loops. (CC-BY-SA 4.0; Gretashum via Wikipedia).
Alternative Description of Image

There’s some good news that this cycle conveys. A warmer world is going to be a wetter world. Increased rainfall would result in more Carbon Dioxide being absorbed from the atmosphere, enhancing this cycle. This would remove additional Carbon Dioxide from the atmosphere and could potentially slow down warming. This is called the Chemical Weathering Feedback Loop, and is considered a negative feedback loop because, while the trigger is warming (which leads to more precipitation), the ultimate result is cooling.
The Geologic leg is not where human activity has disrupted the Long-Term Carbon Cycle.

The Biological Leg of the Carbon Cycle

Humans have disturbed the Biological Leg, which encompasses life, death, burial, and the long-term oxidation of living organisms.

15. One key contribution to Climate Change has been the use of _____ by humans:
    a. Wind Power
    b. Fossil Fuels
    c. Solar Power

Humans have increased the concentration of carbon dioxide in the atmosphere by digging up and burning dead organic matter. Basically, living things died, were buried, compressed into either Coal or Oil, or decomposed by bacteria into Natural Gas, and then dug up by humans. If left alone, these “Fossil Fuels” would remain buried below ground for millions of years, eventually rise back up to the surface of the Earth via crustal upwelling, and oxidize over millions of additional years. To see how this process works, take a lump of coal and set it outside. It doesn’t burn on its own; instead, it slowly oxidizes and emits CO_2.

Indeed, it’s the digging up and burning of fossil fuels that has most disrupted the Carbon Cycle. If left untouched, it would take the same fossil fuels millions of years to rise to Earth's surface and oxidize back into the atmosphere as Carbon Dioxide. However, human activity has made that process significantly faster, and natural processes simply can’t keep up.

How humans have impacted the Carbon Cycle

The remainder of this investigation will cover a few charts regarding human fossil fuel use. Figure 7.3.2 shows the total global fossil fuel usage since the beginning of the Industrial Revolution (approximately 1800). The graph is split up into three color shadings for Coal, Oil, and Natural Gas.

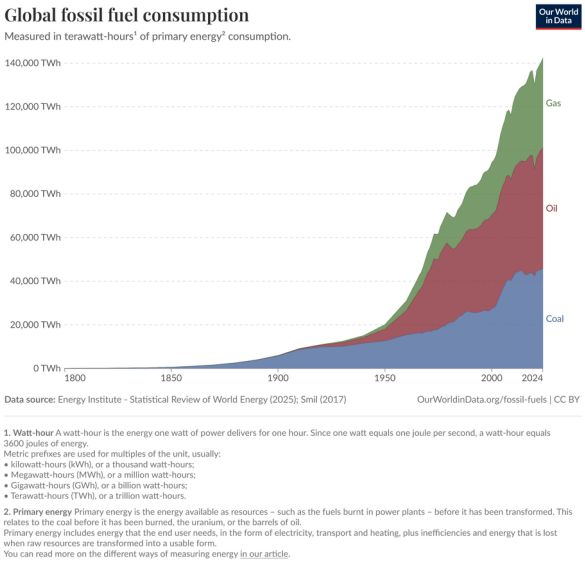


Figure 7.3.2: Global Fossil Fuel Consumption by Type. (CC-BY 4.0; Global Fossil Fuel Consumption via Our World In Data). Alternative Description of Image.

16. Prior to 1950, the vast majority of fossil fuel usage was in the form of:
    a. Oil
    b. Gas
    c. Coal
17. In the past few decades, Coal usage has leveled off. However _____ has seen noticeable increases in usage (hint, look at how “thick” the color wedge is rather than how high on the chart).
    a. Oil
    b. Natural Gas
    c. Both

If you notice, at the very top of the graph, there was a slight dip in fossil fuel usage several years before the graph ends. This

was 2020, and the dip was largely due to decreased travel caused by the COVID-19 Pandemic. However, as the pandemic-related restrictions eased, fossil fuel consumption has continued to increase. So who's to blame for all of this? Figure 7.3.3 shows the Fossil Fuel usage (total) by country in 2024, and Figure 7.3.4 shows the same data but as a line graph for the period ending in 2024.

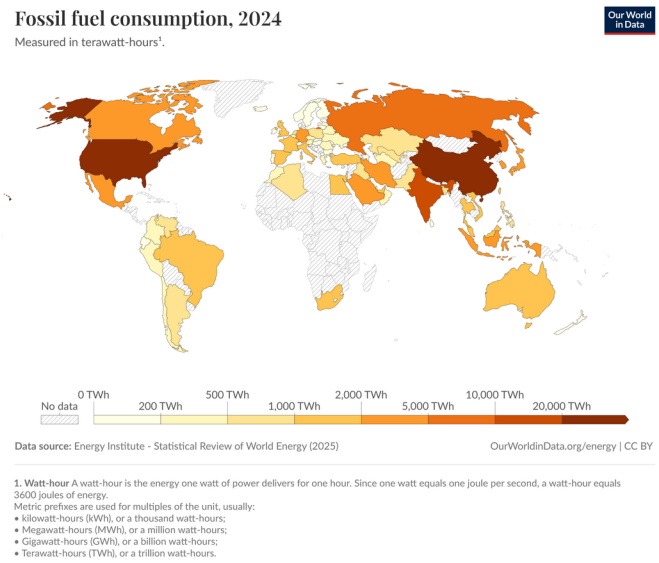


Figure 7.3.3: Map of Fossil Fuel Consumption by Country in 2024. (CC-BY 4.0; Fossil Fuel Consumption via Our World In Data). Alternative Description of Image.

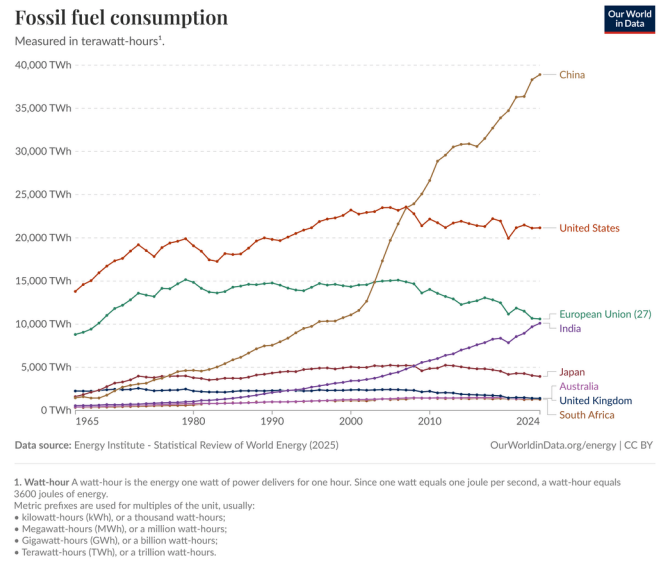


Figure 7.3.4: Line graph of Fossil Fuel Consumption by Country since 1965. (CC-BY 4.0; Fossil Fuel Consumption via Our World In Data). Alternative Description of Image.

18. The country that consumed the most fossil fuel in 2024 was:
    a. The United States
    b. The European Union
    c. China
19. The country that consumed the second most fossil fuel in 2024 was:
    a. The United States
    b. India `
    c. China

This may seem somewhat different from the common understanding. We tend to think that the United States is the largest consumer of fossil fuels, but in fact, the tide has turned over the past few decades. But before we begin to shift blame away from

the US, it's important to investigate why such a change may be occurring and why the United States is not innocent in the change. Rapidly developing countries, such as China and India, are seeing larger increases in their fossil fuel consumption. Figure 7.3.4 shows that since 2000, China has more than tripled its consumption of fossil fuels, and India has more than doubled, while much of the developed world, such as the US, Japan, and the European Union, has leveled off or even decreased its consumption levels. Here are a few key reasons why:

- Massive populations: Both India (1.408 billion) and China (1.412 billion) have populations almost four times that of the United States. In fact, almost one in three humans on Earth is either Chinese or Indian.
- Massive economic growth: Both India and China have seen massive economic growth, with India seeing an over five-fold increase (from $500 billion to $2.9 trillion) in GDP and China seeing an over ten-fold increase (from $1.47 trillion to $14.8 trillion) from 2000 to 2021.
- Outsourcing: As developed countries move into a post-industrial world, they have shifted most of their manufacturing jobs and factories to developing countries, such as China and India. In essence, countries like the United States and members of the European Union are still at fault for much of the world's fossil fuel consumption... but since they have outsourced many of their factories to other countries, they have, in essence, given other countries their problem.

This leads to an ethical question that is beyond the scope of this class... As we begin to reduce the consumption of fossil fuels in order to fight Climate Change, who should be leading the effort? Post-industrial countries like the United States, which had the luxury of using fossil fuels without any hesitation to grow economically, or developing countries like China and India, which are currently experiencing massive economic growth, but ultimately cannot continue on the same consumption path that the United States did, if we want to prevent the worst of Global Warming? Who should be cutting back... us or them?

Before we wrap up this investigation, one piece of information that may help answer that question is each nation's per capita fossil fuel consumption. Figure 7.3.5 is a graph showing per-capita (per-person) fossil fuel consumption in 2021 for the same nations/regions as in Figure 7.3.4.

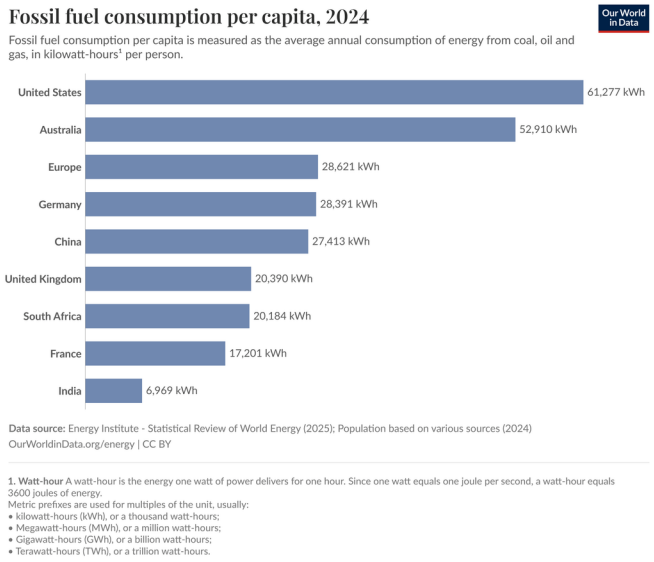


Figure 7.3.5: Fossil Fuel consumption per capita in 2024. (CC-BY 4.0; Fossil Fuel Consumption via Our World In Data). Alternative Description of Image.

20. Although China is currently the largest consumer, on a per-capita basis, the average citizen of the United States consumes _____ as much:
    a. Significantly less
    b. More than twice
    c. More than five times
21. In fact, on a per-capita basis, the United States is:
    a. The largest consumer of fossil fuels
    b. Still significantly lower than other developed nations
    c. About the same as China and India in fossil fuel consumption
22. This shows that, while large developing nations are becoming large Fossil Fuel consumers, the United States _____ if we want to seriously reduce global fossil fuel usage:

a. Still needs to reduce its consumption of fossil fuel
b. No one needs to worry about its consumption of fossil fuel

One quick note: There are a few small, mostly oil-producing countries (Kuwait, Qatar, Trinidad and Tobago, etc.) with very tiny populations but oversized oil industries that contribute to outrageously high per-capita fossil-fuel consumption levels. These countries were intentionally left off this chart because their overall fossil-fuel consumption is very small compared to developed/developing countries, and their higher per-capita usage is driven not by the average citizen but by their fossil-fuel industry.

This page titled 7.3: Long Term Carbon Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

7.4: Accessible Descriptions

Figure 6.1.1: Global Carbon Cycle

Diagram illustrating the global carbon cycle, showing the major carbon reservoirs (stored carbon) and annual carbon exchanges among the atmosphere, land biosphere, oceans, soils, and fossil fuel reserves. Values in parentheses represent the amount of carbon stored in each reservoir in gigatons of carbon (GtC), while arrows show annual carbon fluxes in gigatons of carbon per year (GtC/yr). Red values indicate carbon added by human activities.

The atmosphere contains approximately 800 GtC. Each year, terrestrial plants remove about 120 GtC/yr from the atmosphere through photosynthesis, plus an additional 3 GtC/yr associated with increased uptake linked to human-caused carbon emissions. Plants return approximately 60 GtC/yr to the atmosphere through plant respiration. Soil microbes and decomposition return another 60 GtC/yr to the atmosphere. The land system as a whole has a net terrestrial carbon uptake of about 3 GtC/yr, meaning land ecosystems absorb slightly more carbon than they release.

The terrestrial carbon reservoirs include approximately 550 GtC stored in plant biomass and 2,300 GtC stored in soils. Beneath the surface, fossil fuel deposits contain approximately 10,000 GtC.

Human activities, including fossil fuel combustion, cement production, and land-use change, add approximately 9 GtC/yr to the atmosphere. Of this amount, roughly 4 GtC/yr remains in the atmosphere, shown as the net annual atmospheric carbon increase.

The ocean exchanges large amounts of carbon with the atmosphere. About 90 GtC/yr moves from the ocean to the atmosphere, while approximately 90 GtC/yr plus an additional 2 GtC/yr moves from the atmosphere into the ocean. This creates a net ocean carbon uptake of about 2 GtC/yr. Ocean biological processes include phytoplankton photosynthesis, respiration, decomposition, and transport of carbon into deeper waters.

The ocean carbon reservoirs include approximately 1,000 GtC in the surface ocean, 37,000 GtC in the deep ocean, and 6,000 GtC in reactive marine sediments. The deep ocean is the largest active carbon reservoir shown in the figure.

Overall, the diagram shows that human activities add approximately 9 GtC/yr to the atmosphere, while natural land and ocean sinks remove about 5 GtC/yr combined (3 GtC/yr on land and 2 GtC/yr in the ocean), leaving a net atmospheric increase of approximately 4 GtC/yr.

Table 6.4.1: Carbon reservoirs (stored carbon)

Reservoir	Carbon stored (GtC)
Atmosphere	800
Plant biomass	550
Soil	2,300
Fossil fuel pool	10,000
Surface ocean	1,000
Deep ocean	37,000
Reactive sediments	6,000

Table 6.4.2: Annual carbon fluxes

Process	Flux (GtC/yr)
Photosynthesis	120
Additional terrestrial uptake	+3

Process	Flux (GtC/yr)
Plant respiration	60
Microbial respiration and decomposition	60
Fossil fuels, cement, and land-use change	+9
Ocean to atmosphere exchange	90
Atmosphere to ocean exchange	90
Additional ocean uptake	+2
Net terrestrial uptake	3
Net ocean uptake	2
Net atmospheric increase	4

Table 6.4.3: Carbon budget summary

Component	Net change (GtC/yr)
Human emissions	+9
Land uptake	–3
Ocean uptake	–2
Atmospheric increase	+4

Table 6.4.4: Relative size of carbon reservoirs

Rank	Reservoir	Carbon stored (GtC)
1	Deep ocean	37,000
2	Fossil fuel pool	10,000
3	Reactive sediments	6,000
4	Soil	2,300
5	Surface ocean	1,000
6	Atmosphere	800
7	Plant biomass	550

Notes:

- Units are gigatons of carbon (GtC) and gigatons of carbon per year (GtC/yr).
- Numbers in parentheses indicate stored carbon pools.
- Red values represent carbon introduced by human activities.
- The largest annual natural carbon fluxes are photosynthesis, plant respiration, microbial decomposition, and air-sea gas exchange, each involving approximately 60–120 GtC/yr.
- The deep ocean contains nearly 46 times more carbon than the atmosphere and is the largest active carbon reservoir shown.

Figure 6.2.1: Ocean Acidification Equation

Diagram showing how dissolved carbon dioxide reacts with water to form carbonic acid, which releases hydrogen ions and forms bicarbonate and carbonate ions. Over time, increased hydrogen ion concentration lowers ocean pH, illustrating the process of ocean acidification.

The equation shown on Figure 6.2.1 is as follows:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-} \tag{7.4.1}$$

Figure 6.2.2: Map of Global Change in Ocean pH.

Global map showing projected or observed changes in sea-surface pH across the world's oceans. The map uses a color scale representing pH change (Δ pH), with values ranging from approximately 0.00 (no change) to about −0.12 pH units (largest decrease). Negative values indicate ocean acidification, meaning surface ocean waters have become less alkaline due to the absorption of atmospheric carbon dioxide.

Most ocean regions show a decrease in pH between approximately −0.04 and −0.10. The largest decreases occur in parts of the North Atlantic, the Southern Ocean, and some high-latitude regions, where pH reductions approach −0.10 to −0.12. Much of the tropical and subtropical Atlantic, Pacific, and Indian Oceans show decreases of roughly −0.06 to −0.08. Smaller decreases, generally around −0.04 to −0.06, occur in parts of the equatorial Pacific, the western Pacific, and portions of the Indian Ocean.

The strongest acidification appears in the North Atlantic between eastern North America and western Europe, where pH reductions are commonly about −0.09 to −0.11. Large areas of the Southern Ocean surrounding Antarctica show decreases around −0.08 to −0.10. In contrast, some tropical and subtropical regions exhibit more moderate decreases near −0.05 to −0.07.

No major ocean region on the map shows an increase in pH; all displayed changes are neutral or negative, indicating widespread ocean acidification.

Figure 6.2.3: Time Series of Global Change in Ocean pH

Line graph showing mean seawater pH measured at the ALOHA ocean monitoring station near Hawaii from approximately 1988 to 2025. The horizontal axis represents time, spanning from October 1988 through late 2024 and early 2025. The vertical axis shows seawater pH, ranging from approximately 8.02 to 8.16 pH units. Two lines are displayed: a monthly average record with substantial short-term variability and a smoother annual average showing the long-term trend.

The monthly pH record fluctuates seasonally between approximately 8.03 and 8.15, with typical year-to-year variation of about 0.02 to 0.05 pH units. Despite this short-term variability, the annual average shows a clear long-term decline throughout the record.

In the late 1980s and early 1990s, annual average pH values are approximately 8.11 to 8.12. During the late 1990s and early 2000s, annual averages decline to approximately 8.09 to 8.10. By the late 2000s and early 2010s, annual averages are generally around 8.08 to 8.09. After 2015, the decline continues, with annual averages falling to approximately 8.05 to 8.07. By 2024–2025, annual average pH is approximately 8.04, the lowest value shown in the record.

Overall, the graph shows a decline in mean seawater pH of approximately 0.07 to 0.08 pH units over about 35 years, from roughly 8.11–8.12 to approximately 8.04. Because the pH scale is logarithmic, this represents a substantial increase in ocean acidity even though the numerical change appears small.

The graph illustrates ongoing ocean acidification at the Hawaii monitoring site, with a persistent downward trend superimposed on natural seasonal fluctuations.

Figure 6.2.4: Two-year Carbon Dioxide Concentrations at Mauna Loa Observatory

Line graph showing atmospheric carbon dioxide (CO2) concentrations measured at Mauna Loa Observatory, Hawaii, over approximately the most recent two-year period. The horizontal axis represents time across about 24 months, and the vertical axis shows CO2 concentration in parts per million (ppm). The graph displays a strong seasonal cycle superimposed on a continuing long-term increase in atmospheric CO2.

CO2 concentrations fluctuate annually by roughly 6–10 ppm, rising through autumn, winter, and spring before reaching a seasonal maximum in late spring (typically May), then declining through summer and early autumn. The seasonal decrease is driven

primarily by Northern Hemisphere plant growth, which removes CO2 from the atmosphere through photosynthesis, while the increase during autumn and winter reflects reduced photosynthesis and continued respiration and decomposition.

Across the two-year period, the entire seasonal cycle shifts upward, indicating that atmospheric CO2 continues to increase from year to year. Typical values shown are in the range of approximately 420–430+ ppm, with the second year consistently higher than the first. Annual growth is approximately 2–4 ppm per year, consistent with recent observations from Mauna Loa.

The graph illustrates two simultaneous patterns:

1. A short-term annual oscillation caused by seasonal biological activity.
2. A long-term upward trend caused primarily by human emissions of carbon dioxide from fossil fuel combustion and land-use change.

Overall, the figure shows that atmospheric CO2 is not only varying seasonally but also steadily increasing, with each seasonal peak and minimum occurring at a higher concentration than the year before. This type of record is part of the Mauna Loa CO2 monitoring program and is a modern segment of the Keeling Curve.

Figure 6.3.1: Geologic Leg of the Carbon Cycle and Associated Feedbacks

Two-panel diagram illustrating the geologic carbonate-silicate cycle and its role in regulating atmospheric carbon dioxide (CO_2) and Earth's climate over millions of years.

The upper panel, titled The Geologic Carbonate-Silicate Cycle, shows the movement of carbon among the atmosphere, rocks, oceans, marine organisms, and volcanoes. Atmospheric CO_2 dissolves in rainwater and reacts with rocks through weathering. Two weathering reactions are shown:

- Carbonate rock weathering:
  $CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$
- Silicate rock weathering:
  $2CO_2 + H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$

The resulting calcium ions (Ca^{2+}) and bicarbonate ions (HCO_3^-) are transported by rivers to the oceans. Marine organisms use these materials to build calcium carbonate ($CaCO_3$) shells. The carbonate precipitation reaction is shown as:

- Carbonate precipitation:
  $Ca^{2+} + 2HCO_3^- \rightarrow CO_2 + H_2O + CaCO_3$

The shells accumulate on the seafloor and are buried as carbonate sediments. Over geologic time, burial, metamorphism, and volcanism return carbon to the atmosphere. The metamorphic reaction shown is:

- Metamorphism:
  $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$

Volcanoes then release CO_2 back into the atmosphere, completing the cycle. Large arrows indicate carbon movement among atmospheric CO_2, weathering, oceans, sediment burial, metamorphism, and volcanic degassing.

The lower panel, titled Feedback Cycles of the Carbonate-Silicate Cycle, illustrates a negative climate feedback. Atmospheric CO_2 increases the greenhouse effect, which raises surface temperature. Higher temperatures increase rainfall and accelerate silicate weathering. Increased weathering removes more CO_2 from the atmosphere, reducing greenhouse warming. The feedback loop shown is:

Atmospheric CO_2 → Greenhouse Effect → Surface Temperature → Rainfall and Weathering Rate → Reduced Atmospheric CO_2.

This feedback acts as a long-term climate stabilizer by counteracting changes in atmospheric CO_2 over geologic timescales.

Figure 6.3.2: Global Fossil Fuel Usage by Type since 1800

Stacked area chart showing global fossil fuel consumption from approximately 1800 to 2024, measured in terawatt-hours (TWh)

of primary energy consumption. The chart separates total fossil fuel use into coal, oil, and natural gas, stacked to show both individual contributions and total consumption. The vertical axis ranges from 0 to about 140,000 TWh.

Consumption remains very low during the early 1800s and increases gradually through the nineteenth century, driven almost entirely by coal. Around 1900, total fossil fuel consumption is approximately 5,000–10,000 TWh. Growth accelerates during the twentieth century, particularly after World War II.

Coal dominates fossil fuel consumption until the mid-twentieth century. Oil consumption begins rising rapidly after about 1950, becoming the largest fossil fuel source for several decades. Natural gas consumption grows more slowly at first but accelerates strongly after about 1970 and continues increasing through the present.

By approximately 1950, total fossil fuel consumption reaches about 20,000 TWh. By 1975, it rises to roughly 60,000–70,000 TWh. Around 2000, total consumption approaches 90,000–100,000 TWh. Growth continues through the early twenty-first century, with total fossil fuel consumption exceeding 140,000 TWh by 2024, the highest value shown.

At the end of the record (2024), the approximate contributions are 45,000 TWh from coal, 55,000 TWh from oil, and 42,000 TWh from natural gas, totaling about 142,000 TWh.

The chart also includes source and explanatory notes. The data source is listed as the Energy Institute Statistical Review of World Energy (2025) and Smil (2017).

Two footnotes define key terms:

1. Watt-hour: A watt-hour is the amount of energy delivered by one watt of power over one hour. Since one watt equals one joule per second, one watt-hour equals 3,600 joules. Common multiples include:
   - Kilowatt-hour (kWh): 1,000 watt-hours
   - Megawatt-hour (MWh): 1 million watt-hours
   - Gigawatt-hour (GWh): 1 billion watt-hours
   - Terawatt-hour (TWh): 1 trillion watt-hours
2. Primary energy: Primary energy refers to energy available in natural resources before conversion into usable forms. Examples include coal before combustion, crude oil before refining, natural gas before use, or uranium before electricity generation. Primary energy accounting includes both the useful energy ultimately delivered and losses that occur during energy conversion and distribution.

Overall, the figure shows a dramatic increase in fossil fuel consumption since the Industrial Revolution, with especially rapid growth after 1950 and continued expansion through 2024.

Figure 6.3.3: Fossil Fuel Use by Country in 2024.

Choropleth world map showing fossil fuel consumption by country in 2024, measured in terawatt-hours (TWh) of primary energy consumption. Countries are shaded according to total fossil fuel use, with darker colors representing higher consumption. The scale ranges from 0 TWh to more than 20,000 TWh, with intermediate categories at approximately 200, 500, 1,000, 2,000, 5,000, and 10,000 TWh. Countries with no available data are shown with diagonal hatching.

The map indicates that fossil fuel consumption is concentrated in a small number of large economies. China is the darkest-shaded country and has the highest fossil fuel consumption, exceeding 20,000 TWh. The United States is also among the highest consumers, similarly exceeding 20,000 TWh. India is the next-largest consumer, generally falling within the 10,000–20,000 TWh range. Other major consumers include Russia and Japan.

Countries with consumption between approximately 5,000 and 10,000 TWh include Russia and some other large economies. Countries in the 2,000–5,000 TWh range include Canada, Saudi Arabia, Indonesia, South Korea, Germany, and several major energy-consuming nations. Much of Western Europe falls between 1,000 and 5,000 TWh, while many countries in South America, Africa, Central America, and Southeast Asia fall below 1,000 TWh.

Large portions of Africa show either relatively low fossil fuel consumption or missing data. Countries such as Brazil, South Africa, Mexico, Turkey, Iran, and Australia show moderate-to-high consumption, generally in the 1,000–5,000 TWh range. Small island nations and many lower-income countries are among the lowest-consumption regions shown on the map.

The figure includes a footnote defining watt-hours as a measure of energy:

- A watt-hour is the energy delivered by one watt of power for one hour.
- One watt-hour equals 3,600 joules.
- Common multiples include:
  - Kilowatt-hour (kWh) = 1,000 watt-hours
  - Megawatt-hour (MWh) = 1 million watt-hours
  - Gigawatt-hour (GWh) = 1 billion watt-hours
  - Terawatt-hour (TWh) = 1 trillion watt-hours

Figure 6.3.4: Fossil Fuel Use by Country: 1800-2024.

Multi-line graph showing fossil fuel consumption for selected countries and regions from approximately 1965 to 2024, measured in terawatt-hours (TWh) of primary energy consumption. The horizontal axis represents year, and the vertical axis ranges from 0 to 40,000 TWh. Lines are shown for China, United States, European Union (27), India, Japan, Australia, United Kingdom, and South Africa.

The most prominent trend is the rapid growth of fossil fuel consumption in China. China's consumption rises from roughly 1,000–2,000 TWh in the 1960s to about 10,000 TWh by the mid-1990s, then accelerates sharply after 2000. Around 2005–2007, China surpasses both the European Union and the United States. By 2024, China reaches approximately 38,000–39,000 TWh, the highest value shown on the chart.

The United States remains one of the largest consumers throughout the record. Consumption rises from about 14,000 TWh in 1965 to roughly 20,000 TWh by the late 1970s. It fluctuates around 18,000–24,000 TWh for several decades, peaks near 23,000–24,000 TWh in the mid-2000s, and then gradually declines. By 2024, U.S. consumption is approximately 21,000 TWh.

The European Union (27) increases from roughly 9,000 TWh in the 1960s to about 15,000 TWh around 1980–2005. After 2005, consumption steadily declines, reaching approximately 10,500–11,000 TWh by 2024.

India shows sustained growth throughout the record. Consumption increases from less than 500 TWh in the 1960s to about 2,000 TWh in 1990, around 5,000 TWh in 2010, and approximately 10,000 TWh by 2024. India nearly converges with the European Union by the end of the record.

Japan rises rapidly after 1965, reaching about 5,000 TWh around 2000–2010. Consumption then gradually declines to roughly 4,000 TWh by 2024.

Australia increases gradually from a few hundred TWh in the 1960s to about 1,400–1,600 TWh by 2024.

The United Kingdom peaks around 2,000–2,500 TWh in the 1970s and early 2000s before declining steadily to approximately 1,200–1,400 TWh by 2024.

South Africa shows moderate growth from a few hundred TWh in the 1960s to approximately 1,200–1,400 TWh by the 2010s, remaining relatively stable thereafter.

The chart illustrates diverging regional trends: strong growth in China and India, relative stability followed by decline in the United States, and long-term declines in Europe and the United Kingdom.

The figure includes a footnote defining watt-hours as a measure of energy:

- A watt-hour is the energy delivered by one watt of power for one hour.
- One watt-hour equals 3,600 joules.
- Common multiples include:
  - Kilowatt-hour (kWh) = 1,000 watt-hours
  - Megawatt-hour (MWh) = 1 million watt-hours
  - Gigawatt-hour (GWh) = 1 billion watt-hours
  - Terawatt-hour (TWh) = 1 trillion watt-hours

Figure 6.3.5: Per-Capita Fossil Fuel Usage by Country in 2024

Horizontal bar chart showing fossil fuel consumption per capita in 2024, measured as the average annual energy consumption

from coal, oil, and natural gas in kilowatt-hours (kWh) per person. Countries and regions are ordered from highest to lowest consumption.

The United States has the highest per-capita fossil fuel consumption among the locations shown at 61,277 kWh per person, followed by Australia at 52,910 kWh per person. Both values are substantially higher than those of the remaining countries and regions.

A middle group includes Europe (28,621 kWh/person), Germany (28,391 kWh/person), and China (27,413 kWh/person), all clustered around 27,000–29,000 kWh per person.

The United Kingdom (20,390 kWh/person) and South Africa (20,184 kWh/person) form another group with similar per-capita consumption levels near 20,000 kWh.

France has a lower value of 17,201 kWh/person, while India has the lowest value shown at 6,969 kWh/person.

The chart highlights large differences in fossil fuel use per person. The United States consumes approximately 8.8 times more fossil-fuel energy per person than India, and about 2.2 times more than China. Australia's per-capita consumption is approximately 7.6 times higher than India's.

The figure includes a footnote defining watt-hours as a measure of energy:

- A watt-hour is the energy delivered by one watt of power for one hour.
- One watt-hour equals 3,600 joules.
- Common multiples include:
  - Kilowatt-hour (kWh) = 1,000 watt-hours
  - Megawatt-hour (MWh) = 1 million watt-hours
  - Gigawatt-hour (GWh) = 1 billion watt-hours
  - Terawatt-hour (TWh) = 1 trillion watt-hours

This page titled 7.4: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

8: GLOBAL CIRCULATION AND EL NIÑO

Introduction

As discussed in previous investigations, temperature and precipitation are among the most influential factors in a location's climate. They differentiate a hot, dry desert from a cold, wet subpolar forest. Both temperature and precipitation are strongly influenced by many factors, several of which we have already discussed, such as topography, latitude, and ocean currents. One factor, however, that still needs to be covered in greater depth to understand its influence on climate is wind. It may be argued that wind can often be the single biggest factor in a location's climate. Wind patterns often determine which regions get rain and which don't. Wind drives global ocean currents, transporting heat to different parts of the planet. Wind also moves warm air masses towards cooler regions, and cooler air masses towards warmer regions, fueling storm systems and causing drought, heatwaves, and even wildfires. Figure 8.1 shows a schematic of global wind circulation and the names of common wind patterns.

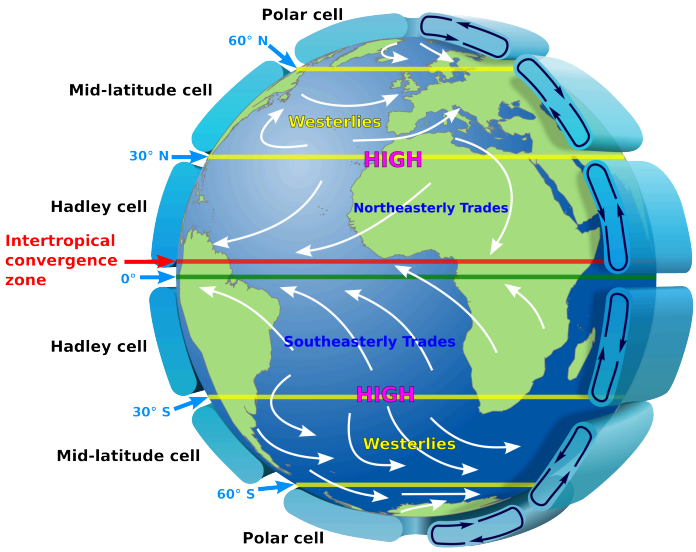


Figure 8.1: Global circulation of Earth's atmosphere displaying Hadley cell, Ferrell cell, and polar cell. (CC BY-SA 3.0; Kaidor via Wikimedia Commons) Alternative description of the image.

In this investigation, let's focus on how wind works, how it factors into Global Circulations, and how it can be responsible for Global Climate Variability.

Learning Objectives

- To determine planetary-scale wind directions.
- Distinguish between the single-cell and three-cell models of global circulation.
- Define the Walker Circulation and the El Niño Southern Oscillation.

Navigational Note

Investigation 7 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

8.1: Why the wind blows

8.2: Other forces acting on the wind

8.3: Atmospheric Circulation
8.4: El Niño-Southern Oscillation
8.5: Accessible Descriptions

This page titled 8: Global Circulation and El Niño is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

8.1: Why the wind blows

Forces that act on the wind

Because wind is air in motion, it is governed by Newton's three laws of motion, which are as follows:

Newton's Laws of Motion

- First Law: An object in motion stays in motion, and an object at rest stays at rest, unless acted upon by a net force.
- Second Law: The net force exerted on an object is equal to the object's mass times its acceleration: $\sum F = m * a$
- Third Law: Every action has an equal and opposite reaction. (We won't need it here.)

Assuming that the mass of the atmosphere stays constant, the net force on the air is proportional to the air's acceleration. In short, forces acting on air accelerate is to cause wind. There are three types of acceleration that we'll cover, and three forces that accelerate the wind are:

- Pressure Gradient Force: Speeds up the wind.
- Coriolis Force: Changes the wind's direction.
- Frictional Force: Slows the wind down.

Pressure Gradient Force

Surface air pressures can vary horizontally between two locations on the Earth's surface. This results in a difference in the number of molecules between the two locations, creating an imbalance. Natural systems tend to seek equilibrium, so air travels from one location to another until the two have the same air pressure. This movement of air results from a force called the Pressure Gradient Force. Here's what you need to know about the pressure gradient force:

- The Pressure Gradient Force arises from a pressure imbalance between two locations.
- The Pressure Gradient Force moves air from areas of high pressure to areas of low pressure.
- The strength of the Pressure Gradient Force is determined by the ratio of the pressure difference between a high-pressure area and a low-pressure area, and by the distance between them.

A good demonstration of how the pressure gradient force works can be made by connecting two identical tanks: one filled with water and the other only half full (Figure $8.1.1$). A connector near the bottom allows water to flow between the tanks. Because there is a difference in the water level, a pressure difference exists near the bottom between the two tanks, and water will flow from the fuller tank to the less full tank until the two tanks have the same water level (Figure $8.1.2$).

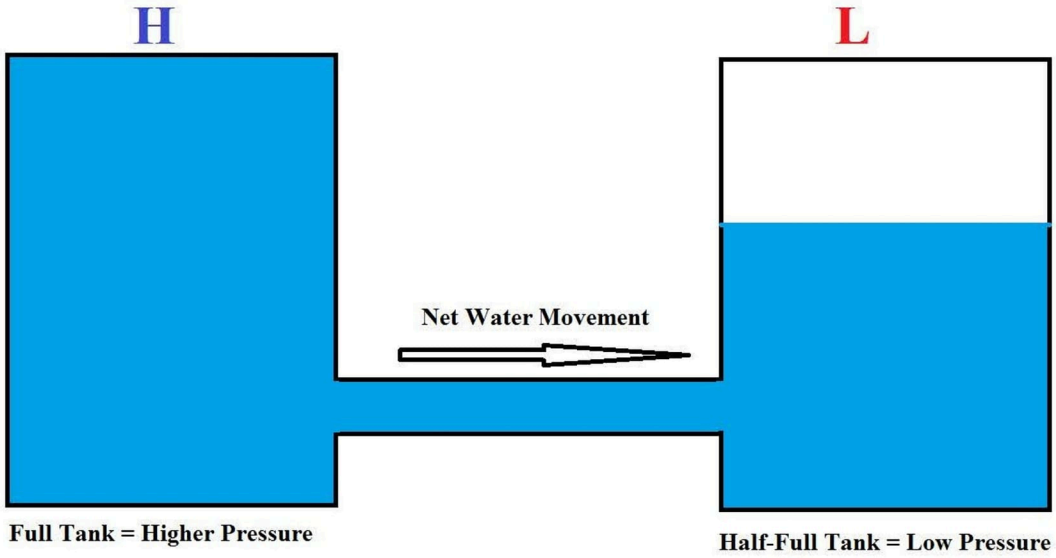


Figure 8.1.1: Imagine two tanks are filled with unequal amounts of water and are connected to each other near the bottom. The full tank will have higher pressure near the base, while the half-full tank will have lower pressure. Net water movement occurs from the higher-pressure region to the lower-pressure tank. (CC BY 4.0; Alicia Mullens)

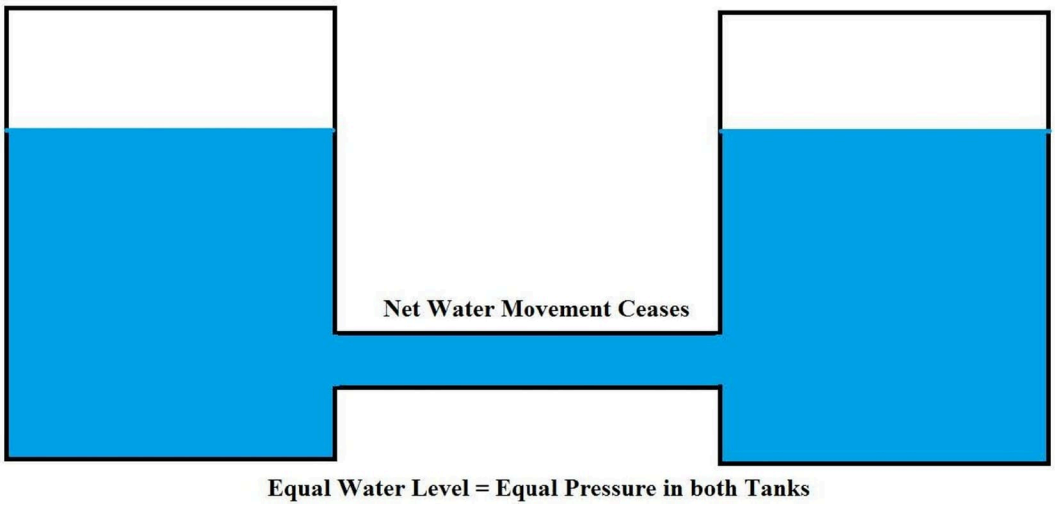


Figure 8.1.2: If both the tanks have equal levels of water, they have equal pressure, and net water movement ceases. (CC BY 4.0; Alicia Mullens)

Let's consider how a similar situation can occur in the atmosphere. Figure 8.1.3 is a simplified weather map, consisting of three isobars that are each 50 km apart, and have a difference of 4 mb from the other. A parcel of air, represented by a red dot, is located at point A, and lies on the 1012 mb isobar.

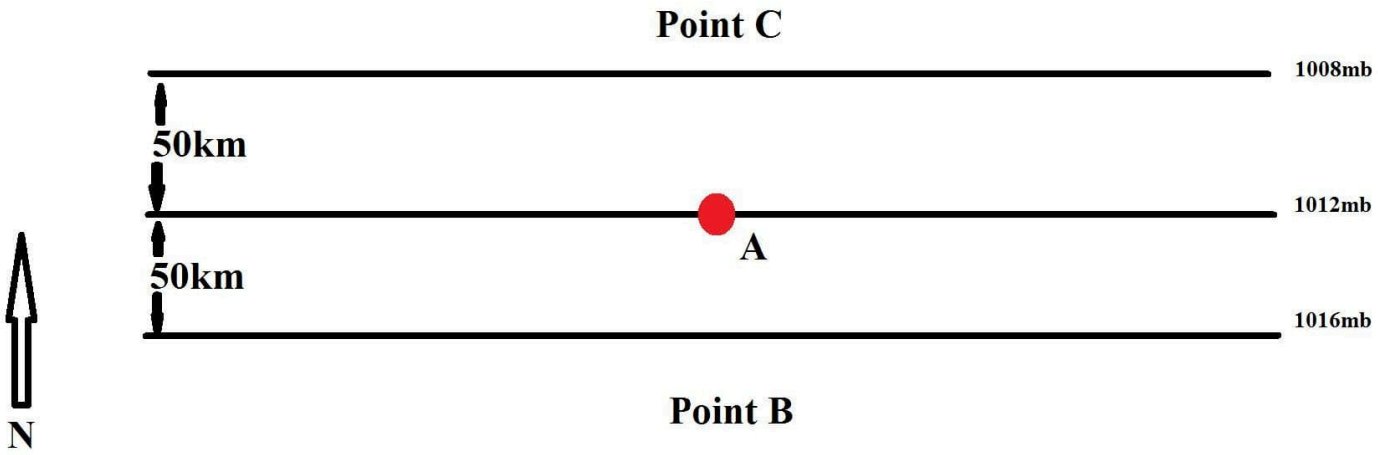


Figure 8.1.3: A simplified surface weather map shows three horizontal isobars separated by 50 km from each other. The 1008 mb pressure isobar is to the north, the 1012 mb isobar is in the middle, and the 1016 mb isobar is to the south. Point A lies on the 1012 mb isobar, Point B lies to the south of the 1016 mb isobar, while Point C lies to the north of the 1008 mb isobar. (CC BY 4.0; Alicia Mullens)

1. Based on the information in Figure 8.1.3, higher pressure is on the ____ side of this map.
   a. north
   b. south
2. If a parcel of air is released from rest at point A and allowed to travel on its own, it will travel towards _____ due to the pressure gradient force.
   a. point B
   b. point C

This page titled 8.1: Why the wind blows is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

8.2: Other forces acting on the wind

The Coriolis Force

As a parcel of air accelerates due to the Pressure Gradient Force, it will begin to experience a new force caused by atmospheric rotation. This force is called the Coriolis Force (Figure 8.2.1). It is an apparent force that changes the direction of a moving object due to Earth's rotation. The apparent deflection of a moving object due to the Coriolis Force is called the Coriolis Effect.

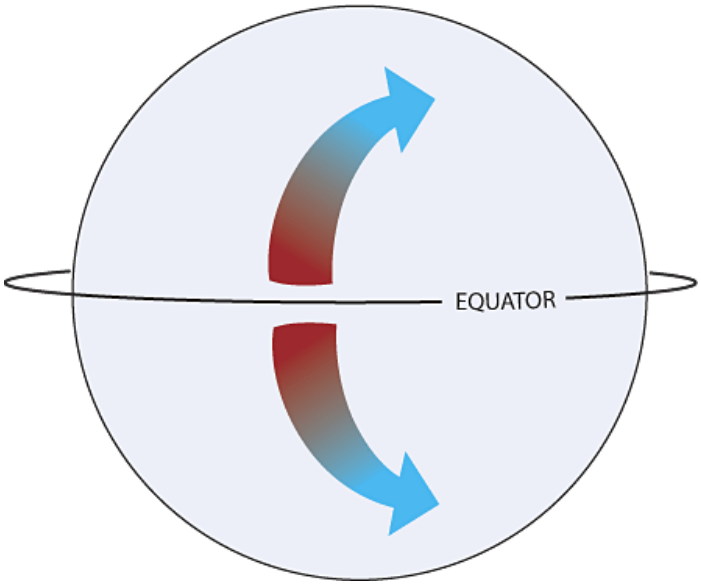


Figure 8.2.1: The rotation of the Earth on its axis deflects the atmosphere toward the right in the Northern Hemisphere and to the left in the Southern Hemisphere, resulting in curved paths. (Public Domain; The Coriolis Effect via NOAA)

A simple demonstration of the Coriolis Effect can be conducted using two index cards. Using a pair of scissors, cut slits into each card so the two cards fit into each other. The two fitted cards serve as our frame of reference for observing the direction of a moving object. We can draw a line from the center of the two cards, along the slit, to represent wind. By rotating one of the cards, we can simulate how wind moving in a straight line appears when the Earth's surface is rotating. The following video provides a nice demonstration of the Coriolis Effect.

Coriolis Effect

Duration of video: 2:54

Video introduction: The Coriolis Effect demonstrates how the rotation of an index card can alter the path of an otherwise straight-moving particle of air. You can also try the experiment at home with a couple of index cards, a pen, two pieces of tape, and a pair of scissors.

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

The direction of rotation plays an important role. The Earth rotates from west to east. When viewed from the North Pole, the Earth appears to spin counterclockwise; from the South Pole, it appears to spin clockwise. Changing the index card's rotation from

counterclockwise to clockwise reverses the direction of wind deflection. Thus, the Coriolis force causes an apparent change in the wind's direction:

- To the right of its direction in the Northern Hemisphere
- To the left of its direction in the Southern Hemisphere

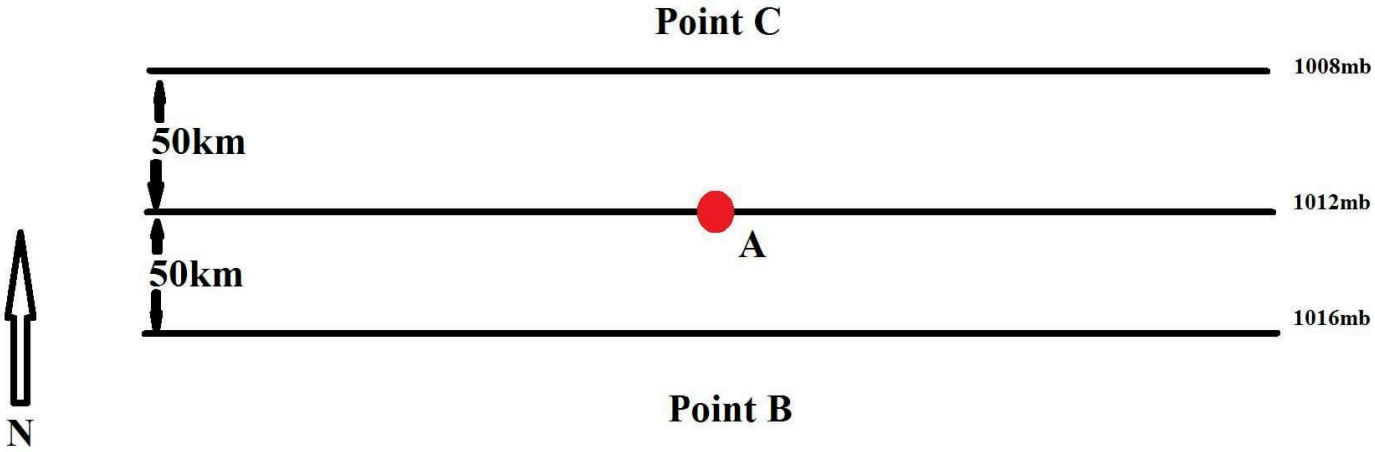


Figure 8.2.2: A simplified surface weather map shows three horizontal isobars separated by 50 km from each other. The 1008 mb pressure isobar is to the north, the 1012 mb isobar is in the middle, and the 1016 mb isobar is to the south. Point A lies on the 1012 mb isobar, Point B lies to the south of the 1016 mb isobar, while Point C lies to the north of the 1008 mb isobar. (CC BY 4.0; Alicia Mullens)

3. Returning to the simplified weather map in Figure 8.2.2, assuming we're in the Northern Hemisphere and North is at the top, West is on the left, and East is on the right. As the air particle accelerates, the Coriolis force would turn the wind:
   a. to the East
   b. to the West

The magnitude of the Coriolis force is based on three key factors: size, speed, and latitude

- **Size:** Only large enough motions will feel a Coriolis tug. So contrary to popular belief, the water in your toilet bowl doesn't rotate due to the Coriolis force.
- **Speed:** The faster the wind, the stronger the Coriolis Force.
- **Latitude:** The further you are away from the equator, the stronger the Coriolis force. This is why cyclones or hurricanes don't form over the equator.

As the air parcel in Figure 8.2.2 accelerates, it will be tugged further and further to the right of its path (Figure 8.2.3 and Figure 8.2.4). Eventually, the direction and magnitude of the Coriolis force will become equal and opposite to the direction of the Pressure Gradient Force (PGF), causing the wind to flow parallel to adjacent isobars (Figure 8.2.5). This phenomenon is known as the Geostrophic (Earth-turning) Balance and will be investigated further later.

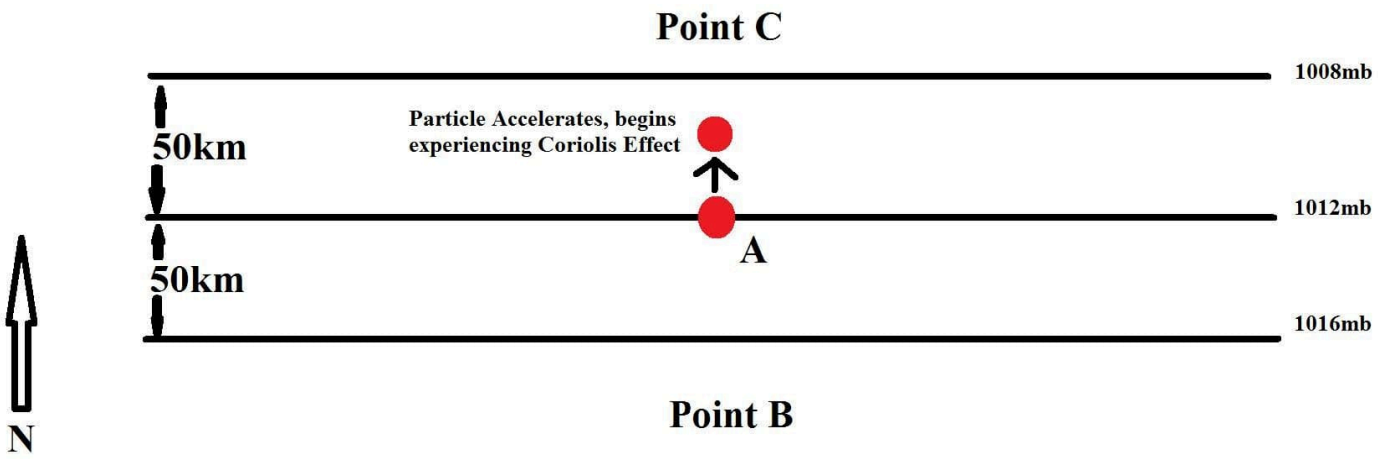


Figure 8.2.3: A parcel is located at Point A, 50 km south of Point C and 50 km north of Point B. The parcel will experience the Pressure Gradient Force (PGF) and begin moving northward toward the lower-pressure area (Point C). Once the parcel accelerates, it experiences the Coriolis force, which causes it to turn to the right in the Northern Hemisphere. (CC BY 4.0; Alicia Mullens)

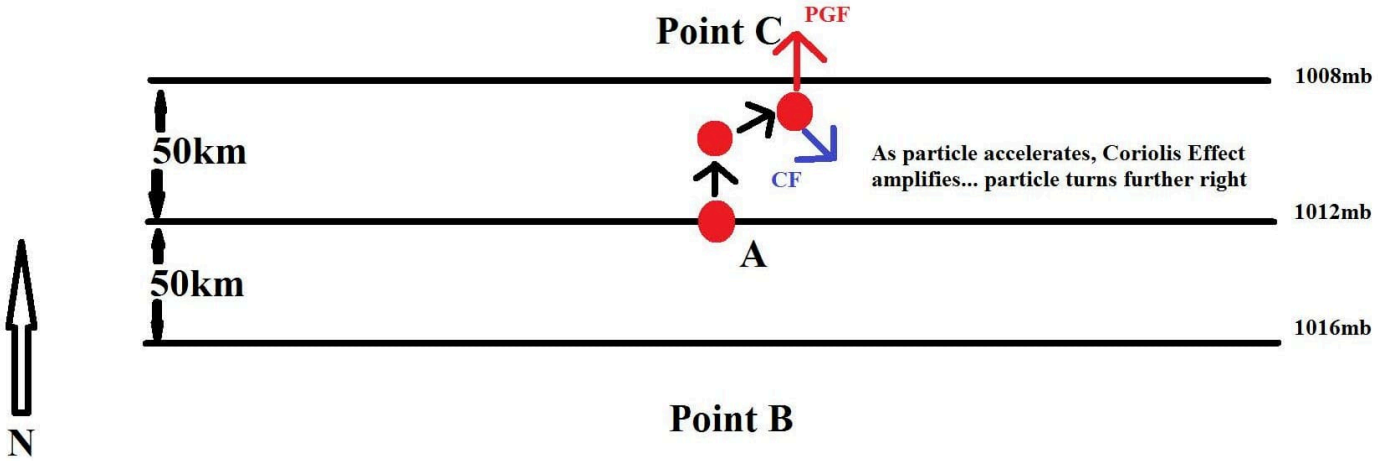


Figure 8.2.4: As the parcel accelerates from Point A, the Coriolis Force intensifies, curving the wind further to the right, while PGF continues to pull the parcel towards lower pressure (Point C). (CC BY 4.0; Alicia Mullens) Alternative description of the image.

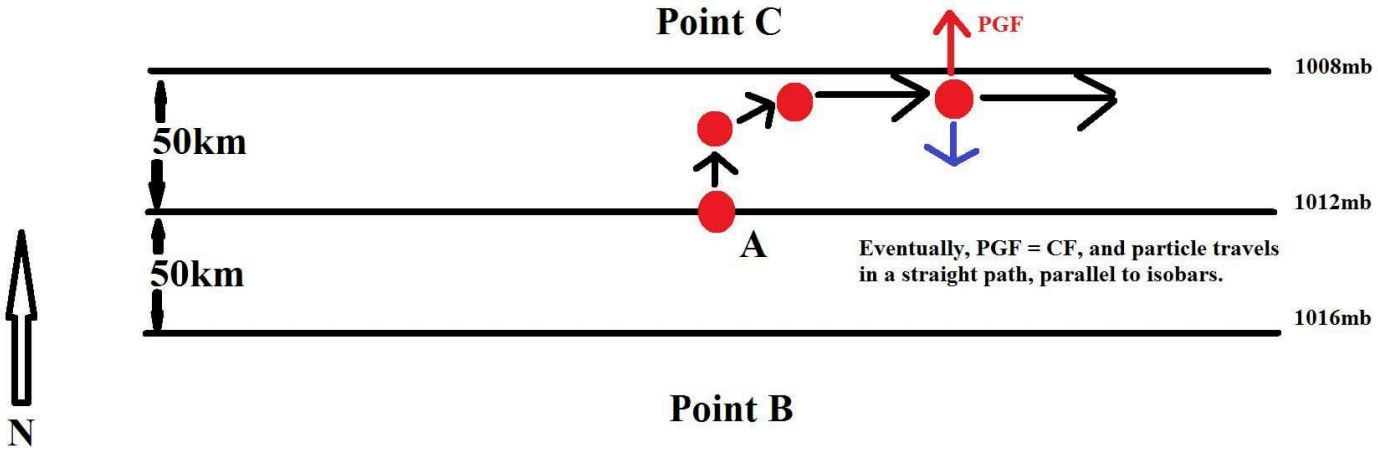


Figure 8.2.5: PGF continues to pull the parcel towards lower pressure (Point C) while CF is now directed in the opposite direction (Point B), as the parcel moves towards the right. Eventually, the Pressure Gradient Force (PGF) equals the Coriolis Force (CF) and the parcel travels in a straight path, parallel to the isobars. This is called Geostrophic flow. (CC BY 4.0; Alicia Mullens) Alternative description of the image.

4. At this point (Figure 8.2.5), the Pressure Gradient and Coriolis Forces _____ causing the wind to continue in a straight path due to inertia (Newton's first law).
   a. cancel each other out,
   b. amplify each other

Friction

The Pressure Gradient and Coriolis forces are the only forces we need to worry about in the upper atmosphere. However, near Earth's surface, trees, buildings, terrain, and other objects slow the wind. Combined, the drag caused by these objects exerts a force known as friction. Friction is always directed opposite the net wind direction. Before we jump into the effects of friction, let's do a brief review of the factors that affect the Pressure Gradient and Coriolis Forces:

- The Pressure Gradient Force is affected by differences in pressure and distance between isobars.
- The Coriolis Force is affected by Latitude, size, and speed.

5. Considering the setup in Figure $8.2.5$, Friction would slow the wind down. Which force would be affected by the slowing down of the wind?
   a. Pressure Gradient Force
   b. Coriolis Force

6. As a result, which force will become stronger?
   a. Pressure Gradient Force
   b. Coriolis Force

7. This would throw the wind off from Geostrophic Balance, causing the parcel from Figure $8.2.5$ to turn:
   a. Towards lower pressure
   b. Away from pressure

These three forces (Pressure Gradient, Coriolis, and Friction) constantly tug on the wind in one direction or another, resulting in winds that rotate around high- and low-pressure systems. Some winds converge and rise within low-pressure systems, and others diverge and sink over high-pressure systems. While these forces may appear short-lived or random, the uniformity of Earth's rotation and its revolution around the Sun results in regions of the Earth with semi-permanent low- and high-pressure systems. Thus, in some regions, wind direction and speed can remain the same year over year. This is often called the general circulation, which refers to the large-scale, long-term global patterns of winds and ocean currents. Let's examine the general circulation of the atmosphere to provide context for how these motions affect a location's climate.

This page titled 8.2: Other forces acting on the wind is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

8.3: Atmospheric Circulation

Single Cell Model

To understand the general circulation, let's create a model to simulate winds on the Earth. A model of the atmosphere is a simplified version of the Earth's Atmosphere. Let's assume Earth has no land and is entirely covered by water. Thus, wind can flow unobstructed by mountains. The Earth's rotation also adds some complexity, so for now, let's assume the Earth does not rotate and has no 23.5-degree tilt. It is still spherical, the same distance from the Sun, and the Sun's energy heats the entire globe.

On this simplified model of Earth, let's understand how large-scale winds will orient. To do that, we first need to revisit how sunlight varies with latitude. Tropical latitudes, such as the Equator, receive more direct sunlight year-round and, therefore, tend to be much warmer, while the poles receive significantly less sunlight year-round and, therefore, tend to be much colder. Since warm air rises and cold air sinks, air rises at the equator, producing low pressure along the equator all around the globe. Air also sinks at the poles, producing high pressure at the North and South poles. On Earth's surface, winds blow from high surface pressure to low surface pressure. At higher altitudes, air that rose from the surface will now return towards regions of higher surface pressure, completing a cycle of air movement.

8. Based on this model, surface winds on Earth should blow from the:
   a. Equator to the Poles
   b. Poles to the Equator

Figure 8.3.1 shows the Northern Hemisphere with selected latitudes indicated. You should print out or save Figure 8.3.1 to answer the following question.

9. Draw/label the left half of the image based on the information above and your answer to question 10. I.e., label which latitude has high pressure, which latitude has low pressure. You can draw where air is rising and where air sinks back to the surface on the left side of the figure. Please leave the right half of the image unlabeled and submit your figure.

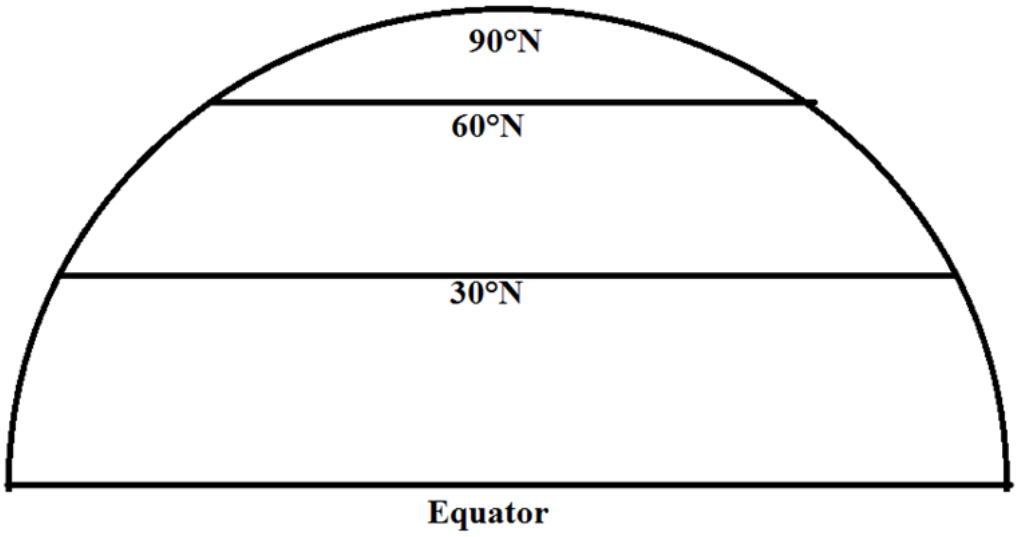


Figure 8.3.1: A simplified map of the Northern Hemisphere. (CC BY 4.0; Alicia Mullens)

Congratulations, you have just constructed the single-cell model of the atmosphere! Remember, this model assumes the Earth is a uniform ball of water with no tilt or rotation. However, it's a good first step toward modeling atmospheric circulation and accurately simulating weather at both the Equator and the Poles. However, the Earth does rotate, has a tilt, and contains land on its surface. As a result, the single-cell model can't tell us everything we need to know. It only gives us insight into conditions at the Equator and the Poles.

Three-cell Model

Let's improve our simplified single-cell model by adding Earth's rotation. If Earth rotates, the Coriolis Force will act on any moving wind. This causes the single circulation between the equator and the poles to break up into three separate circulations.

- The Hadley Cell: Rising air over the equator travels poleward towards 30°N and 30°S, where it sinks back to the surface and returns back to the equator along the surface.
- The Ferrell Cell: Sinking air over 30°N travels northward along the surface to 60°N, where it rises up to the tropopause and then returns to 30°N at a higher altitude.
- The Polar Cell: Rising air over 60°N travels northward towards the pole (90°N), where it sinks back to the surface, and then returns to 60°N along the surface.

You should print out or save Figure 8.3.1, again, to answer the following question.

10. Draw/label the right half of the image based on the information above. Label which latitudes have high pressure, which latitudes have low pressure in the new three-cell model. You can draw where air is rising and where air sinks back to the surface on the right side of the figure. Remember, unlike in question 11, you'll have 3 cells this time. Finally, submit your figure.

11. The pressure systems over the Equator and the Poles are the same as in the single-cell model. However, in the three celled model, there is also a _____ surface pressure at 30°N/S and a _____ surface pressure at 60°N/S.
    a. high; low
    b. low; high
    c. high; high
    d. low; low

Congratulations, you have just drawn the three-cell model of the atmosphere! While we still haven't added land, this is a very good approximation of the surface and higher-altitude winds and pressures across the Earth. Figures 8.3.2 and 8.3.3 show the average position of high and low pressures across the planet for January and July.

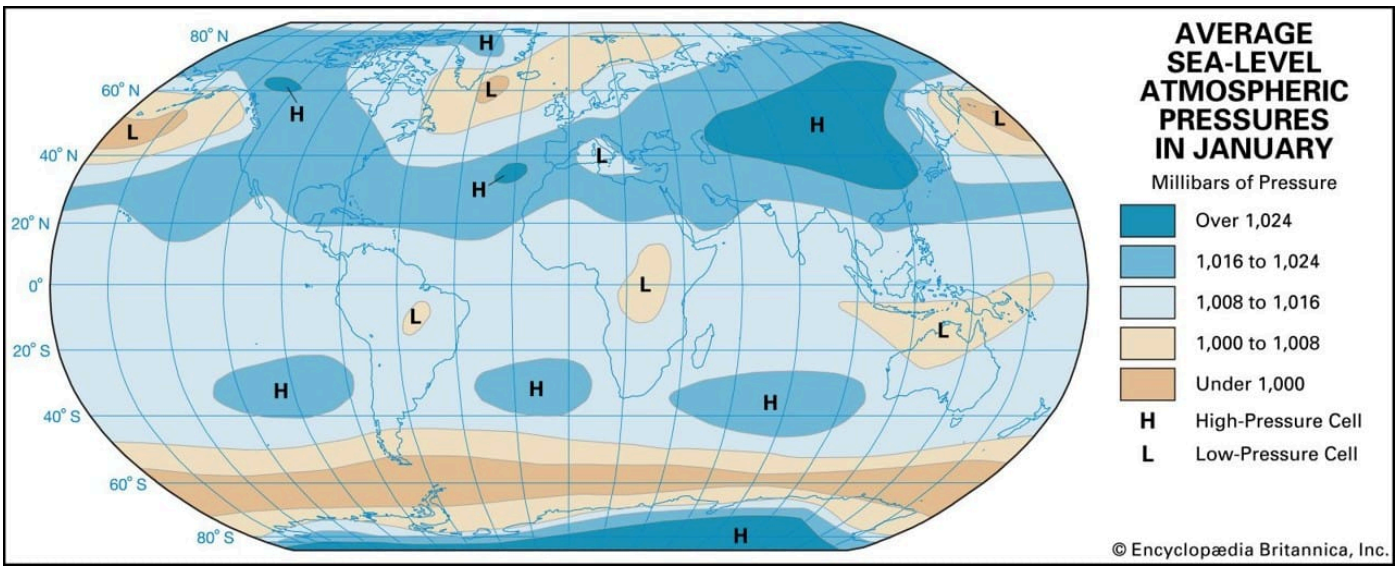


Figure 8.3.2: Map of global mean air pressure at sea level in January. Average positions of surface high-pressure systems are shown in dark blue, while surface low-pressure systems are shown in yellow/brown. (CC BY-NC 4.0; Atmospheric pressure and wind via Encyclopedia Britannica) Alternative description of the image.

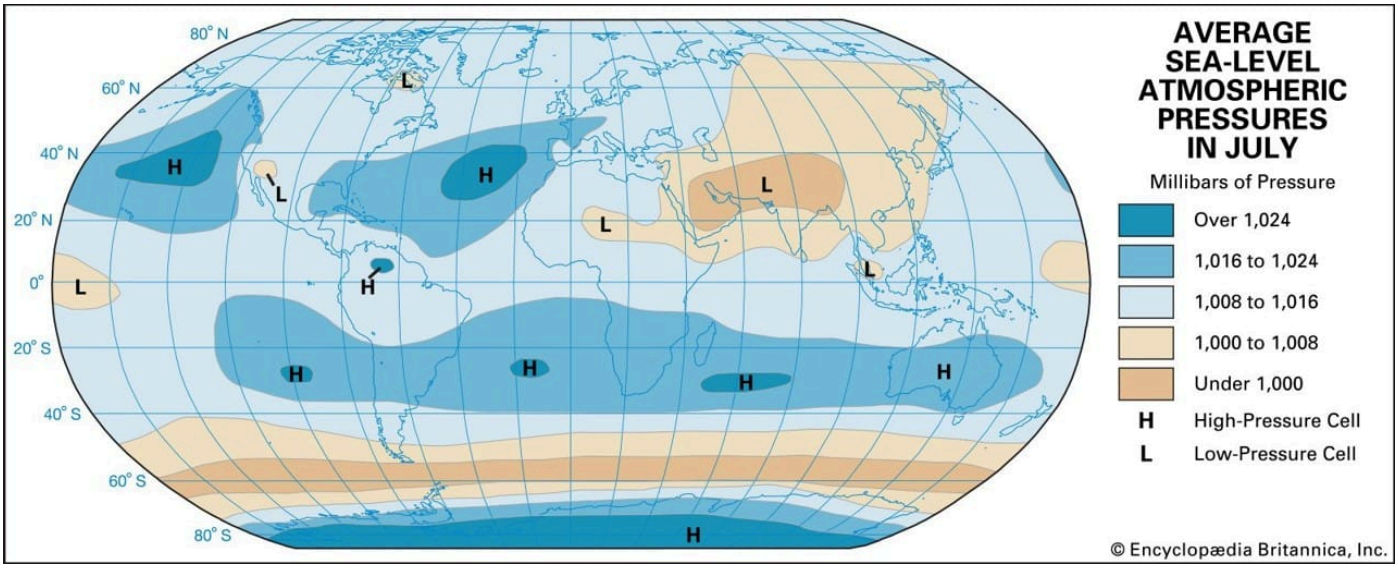


Figure 8.3.3: Map of global mean air pressure at sea level in July. Average positions of surface high-pressure systems are shown in dark blue, while surface low-pressure systems are shown in yellow/brown. (CC BY-NC 4.0; Atmospheric pressure and wind via Encyclopedia Britannica) Alternative description of the image.

A key consequence of this is the location of deserts and rainforests. Low pressure near the equator yields heavy rainfall, creating rainforests, while high-pressure regions at 30°N/S yield droughts, producing deserts. Figures 8.3.2 and 8.3.3 show the location of deserts and rainforests on Earth. You'll notice that it correlates well with the positions of high and low pressures on figures 8.3.2 and 8.3.3.

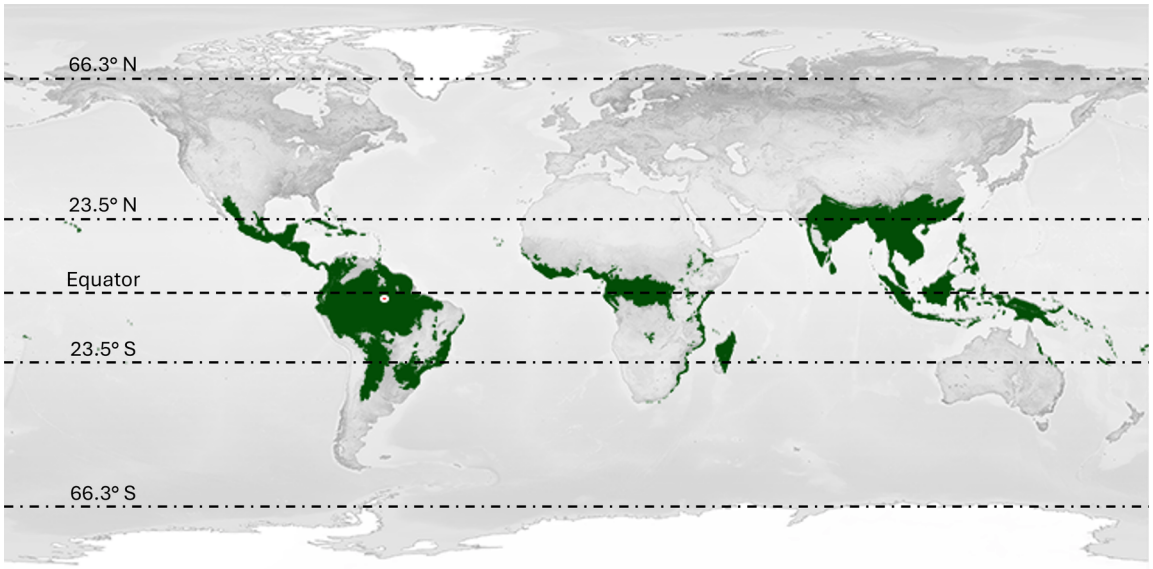


Figure 8.3.4: A map of the world's rainforests. (Public Domain; Biome Rainforest via NASA) Alternative description of the image.

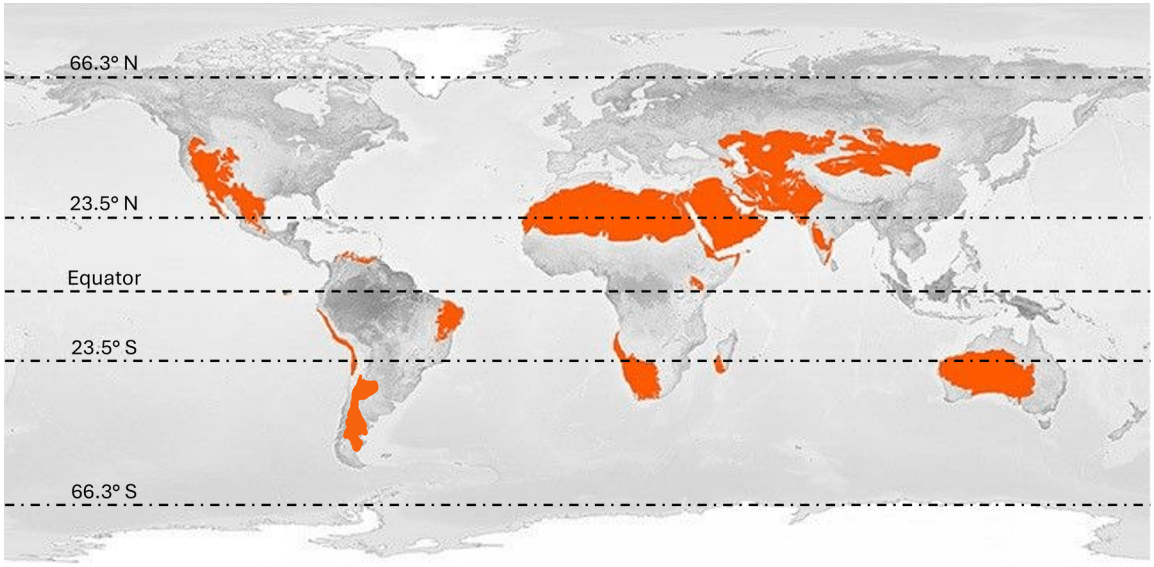


Figure 8.3.5: A map of the world's deserts. (Public Domain; Biome Desert via NASA) Alternative description of the image.

Another interesting consequence is the formation of ocean currents, as shown in Figure 8.3.6. The pressure systems in Figures 8.3.2 and 8.3.3 drive global wind circulations that fuel those ocean currents.

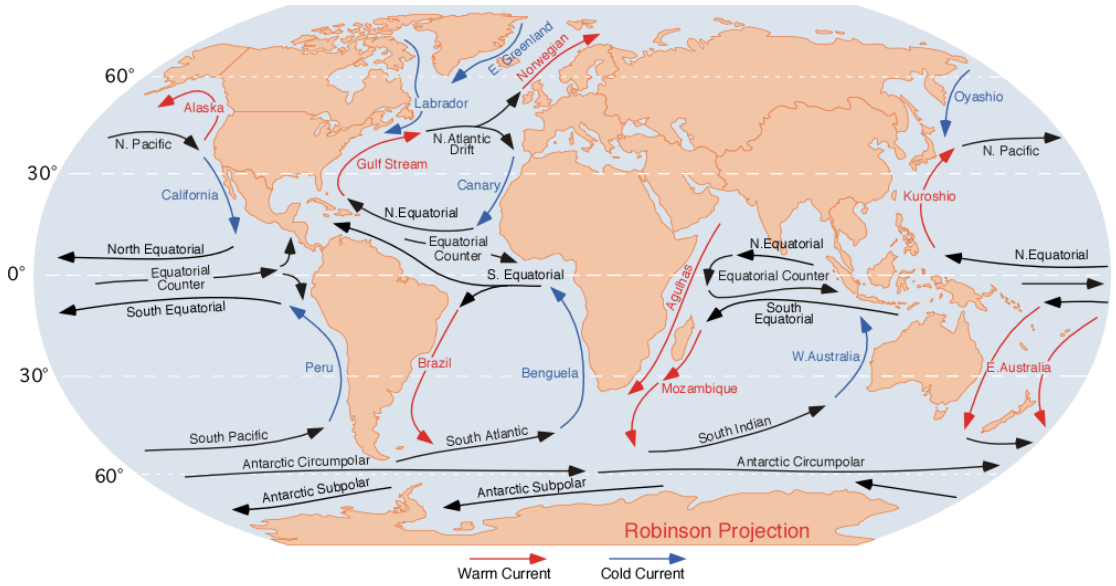


Figure 8.3.6: A map of global surface ocean currents. (Public Domain; Dr Michael Pidwirny via Wikimedia Commons) Alternative description of the image.

Trade Winds

A key consequence of the general positions of high and low pressure around the world is the presence of prevailing (meaning almost permanently present) wind patterns. There are several key wind patterns in the atmosphere (such as the Jet Stream), but one of the most important is the Trade Winds. Based on the three-cell model, there is low pressure at the equator and high pressure at 30°N and 30°S. Figure 8.3.7 is a simplified map showing a band of high pressure at 30°, and low pressures at the Equator.

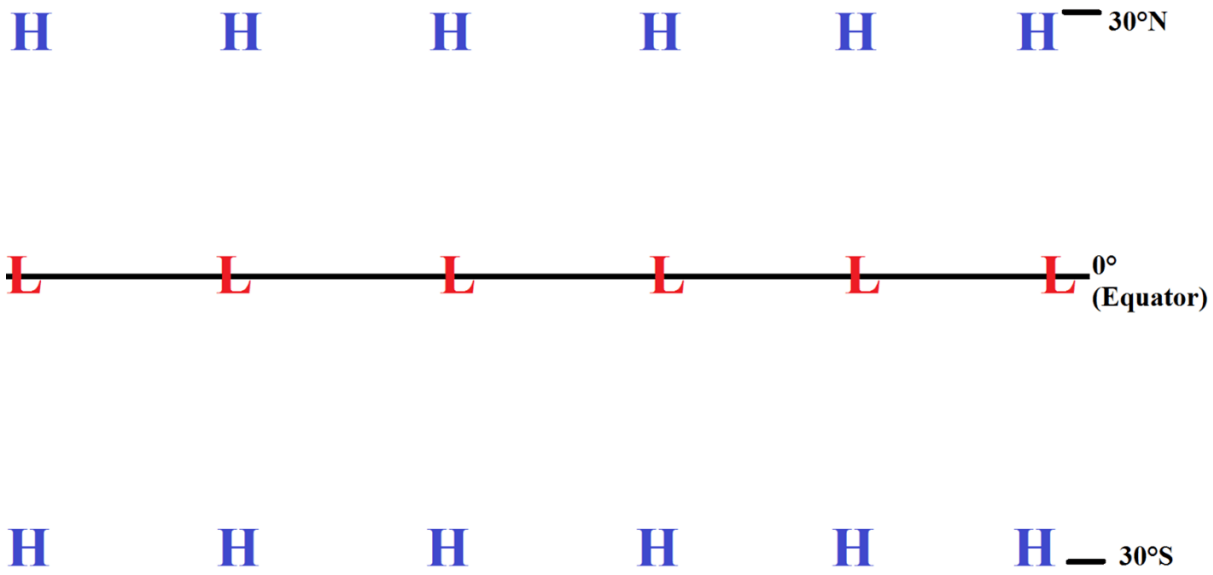


Figure 8.3.7: A map of surface high-pressure systems at 30° N and S, and low-pressure systems at the Equator. (CC BY 4.0; Alicia Mullens)
Alternative description of the image.

12. The Pressure Gradient Force should direct the surface wind:
    a. from the equator to the 30° N and S
    b. from 30° N and S to the equator

13. In the Northern Hemisphere, the Coriolis Force, which directs winds to the right (of the direction the wind is moving, not yours), would turn the wind to the ____.
    a. East
    b. West

14. Meanwhile, in the Southern Hemisphere, the Coriolis Force, which directs winds to the right (of the direction the wind is moving, not yours), would turn the wind to the ____.
    a. East
    b. West

15. This results in a band of winds that travel _____ along the equator.
    a. east to west
    b. west to east

16. Print out or save Figure 8.3.7. Draw arrows to show these winds based on your answers to questions 15-18. Submit the figure.

These winds are called the **Trade Winds**. These constant winds in the tropics enabled early European sailors, explorers, and traders to travel across the Atlantic and Pacific oceans towards the Americas. They also transport nitrate- and phosphate-rich Saharan dust to Latin America and Brazil, where the Amazon rainforest benefits greatly from these nutrients. They promote the upwelling of cold, nutrient-rich waters off the coast of Peru and monsoons in East Asia.

However, every few years, something changes in the Equatorial Pacific. The Trade winds weaken, and the equatorial counter current strengthens. Whenever this happens, weather extremes such as droughts, floods, and heatwaves affect people across different continents. While South American countries like Chile and Peru face flooding, Australia and East Asia suffer from droughts and Heatwaves. In Africa, eastern countries like Kenya suffer from increased rainfall and deadly diseases, while southern countries, such as South Africa, face drought. Even Europe is not spared, with northern countries facing colder-than-average winters and southern countries experiencing heavier-than-average rainfall and flooding. In the next section, let's explore this global climate phenomenon that wreaks havoc across the planet.

This page titled 8.3: Atmospheric Circulation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

8.4: El Niño-Southern Oscillation

The Walker Circulation

The Walker Circulation occurs in the equatorial eastern Pacific and begins with the trade winds, which commonly blow from East to West. As the winds blow along the ocean surface, they push warm surface waters to the west as well. As a result, warm surface waters accumulate in the Western Pacific, near Asia, Indonesia, and Australia, while cooler surface waters upwell (rise from below) in the Eastern Pacific, along the coast of Peru. Figure 8.4.1 shows the Walker Circulation during such neutral conditions.

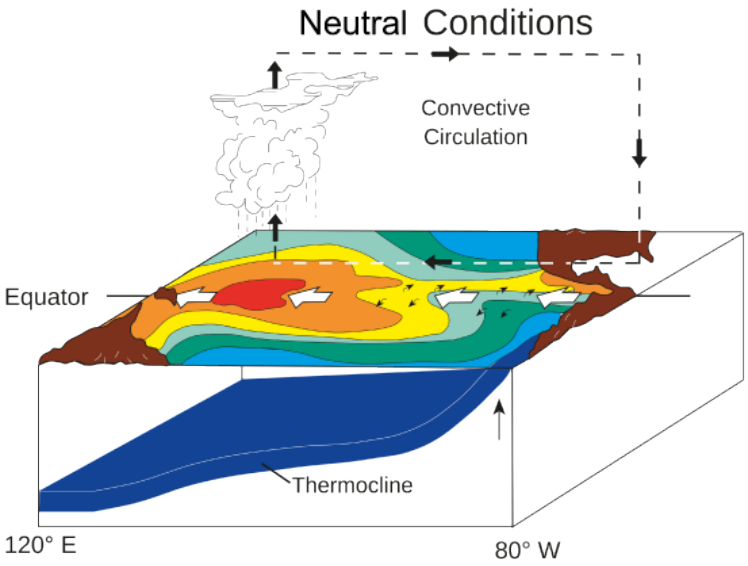


Figure 8.4.1: The Walker Circulation during Neutral Conditions. (Public Domain; Schematic Diagrams via NOAA/PMEL). Alternative description of the image.

Using this information, let's understand the atmospheric dynamics of the Neutral Phase of the Walker Circulation.

17. Warmer sea surface temperatures in the western Pacific create warm, rising air, and thus _____ pressure conditions near east Asia.
    a. high
    b. low
18. Meanwhile, cooler sea-surface temperatures in the eastern Pacific produce cooler, sinking air, and thus _____ pressure conditions near South America.
    a. high
    b. low

While it's very tempting to focus on the longitude coordinates and believe that the left side of Figure 8.4.1 is the "eastern" Pacific, while the right side is the "western" Pacific. This is not true. The reason the coordinates switch from west to east while traveling west on the map is that you cross the International Date Line and enter the Eastern Hemisphere. The west remains on the left, and the east remains on the right. Thus, the eastern Pacific refers to the Pacific Ocean along the coasts of North and South America, whereas the western Pacific refers to the Pacific Ocean along the coasts of East Asia and Australia.

The surface air rises to higher altitudes over Indonesia, moves back toward Central and South America, and descends to the surface due to the region's high pressure. This air circulation in the equatorial Pacific has significant implications for the local climate.

19. The western Pacific has warm, rising air and more moisture, which allows for the formation of:
    a. Stormy weather
    b. Calm clear weather

20. On the other hand, the eastern Pacific has cooler sinking air and less moisture, which makes it:
    a. Stormier
    b. Drier

Following the 1982-1983 El Niño event, which led to numerous extreme weather events worldwide, a series of buoys jointly operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) and the Japanese Meteorological Agency (JMA) were deployed along the Equatorial Pacific. This array is called the TAO/Triton Array, and the locations of the buoys are shown in Figure 8.4.2.

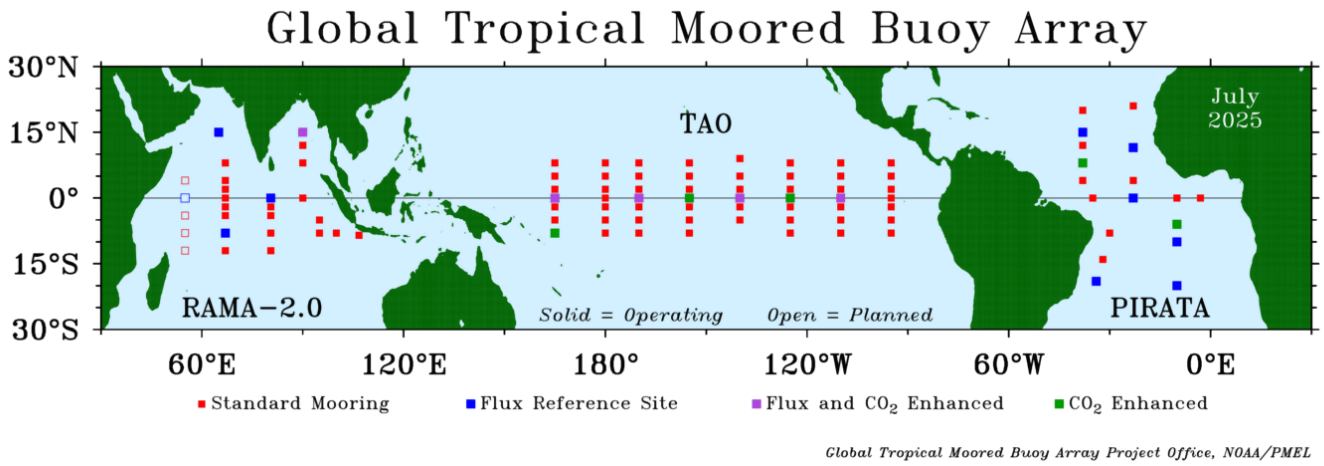


Figure 8.4.2: Positions of the Global Tropical Moored (TAO/Triton) Buoy Array across the Equatorial Pacific (Public Domain; Global Tropical Moored Buoy Array via NOAA/PMEL). Alternative description of the image.

Sensors on the buoys measure various oceanographic and meteorological parameters, such as sea surface temperature (SST), wind speed and direction, air temperature, and humidity. The data is then transmitted in near-real time via NOAA's polar-orbiting satellites to NOAA's Pacific Marine Environmental Laboratory (PMEL). The data is then plotted on maps, such as Figure 8.4.3 , which shows 5-day SST and wind speed means as well as anomalies for the period ending July 2, 2018. These maps enable oceanographers and meteorologists to closely examine the behavior of the Walker Circulation.

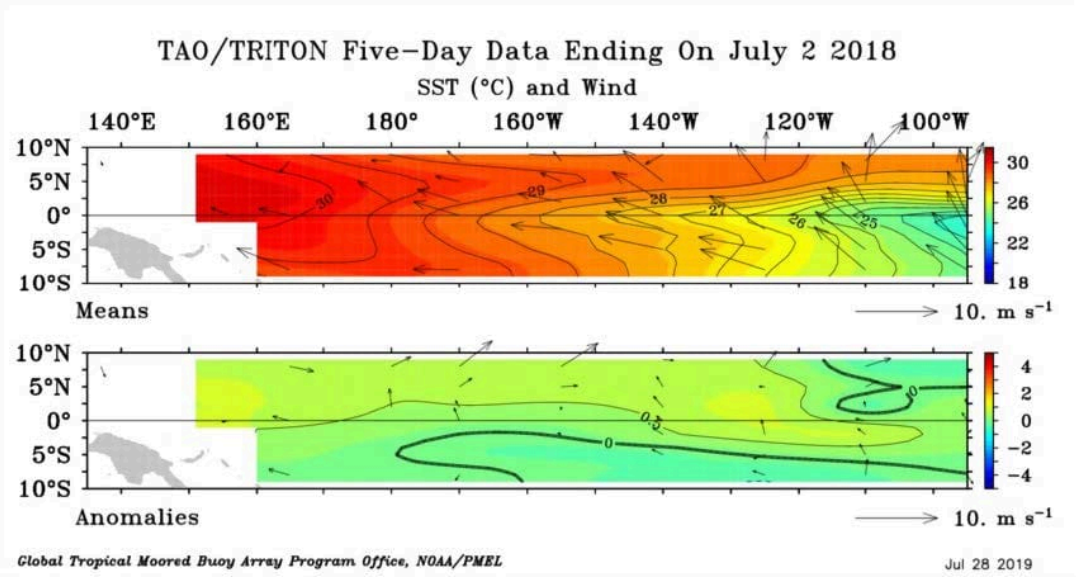


Figure 8.4.3: TAO/Triton measured Sea Surface Temperature (SST) and wind speed mean values (top) and anomalies (bottom) for the 5-day period ending July 2, 2018. (Public Domain; Monthly Mean SST and Winds via NOAA/PMEL). Alternative description of the image.

There are two panels on Figure 8.4.3. The top panel shows 5-day mean observed sea surface temperatures and wind vectors. Here's how to read these:

• Temperature: Blues are cold, greens are mild, yellows are warm, reds are hot.

• Wind Vectors: The arrow points in the direction the wind is blowing towards, and the length of the arrow indicates how fast the wind is moving.

21. According to Figure 8.4.3, the hottest sea surface temperatures (top panel) are located _____, while the coldest sea surface temperatures are located _____.
    a. In the western Pacific; in the eastern Pacific
    b. In the central Pacific; in the eastern Pacific
    c. In the eastern Pacific; in the western Pacific

The bottom panel in Figure 8.4.3 indicates anomalies in SST and winds, which are differences from the average. For example, if the class average on a test was 80% and someone earned 85%, that would be 5% above average, hence a 5% positive anomaly. Anomalies are shaded in the same manner as the mean SST. Colder waters are represented by dark blue and purple; near-average temperatures are shaded in green; hot anomalies are depicted in orange and red. There are also isolines (lines of constant value) to help detect the pattern of anomalies.

22. The anomalies in Figure 8.4.3, indicate that the sea surface temperatures were:
    a. Much hotter (more than +3°C) than normal
    b. Much colder (less than -3°C) than normal
    c. Almost completely normal

These conditions represent the “neutral condition" of the Walker circulation.

El Niño

However, every few years, key components of the Walker Circulation shift. The trade winds, which usually carry warm water to the Western Pacific, either slow or reverse, allowing warm water to accumulate over the eastern Pacific. This allows for the collection of warmer, rising air and lower surface pressure to build in the eastern Pacific, near Peru. On the other hand, as the trade winds slacken, there is less warm water over the western Pacific, leading to less warm air and drier conditions near East Asia. Because this always happens around Christmas, Peruvians began calling it "El Niño". Officially, it is called the El Niño-Southern Oscillation(ENSO). Figure 8.4.4 shows the Walker Circulation during the El Niño phase. You'll notice that the Walker circulation from Figure 8.4.1 has reversed.

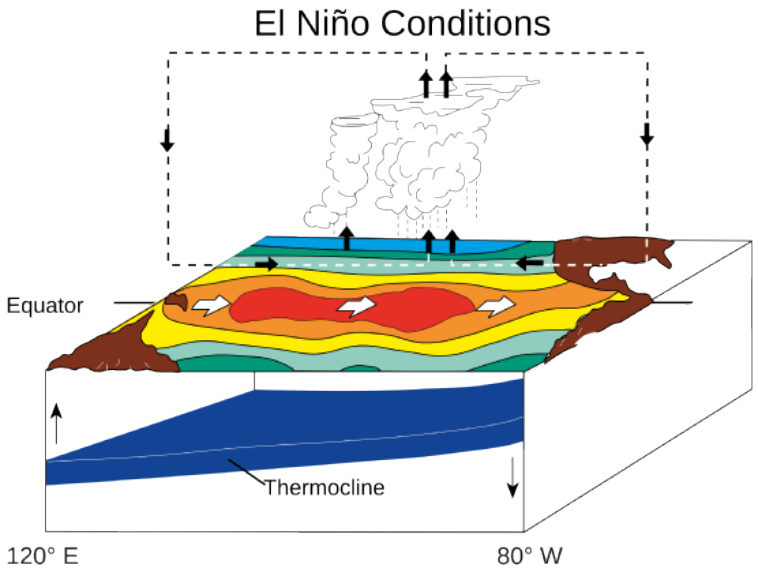


Figure 8.4.4: The Walker Circulation in an El Niño phase. (Public Domain; Schematic Diagrams via NOAA/PMEL) Alternative description of the image.

La Niña

La Niña is the opposite of El Niño. During this phase of the Walker Circulation, rather than weakening or reversing from the Neutral

Phase, the trade winds intensify. This intensification of the east-to-west Trade winds leads to more warm water accumulating over the western Pacific, near East Asia, which in turn fuels more warm, rising air. On the other hand, the eastern Pacific, near Peru, experiences even cooler-than-average sea surface temperatures and sinking air. Figure 8.4.5 shows Walker Circulation during the La Niña Phase.

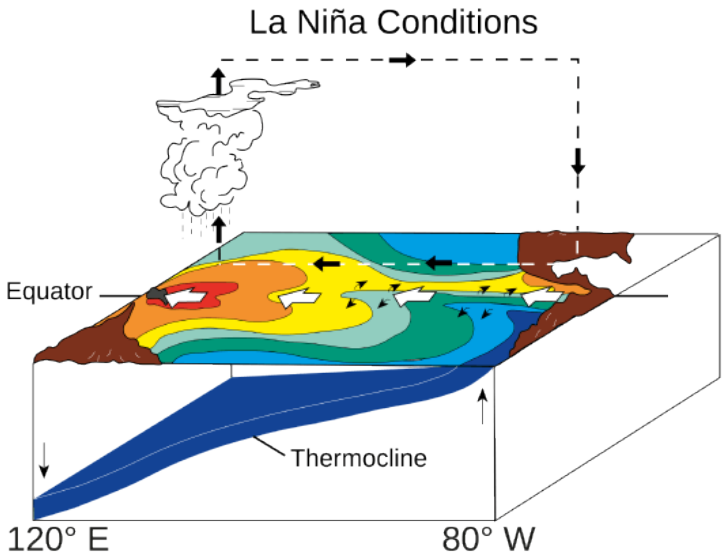


Figure 8.4.5: The Walker Circulation during La Niña. (Public Domain; Schematic Diagrams via NOAA/PMEL) Alternative description of the image.

Let us assess whether we can identify these changing sea-surface temperature patterns and wind directions using the TAO/Triton buoy array in the equatorial Pacific. Figure 8.4.6 shows the TAO/Triton measured mean sea surface temperature, winds, and anomalies for December 2015.

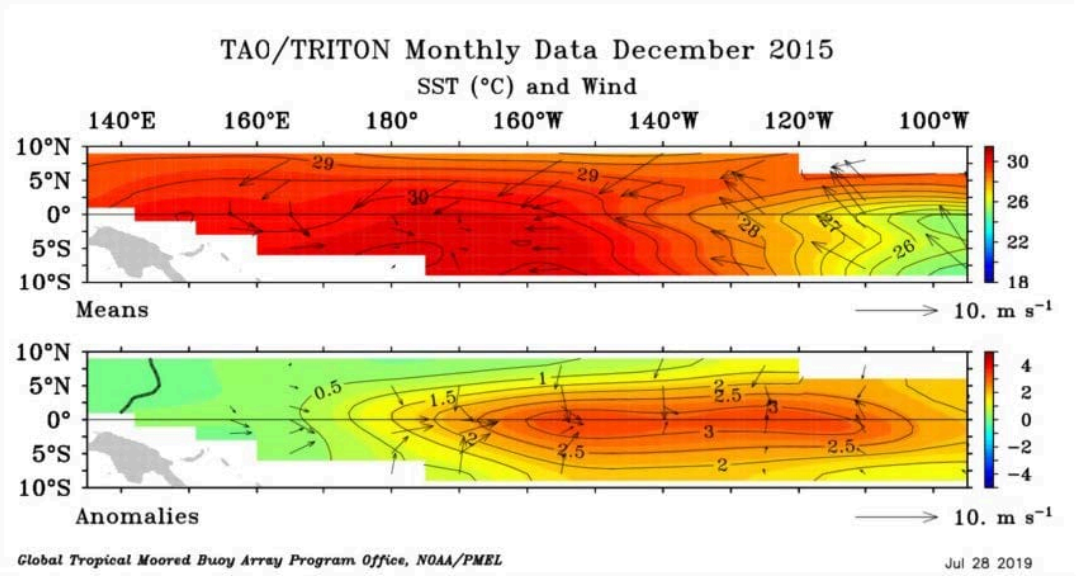


Figure 8.4.6: Sea-surface temperatures and anomalies for December 2015. (Public Domain; Monthly mean SST and Winds via NOAA/PMEL) Alternative description of the image.

23. According to the lower panel in Figure 8.4.6, in the central and eastern Pacific, the most significant temperature anomalies were:
    a. Very cold (colder than -2°C below normal)
    b. Closer to average
    c. Very hot (hotter than +2°C above normal)

24. These conditions indicate that the Walker Circulation was in a(n) _____ phase.
    a. La Niña
    b. El Niño
    c. Neutral

Figure 8.4.7 shows data from the TAO/Triton array during December 2010. You'll notice that the sea-surface temperatures and wind speed anomalies are different from Figure 8.4.6. Sea-surface temperatures are much cooler in the eastern Pacific, and the trade winds are blowing stronger from east to west.

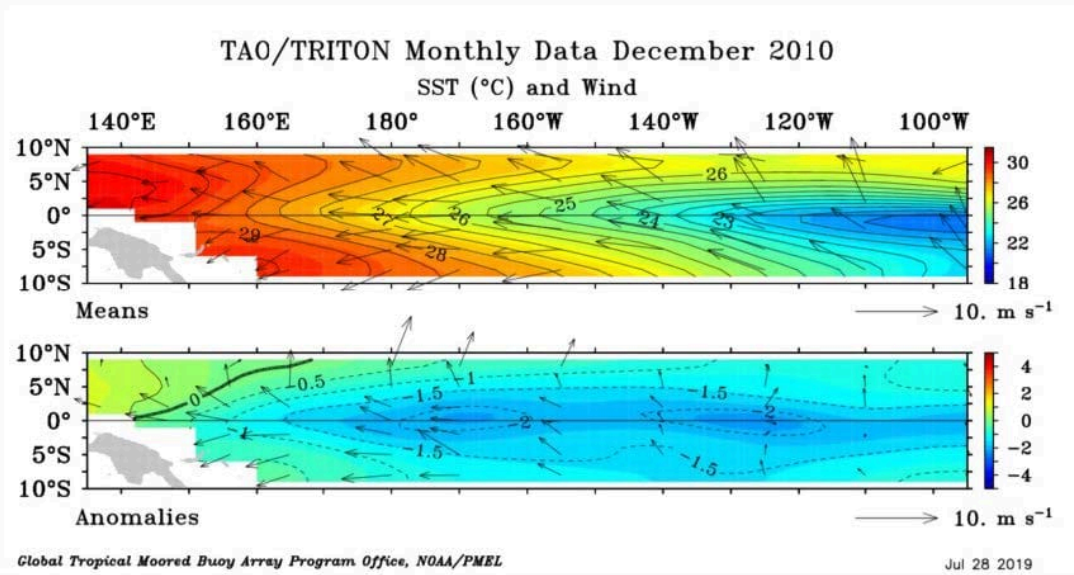


Figure 8.4.7: TAO/Triton sea-surface temperatures and wind anomalies for December 2010. (Public Domain; Monthly mean SST and Winds via NOAA/PMEL) Alternative description of the image.

25. Considering mean temperatures, trade winds and anomalies in Figure 8.4.7, we can confidently say that during December 2010, the Walker Circulation was in a(n) _____ phase.
    a. Neutral
    b. El Niño
    c. La Niña

Additional Reading

In this investigation, we didn't cover the impacts of El Niño and La Niña because the focus was on identifying the signatures and detecting their presence. If you want to learn more about the effects of El Niño and La Niña on our weather, check out the following links.

- How El Niño and La Niña Affect California Weather - El Niño often brings wetter, cooler conditions and increased rainfall to Central and Southern California. At the same time, La Niña typically leads to drier, warmer conditions, increasing drought and wildfire risks in the south.
- El Niño and La Niña Affect Weather in the U.S. and Worldwide: El Niño suppresses Atlantic hurricane activity by increasing vertical wind shear. La Niña, by contrast, reduces vertical wind shear, leading to stronger and more frequent Atlantic hurricanes.

This page titled 8.4: El Niño-Southern Oscillation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

8.5: Accessible Descriptions

Figure 7.1 Global Atmospheric Circulation Model

A simplified diagram of Earth shows global atmospheric circulation patterns. The globe is centered on the Atlantic Ocean, with the Americas on the left and Europe and Africa on the right. Latitude lines are marked at 0° (Equator), 30° North and South, and 60° North and South. The diagram illustrates how air moves around the planet in three main circulation cells in each hemisphere: Hadley cells, Mid-latitude (Ferrel) cells, and Polar cells.

Key Features and Labels

- The Equator (0°) is marked with a red horizontal line labeled “Intertropical Convergence Zone (ITCZ)”.
- Areas of rising and sinking air are labeled:
  - “HIGH” pressure zones near 30° North and South
  - “LOW” pressure zone near the Equator
- Curved arrows show the direction of air movement both vertically and horizontally.

Circulation Cells

1. Hadley Cells (0° to 30° North and South)

- Warm air rises at the Equator (ITCZ), creating a low-pressure zone.
- This air moves poleward at high altitude.
- Around 30° latitude, the air cools and sinks, forming high-pressure zones.
- Surface air then flows back toward the Equator.

2. Mid-latitude (Ferrel) Cells (30° to 60° North and South)

- Air flows poleward at the surface from 30° to 60° latitude.
- Around 60°, this air rises due to interaction with colder polar air.
- At higher altitudes, air flows back toward 30°.

3. Polar Cells (60° to 90° North and South)

- Cold air sinks at the poles (90°), creating high-pressure zones.
- Surface air flows toward 60° latitude.
- At about 60°, the air rises and returns poleward aloft.

Global Wind Belts

The diagram labels major wind patterns:

- Northeasterly Trade Winds (Northern Hemisphere): Blow from northeast to southwest between 30°N and the Equator.
- Southeasterly Trade Winds (Southern Hemisphere): Blow from southeast to northwest between 30°S and the Equator.
- Westerlies (mid-latitudes): Blow from west to east between 30° and 60° in both hemispheres.

Figure 7.2.4 The Coriolis Force turns the parcel to the right

This labeled diagram illustrates how an air parcel responds to the pressure-gradient force and the Coriolis force in the Northern Hemisphere.

Diagram Structure:

- The image consists of three horizontal lines, each representing a different isobar (a line of equal atmospheric pressure):
  - Bottom Line (Point B): 1016 millibars (mb)
  - Middle Line (Point A): 1012 mb
  - Top Line (Point C): 1008 mb
- The vertical distance between each isobar is labeled as 50 kilometers.
- A northward-pointing arrow on the far left indicates the direction of motion (with north at the top).

- A red circle represents an air parcel starting at Point A (1012 mb).
- The parcel initially moves northward toward lower pressure (Point C) due to the pressure gradient force, which is shown as a thick red upward arrow labeled PGF.
- As the parcel accelerates northward, the Coriolis force (CF) begins to deflect its path to the right, as shown by a blue arrow pointing eastward.
- Three red dots trace the curving path of the air parcel:
  - First directly northward.
  - Then deflected slightly northeast.
  - Finally curving more to the right as the Coriolis force increases.
- The rightward deflection continues until the Coriolis force balances the pressure-gradient force, at which point the parcel moves in a straight line parallel to the isobars, achieving geostrophic balance (not yet fully reached in this diagram).
- A text label on the right side explains: "As the particle accelerates, the Coriolis Effect amplifies, and the particle turns further right."

Figure 7.2.5 Geostrophic Flow is achieved

This is a labeled atmospheric diagram showing the path of an air parcel under the influence of the pressure gradient force and the Coriolis effect, culminating in geostrophic balance.

Diagram Structure:

- The diagram contains three horizontal lines representing atmospheric isobars, or lines of equal pressure:
  - Bottom Line (Point B): 1016 millibars (mb)
  - Middle Line (Point A): 1012 mb
  - Top Line (Point C): 1008 mb
- Vertical spacing between isobars is labeled as 50 kilometers, showing equal pressure intervals from the surface upward.
- On the left side, an upward-pointing arrow labeled "N" denotes North, establishing that the top of the diagram is the direction toward lower pressure.

Air Parcel Motion and Forces:

- A red dot at Point A shows the initial position of the air parcel.
- The parcel moves northward from 1012 mb to 1008 mb due to the pressure gradient force (PGF), represented by a large red arrow pointing straight up.
- As the parcel moves, it is deflected to the right (eastward) by the Coriolis force (CF), shown as a blue arrow pointing rightward.
- The parcel's motion path is illustrated by several sequential red dots that curve from vertical to horizontal.
- Eventually, the parcel reaches a point where the Coriolis force exactly balances the pressure-gradient force, and it begins to move in a straight path parallel to the isobars, indicated by a horizontal black arrow.
- This final condition is labeled with the explanation: "Eventually, PGF = CF, and the particle travels in a straight path, parallel to isobars."

Figure 7.3.2 Global Map of Average Sea-Level Atmospheric Pressure in January

This is a world map in an oval (Robinson-style) projection titled “Average Sea-Level Atmospheric Pressures in January.” It shows how atmospheric pressure is distributed globally in January.

Chart Structure and Legend

- The map displays continents in light tan and oceans in shades of blue.
- A color scale indicates pressure levels in millibars (mb):
  - Dark teal/blue: Over 1,024 mb (highest pressure)
  - Medium blue: 1,016 to 1,024 mb
  - Light blue-gray: 1,008 to 1,016 mb
  - Light tan: 1,000 to 1,008 mb
  - Darker tan/orange: Under 1,000 mb (lowest pressure)
- Letters mark pressure centers:
  - “H” indicates a high-pressure system
  - “L” indicates a low-pressure system

Latitude lines are labeled at approximately 80°N, 60°N, 40°N, 20°N, the Equator (0°), 20°S, 40°S, 60°S, and 80°S.

Northern Hemisphere Patterns (Winter Season)

In January, the Northern Hemisphere is in winter, and the map shows strong pressure contrasts:

- High-pressure systems (H):
  - A large, intense high-pressure area over central and eastern Asia (Siberian High).
  - Additional high-pressure zones over the North Atlantic and North Pacific Oceans.
- Low-pressure systems (L):
  - Prominent lows near Iceland and the North Atlantic (Icelandic Low).
  - A low-pressure area over the North Pacific near Alaska (Aleutian Low).

These patterns reflect cold, dense air over continents (high pressure) and relatively warmer ocean areas (low pressure).

Tropical Region (Near the Equator)

- Around the Equator, pressures are generally lower (around or below 1,008 mb).
- This corresponds to the Intertropical Convergence Zone (ITCZ), where warm air rises.
- Some localized low-pressure areas appear over northern South America and central Africa.

Southern Hemisphere Patterns (Summer Season)

In January, the Southern Hemisphere is in summer:

- High-pressure systems (H):
  - Broad high-pressure belts over the South Atlantic, South Pacific, and Indian Oceans, roughly between 20°S and 40°S.
- Low-pressure systems (L):
  - Lower pressure over continental regions, including parts of South America, southern Africa, and Australia, due to heating of land surfaces.
- Around Antarctica (near 60°S to 70°S):
  - A band of lower pressure (subpolar low belt) encircles the continent.
  - The interior of Antarctica shows higher pressure due to cold, dense air.

Figure 7.3.3 Global Map of Average Sea-Level Atmospheric Pressure in July

This image is a world map in an oval (Robinson-style) projection titled “Average Sea-Level Atmospheric Pressures in July.” It shows the global distribution of sea-level atmospheric pressure in July.

Chart Structure and Legend

- Continents are shown in light tan; oceans are shaded in varying blues.
- A legend on the right indicates pressure ranges in millibars (mb):
  - Dark blue/teal: Over 1,024 mb (highest pressure)
  - Medium blue: 1,016 to 1,024 mb
  - Light blue-gray: 1,008 to 1,016 mb
  - Light tan: 1,000 to 1,008 mb
  - Darker tan/orange: Under 1,000 mb (lowest pressure)
- Letters mark pressure systems:
  - “H” = High-pressure cell
  - “L” = Low-pressure cell

Latitude lines are labeled at intervals from about 80°N to 80°S, including the Equator.

Northern Hemisphere Patterns (Summer Season)

In July, the Northern Hemisphere is in summer, and pressure patterns shift compared to winter:

- Low-pressure systems (L):
  - A large, dominant low-pressure region over South and Central Asia (often called the Asian Low), extending across parts of the Middle East and India.
  - Additional smaller low-pressure areas appear over northern Africa and parts of North America due to strong land heating.
- High-pressure systems (H):
  - Strong subtropical highs over the North Atlantic (Azores High) and North Pacific (Hawaiian High).
  - These highs are located over oceans, roughly between 20°N and 40°N.

Tropical Region (Near the Equator)

- The Equatorial zone shows relatively low pressure (around or below 1,008 mb).
- This corresponds to the Intertropical Convergence Zone (ITCZ), where warm air rises and surface winds converge.
- The ITCZ appears slightly shifted north of the Equator in July, following the sun’s position.

Southern Hemisphere Patterns (Winter Season)

In July, the Southern Hemisphere is in winter:

- High-pressure systems (H):
  - Strong high-pressure areas over continental interiors, including Australia, southern Africa, and parts of South America, due to cooler land temperatures.
  - Persistent high-pressure belts over the southern oceans between about 20°S and 40°S.
- Low-pressure systems (L):
  - A continuous band of lower pressure around 60°S, known as the subpolar low-pressure belt, encircling Antarctica.
- Antarctica:
  - The interior shows very high pressure, associated with extremely cold, dense air.

Figure 7.3.4 A map of the world's rainforests

The image is a global map showing the distribution of tropical rainforests. The continents are displayed in light gray, and rainforest regions are highlighted in dark green. Several dashed horizontal lines mark key lines of latitude: 66.3° North, 23.5° North, the Equator, 23.5° South, and 66.3° South. The map emphasizes that tropical rainforests are concentrated near the Equator, within the band between the Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S).

Latitude Markers

Five dashed horizontal latitude lines are labeled:

- 66.3° N (Arctic Circle)
- 23.5° N (Tropic of Cancer)
- Equator (0°)
- 23.5° S (Tropic of Capricorn)
- 66.3° S (Antarctic Circle)

The rainforest regions appear almost entirely between 23.5° N and 23.5° S.

Major Rainforest Regions Highlighted

1. South America (Amazon Basin)

- The largest continuous dark green area appears in northern South America.
- Covers much of Brazil and extends into Peru, Colombia, Venezuela, Ecuador, Bolivia, and surrounding countries.
- Centered on the Equator.
- This represents the Amazon Rainforest, the largest tropical rainforest in the world.

2. Central America

- A narrow band of green runs through southern Mexico and into Central American countries such as Guatemala, Costa Rica, and Panama.
- Connects northward from the Amazon region.

3. Central and West Africa

- A large dark green region appears around the Equator in central Africa.
- Covers parts of the Democratic Republic of the Congo, Republic of the Congo, Gabon, Cameroon, and neighboring countries.
- Represents the Congo Basin rainforest.

4. Southeast Asia

- Extensive green areas appear in:
  - Southern India and Sri Lanka
  - Mainland Southeast Asia
  - The Malay Peninsula
  - Indonesia
  - The Philippines
  - Papua New Guinea

This region is part of the third-largest global concentration of tropical rainforests.

5. Madagascar

- A smaller green area appears along Madagascar's eastern coast, off the southeast coast of Africa.

Figure 7.3.5 A map of the world's deserts

The image is a global map showing the distribution of the world’s major desert regions. Continents are displayed in light gray with subtle shading. Desert areas are highlighted in bright orange. Dashed horizontal lines mark important latitudes: 66.3° North, 23.5° North (Tropic of Cancer), the Equator, 23.5° South (Tropic of Capricorn), and 66.3° South. The map shows that most deserts

occur near 23.5° North and 23.5° South, though some extend into higher latitudes.

Latitude Reference Lines

Five dashed lines appear across the map:

- 66.3° N (Arctic Circle)
- 23.5° N (Tropic of Cancer)
- Equator (0°)
- 23.5° S (Tropic of Capricorn)
- 66.3° S (Antarctic Circle)

Most desert regions cluster near the Tropics rather than near the Equator.

Major Desert Regions Highlighted

North America

- Southwestern United States and northern Mexico (including areas such as the Mojave, Sonoran, and Chihuahuan deserts).
- Located near and just north of 23.5° N.

South America

- A narrow strip along the west coast (the Atacama Desert in Chile and Peru).
- A large desert region in southern Argentina (Patagonian Desert), extending farther south than most tropical deserts.

Africa

- A vast continuous region across North Africa, representing the Sahara Desert, centered around 23.5° N.
- Smaller desert areas in southwestern Africa (the Namib Desert) and southern Africa (the Kalahari region).

Middle East and North Africa

- The Arabian Peninsula extends eastward from the Sahara across Saudi Arabia and surrounding regions.

Central and East Asia

- A large desert region in Mongolia and northern China (Gobi Desert).
- Additional arid regions extend westward into Central Asia.

Australia

- A broad desert region across central Australia, centered near 23.5° S.

Figure 7.3.6 A Map of Global Ocean Currents

The image is a world map in the Robinson projection showing the major global ocean currents. Landmasses are shaded light tan, oceans are light blue-gray, and currents are represented by directional arrows.

- Warm currents are shown in red arrows.
- Cold currents are shown in blue arrows.
- Some neutral or connecting flows appear in black.
- Latitude reference lines are shown at approximately 60°, 30°, 0° (Equator), −30°, and −60°.

- A legend at the bottom indicates red for warm currents and blue for cold currents.

Major Currents by Ocean Basin

Atlantic Ocean

Warm Currents (Red):

- Gulf Stream: Flows northward along the eastern United States, then northeast toward Europe.
- Brazil Current: Flows southward along the east coast of South America.
- North Atlantic Drift: Extension of the Gulf Stream moving toward northwestern Europe.
- Norwegian Current: Continues warm water into the Arctic region.

Cold Currents (Blue):

- Labrador Current: Flows southward from the Arctic along eastern Canada.
- Canary Current: Flows southward along northwest Africa.
- Benguela Current: Flows northward along southwest Africa.

The Atlantic shows a large clockwise circulation (gyre) in the Northern Hemisphere and a counterclockwise circulation in the Southern Hemisphere.

Pacific Ocean

Warm Currents (Red):

- Kuroshio Current: Flows northward along the east coast of Japan.
- East Australia Current: Flows southward along eastern Australia.
- North Pacific Drift: Moves eastward across the northern Pacific.

Cold Currents (Blue):

- California Current: Flows southward along the west coast of North America.
- Peru (Humboldt) Current: Flows northward along the west coast of South America.
- Oyashio Current: Flows southward from the Arctic toward Japan.
- West Australia Current: Flows northward along Western Australia.

The Pacific also shows circular gyres:

- Clockwise in the Northern Hemisphere
- Counterclockwise in the Southern Hemisphere

Indian Ocean

Warm Currents:

- Mozambique Current and related flows moving southward along southeast Africa.
- South Equatorial flows across the basin.

Cold Currents:

- West Australia Current along Western Australia.

The Indian Ocean circulation reverses seasonally in parts due to monsoon winds (not explicitly labeled but implied by current structure).

Equatorial Currents

Across all three major oceans:

- North Equatorial Current flows westward just north of the Equator.
- South Equatorial Current flows westward just south of the Equator.
- Equatorial Countercurrent flows eastward between them.

These currents form part of the tropical circulation system.

Southern Ocean

- The Antarctic Circumpolar Current flows continuously eastward around Antarctica.
- The Antarctic Subpolar Current also circles Antarctica.

These currents connect the Atlantic, Pacific, and Indian Oceans.

Figure 7.3.7 A map of surface high and low pressures.

A simplified diagram showing the typical distribution of atmospheric pressure at the equator and around 30 degrees latitude in both the Northern and Southern Hemispheres. It represents the pressure pattern associated with Earth's tropical atmospheric circulation and the trade winds. Three latitude zones are identified on the right side: 30°N at the top, 0° (Equator) across the middle, and 30°S at the bottom.

- At the equator, a thick horizontal black line extends almost completely across the image. Six large red letters "L," representing low atmospheric pressure, are evenly spaced along this line. The right side of the line is labeled "0° (Equator)."
- Near the top of the diagram, six large blue letters "H," representing high atmospheric pressure, are evenly distributed across the region corresponding to approximately 30°N. A short black line beside the final "H" points to the label "30°N."
- Near the bottom, another row of six blue letters "H" represents high atmospheric pressure around 30°S. A short black line beside the final "H" points to the label "30°S."

Figure 7.4.1 The Walker Circulation during Neutral Conditions

This figure illustrates normal atmospheric and oceanic circulation patterns across the tropical Pacific Ocean under non-El Niño conditions.

Layout:

- This is a 3D cross-section of the equatorial Pacific Ocean, oriented with:
  - Australia and Southeast Asia (west) on the left side (labeled ~120°E longitude)
  - South America (east) on the right side (labeled ~80°W longitude)
  - The Equator runs horizontally across the center.
- Ocean and Atmosphere Features:
  - Warm ocean surface waters are piled up in the western Pacific due to easterly trade winds.
  - Cooler ocean water dominates the eastern Pacific, near the coast of South America.
  - A sloping thermocline—the boundary between warm surface water and cold deep water—is shown dipping deeper in the west and rising toward the surface in the east.
  - Upwelling is occurring along the South American coast, where cold water is rising to the surface.
  - White arrows near the ocean surface indicate the direction of surface winds (easterlies)—from east to west.
  - Convective clouds and rising air are located over the warm waters of the western Pacific, indicating strong convection and thunderstorm activity.
  - Dashed arrows indicate the atmospheric return flow aloft, moving from west to east and completing the Walker convective circulation loop.

Annotations:

- Labeled “Neutral Conditions” at the top, this configuration shows typical Walker Cell circulation:
  - Surface winds blow from east to west (trade winds).
  - Warm water and rising air in the western Pacific support deep convection and rainfall.
  - Cooler water and sinking air in the eastern Pacific result in dry conditions.

Figure 7.4.2 Positions of TAO/Triton Array Buoys

This map displays the Global Tropical Moored Buoy Array, which consists of oceanographic buoys distributed across the tropical Pacific, Indian, and Atlantic Oceans as of July 2025. These buoys cover vast regions across the respective oceans and are part of three regional networks used for long-term climate and ocean monitoring.

- RAMA-2.0 (Indian Ocean, left side of map)
- TAO (Pacific Ocean, center of map)
- PIRATA (Atlantic Ocean, right side of map)

Map Layout:

- The map spans latitudes from 30°N to 30°S and longitudes from 60°E to 0°E, wrapping around the globe from the Indian Ocean to the Atlantic.
- Landmasses include Africa, South America, Southeast Asia, and Australia.
- Buoy positions are marked across the ocean basins with various colored squares, each color representing a different type of mooring instrumentation.

Buoy Types and Symbols:

Each square represents a buoy site.

- Solid squares = currently operating
- Open squares = planned deployment
- Colored coding represents standard mooring (red), flux reference sites (blue), flux and CO_2 enhanced (purple), and CO_2 enhanced (green) buoy locations.

Figure 7.4.3 Sea Surface Temperatures for July 2018

This figure contains two horizontal panels representing TAO/TRITON ocean monitoring data for the equatorial Pacific Ocean, covering the five-day period ending July 2, 2018. The panels display sea surface temperature (SST) and surface wind vectors, with the lower panel also showing anomalies relative to climatological averages.

Top Panel – “Means” (Sea Surface Temperature and Wind):

- The top panel shows SST in degrees Celsius (°C) across a horizontal section of the equatorial Pacific, from 140°E to 100°W longitude, and 10°S to 10°N latitude.
- A gradient ranges from:
  - 30°C in the western Pacific near 140°E,
  - 20–26°C as it moves eastward toward South America.
  - Contour lines labeled (e.g., 30, 29, 28...) indicate lines of equal SST (isotherms).
  - Wind vectors (arrows) represent average surface winds, generally showing easterly trade winds blowing from east to west across the central Pacific.

Bottom Panel – “Anomalies” (SST and Wind Deviations from Normal):

- This panel shows SST anomalies (differences from long-term averages) for the same region and time period.

- The color gradient ranges from:
  - +2 to +4°C for positive anomalies (warmer than normal),
  - -2 to -4°C for negative anomalies (cooler than normal).
- Overall, the anomalies are mostly near zero, indicating neutral ENSO conditions (neither El Niño nor La Niña).
- Contour lines labeled with numbers (e.g., 0, +1, -1) delineate SST anomaly values.
- Wind anomaly vectors (arrows) show small deviations in direction and magnitude, indicating slight variations from typical trade wind patterns.

Figure 7.4.4 The Walker Circulation during El Niño

This is a 3D schematic cross-section of the equatorial Pacific Ocean, illustrating El Niño conditions within the El Niño–Southern Oscillation (ENSO) cycle.

Layout:

- The diagram spans from 120°E (left) to 80°W (right) along the equator, depicting ocean and atmospheric patterns across the tropical Pacific.
- The left side represents the western Pacific (near Indonesia and Australia).
- The right side represents the eastern Pacific (near South America).

Key Features:

Ocean Structure:

- Warm surface water stretches uniformly across the Pacific, from west to east.
- Cooler water is confined to deeper layers and pushed downward throughout the entire basin.
- The thermocline, the boundary between warm surface water and cooler deep water, is shown as flat and deep, unlike in normal conditions when it is tilted.
- Upwelling of cold water is suppressed near South America.

Surface Winds:

- The usual trade winds (from east to west) are weakened or reversed.
- Black arrows along the ocean surface indicate weakened or reversed wind direction, blowing from west to east across the equator.

Atmosphere:

- Rising air and deep convection (clouds and upward arrows) are now centered in the central and eastern Pacific, rather than over the western Pacific.
- Dashed white arrows show upper-level atmospheric return flow, completing a disrupted Walker circulation loop.
- Rainfall and thunderstorm activity are displaced eastward, toward the central Pacific.

Figure 7.4.5 The Walker Circulation during La Niña.

This is a 3D schematic cross-section of the equatorial Pacific Ocean, illustrating La Niña conditions, a component of the El Niño–Southern Oscillation (ENSO) climate pattern.

Layout:

- The cross-section extends from 120°E (left) to 80°W (right) along the equator.
- Western Pacific (left side) represents the region near Australia and Southeast Asia.
- Eastern Pacific (right side) represents the region near South America.

Ocean Features:

- Warm surface waters are pushed farther west than normal, accumulating in the western Pacific.
- The eastern Pacific is dominated by cooler waters.
- The thermocline, the boundary between warm and cold water, is steeper than normal, being much shallower near South America and deeper in the western Pacific.
- Strong upwelling of cold, nutrient-rich water is shown off the coast of South America.

Atmospheric Circulation:

- Surface trade winds (arrows along the surface) are stronger than normal, blowing east to west across the Pacific.
- These winds drive warm surface water westward and enhance upwelling in the east.
- Rising air and deep convection (indicated by black upward arrows and clouds) are concentrated over the western Pacific, where the water is warmest.
- A dashed white arrow above the surface indicates upper-level atmospheric return flow moving west to east, completing the Walker circulation.
- Sinking air and dry conditions are shown over the eastern Pacific, near South America.

Figure 7.4.6 Sea Surface Temperatures and Anomalies for December 2015

This figure shows sea surface temperature (SST) and wind data across the equatorial Pacific Ocean during December 2015, based on measurements from the TAO/TRITON buoy array. The data is presented in two horizontal panels:

Top Panel – “Means” (Sea Surface Temperature and Wind):

- This panel shows average SSTs (in °C) and surface winds between 10°N and 10°S latitude, from 140°E to 100°W longitude.
- The SSTs are displayed using a color gradient from:
  - 30°C in the western and central Pacific,
  - 26–28°C in the east,
  - 18–22°C near South America.
  - Isotherms (contour lines) mark temperatures at 1°C intervals (e.g., 30°C, 29°C, 28°C).
  - Wind vectors (arrows) show the direction and magnitude of surface winds:
- Arrows mostly point from west to east across the central and eastern Pacific,
- Indicating weakened or reversed trade winds, which are typical of El Niño events.

Bottom Panel – “Anomalies” (SST and Wind):

- This panel shows deviations from the average (climatological) conditions.
- Color shading indicates SST anomalies (in °C), with:
  - Positive anomalies (+2 to +3.5°C) in the central and eastern equatorial Pacific.
  - The strongest warming occurs between 160°W and 100°W, peaking at about +3.5°C.
  - Areas with cooler-than-normal SSTs (very limited in this case).
- Contour lines trace SST anomaly values (e.g., 1.5, 2.0, 3.0).
- Wind anomaly vectors point eastward, indicating weakened or reversed easterly winds, consistent with El Niño.

Figure 7.4.7 Sea Surface Observations and Anomalies for December 2010

This figure presents monthly sea surface temperature (SST) and wind data from the TAO/TRITON buoy array for the equatorial Pacific Ocean during December 2010. It includes two horizontal panels:

Top Panel – “Means” (Sea Surface Temperature and Wind):

- The panel displays average SSTs and wind vectors between 10°N and 10°S latitude, from 140°E to 100°W longitude.
- A gradient represents SSTs from:

    - 30°C in the western Pacific,
    - 18–24°C as it moves eastward toward South America.
    - Contour lines (isotherms) labeled at 1°C intervals (e.g., 29, 28, 26°C) trace regions of equal temperature.
    - Arrows show surface wind direction and speed:
- Arrows point strongly from east to west, indicating intensified easterly trade winds typical of La Niña.

Bottom Panel – “Anomalies” (SST and Wind):

- This panel shows anomalies (differences from the long-term average).
- SST anomalies from -1°C to -3°C dominate the central and eastern Pacific, showing cooler-than-average water.
- Contour lines labeled -1.5, -2.0, etc., trace the extent of cold anomalies.
- Wind anomaly vectors show stronger-than-normal easterlies, reinforcing the cooling effect.

This page titled 8.5: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

9: PREDICTING THE FUTURE

Introduction

The scariest reality of Global Climate Change is that without intervention, our future could look very grim. Weather patterns, coastlines, and even ecosystems are all highly sensitive to temperature changes. Coral reefs, for example, can only grow within a very narrow temperature range. Even a slight warming can cause them to lose the protective algal layer covering them, making them more vulnerable to harm. As our planet continues to warm, it's important for humanity to prepare for the additional warming, its impacts on local climates and agriculture, and possibly even to find ways to mitigate it. Furthermore, we need to know the consequences of additional warming to understand the threat we are facing – how many homes will be lost to sea-level rise? Will hurricanes/tornadoes/other extreme weather events become more common, or occur in new places? What regions of the world are going to lose their capability to grow food and raise livestock... and what regions are going to gain that capability?



Figure 9.1: There is still much uncertainty about our future. We could either create a world that is desolate or bountiful. (Public Domain; Emmanuella Ackon via Wikimedia Commons).

There are many unknowns to consider, and there's no way this investigation can do justice to the subject of future climate justice. Just like the topics covered in Investigation 7 are explored more deeply in entire courses, entire majors, and even entire career tracks, the same can be said about the topics covered in this investigation. Instead, this investigation provides a brief preview of the tools at our disposal and the challenges we face in making future predictions. Finally, the investigation will conclude by briefly examining a series of emissions scenarios that provide a snapshot of what the future could look like if we are able to get our greenhouse gas emissions under control, and a snapshot of what could happen if we don't.

Objectives

- Determine if sudden Climate Change has occurred in the past.
- Investigate Climate Models and briefly utilize a simplified climate model.
- Define the SSP-RCP scenarios for future emissions.

Navigational Note

Investigation 8 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

9.1: Analog Forecasting
9.2: Emissions Scenarios
9.3: Accessible Descriptions

This page titled 9: Predicting the Future is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

9.1: Analog Forecasting

Can we use the past to predict the future?

In Investigation 7, we covered El Niño and La Niña and briefly explored some of the impacts of these variations in the Walker Circulation on the Equatorial Pacific. These phenomena have global consequences through a set of “teleconnections,” which is just a fancy way of saying that a variation in one part of the world influences another. Let's consider one example of how these teleconnections work: In 1982/83 and 1997/98, extraordinarily strong El Niño events occurred, and in both cases, many regions of California saw record-high rainfall. There have been other weak-to-moderate El Niño events that also enhanced rainfall in the region. As a result, whenever an El Niño event is occurring, Californians know to expect higher-than-normal chances for rainfall during the rainy season, and weather forecasters consider the presence of an El Niño event in predicting how much rain will occur during a rainy season. Basically, what everyone is doing is a type of Analog Forecasting: Using a past outcome to predict a future outcome. Since the El Niño events of 1982/83 and 1997/98 produced significant rainfall, a future El Niño should do so as well. If it happened before and the conditions are the same, it makes sense to predict it could happen again. We can do the same with Climate Change... we can look at prior abrupt climate shifts to help us predict what may happen in the future.

Reconstructing Past Climates

To find a potential analog for today’s rapid climate change, we need to use various tools to look back into the past. Since we only have direct temperature records dating back to approximately 1880, we need to find alternatives, known as Proxies, to look further into the past. Thankfully, the Earth System provides a number of such proxies for us. While there are many proxies we can look at, the two most fundamental for looking far into the past are Sediment Cores and Ice Cores. The collection methods of both are very similar, but the cores themselves are very different:

Sediment Cores: Gases, rainwater, fossils, and other elements of the current atmosphere/land makeup are constantly being mixed together through the process of weathering, which occurs when rainwater dissolves a small amount of rock from the Earth’s surface. This dissolved mixture becomes sediment, which then travels down to the ocean via rivers and streams, precipitates in the deep ocean, and finally deposits onto the ocean floor. Over millions of years, additional sediment precipitates and accumulates on top, creating a series of sediment layers that contain many elements of the Earth system at that time. Figure 9.1.1 is a set of sediment cores, which are drilled from the ocean floor and studied by Paleoclimatologists. These sediment cores can be chemically analyzed to measure Carbon Dioxide concentrations, detect fossils, and identify useful Oxygen isotopes that can tell us much about past climate. We’ll investigate the data from a sediment core in the next section on the Paleocene-Eocene Thermal Maximum.



Figure 9.1.1: A set of sediment cores representing climate from tens of thousands, to millions of years ago. (CC-BY-SA 2.5; Hannes Grobe AWI/ CRP via Wikimedia Commons). Alternative Description of Image.

Ice Cores: The concept is very similar for ice cores, with the main difference being that they are retrieved from research bases on ice sheets and in permanently frozen regions (such as Antarctica). The most famous research station for collecting ice cores is the Vostok Research Station in Antarctica. Figure 9.1.2 is a map showing its location, and Figure 9.1.3 is an image of an ice core.

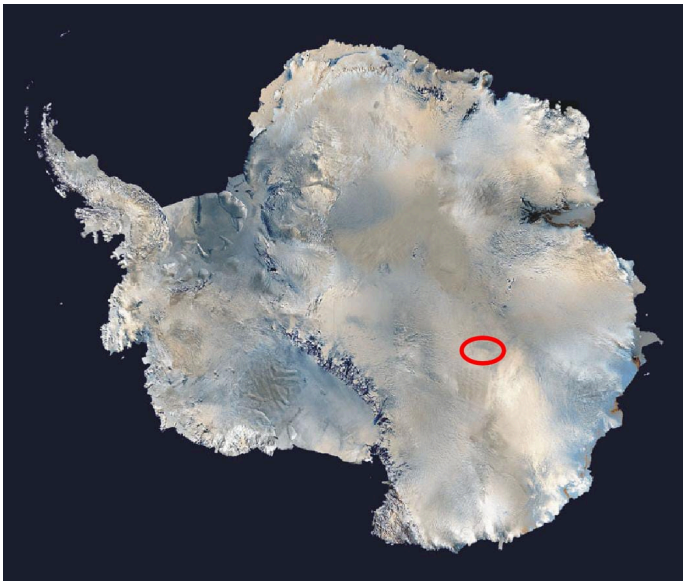


Figure 9.1.2: Location of Vostok Research Station in Antarctica (Circled in red). The station is located in East Antarctica, southeast of the center of the continent and inland from the coast. (Public Domain; NASA via Wikipedia)

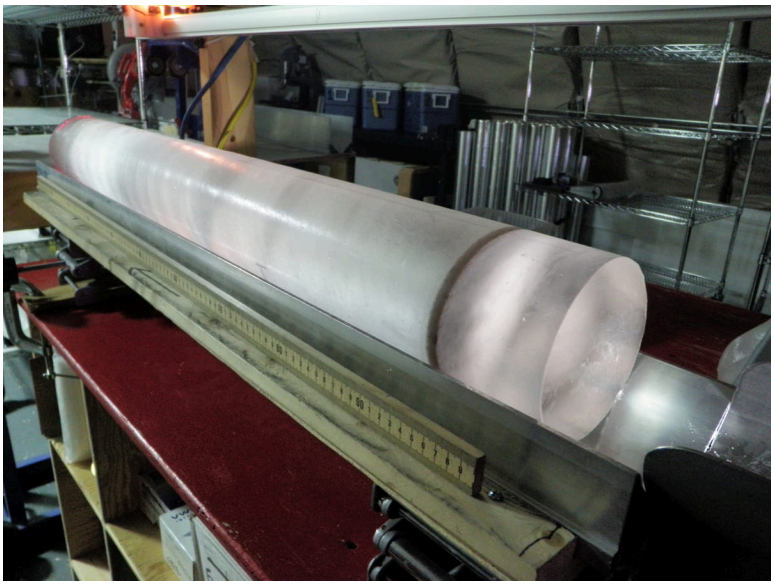


Figure 9.1.3: Image of an ice core taken from the WAIS Divide Research Station, in Antarctica. The dark band is a layer of volcanic ash that settled from an eruption approximately 21,000 years ago. (Public Domain; Heidi Roop via National Snow and Ice Data Center). Alternative Description of Image.

We can reconstruct the past using various elements extracted from these cores, including bubbles of ancient air in ice cores, and the presence of oxygen-18 isotopes in both ice and sediment cores. Let's now look at one particularly interesting period found in these data – The PETM.

The Paleocene-Eocene Thermal Maximum (PETM)

In order for us to find a "similar" period of sudden, intense warming caused by a rapid increase in Greenhouse Gasses, we need to look back millions of years (Carbon Dioxide Concentrations haven't been as high as they currently are in hundreds of thousands of years, and the rate of increasing temperature hasn't been as fast as it currently is in millions of years... in fact, we are warming at a rate over 10-times faster than we did when coming out of the last ice age). While there obviously isn't an ancient period when humans induced rapid warming, the temperature record shows a similar spike at the end of the Paleocene, about 10 million years after the extinction of most Dinosaurs. Figure 9.1.4 is an infographic showing temperature reconstructions for the past 65 million years.

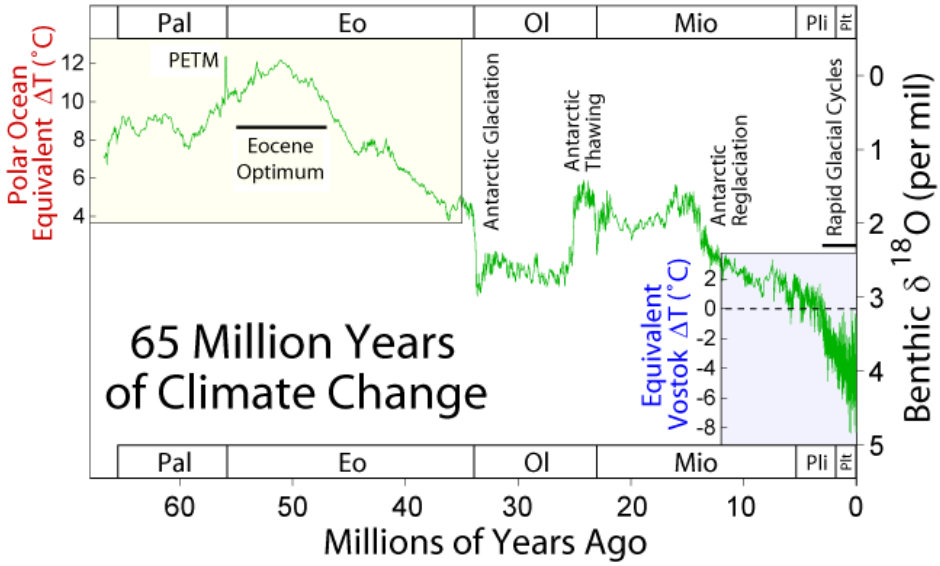


Figure 9.1.4: Reconstruction of Global Temperature estimates based on Polar Ocean Sediment Core data until approximately 35 million years ago and Ice Core Data from the Vostok Ice Core for the past 12 million years. All values are differences from the 20th-century average. (CC-BY-SA 3.0; Robert A. Rhode via Wikimedia Commons). Alternative Description of Image.

1. We're going to focus on the Tan-highlighted rectangle in the upper-left-hand corner. The PETM is labeled next to a green spike in temperature (the green line represents the temperature difference from the modern average). From this, we can see that the PETM occurred approximately 56 million years ago, when global average temperatures were approximately _____ warmer than they are today.
   a. 2°C
   b. 10°C
   c. 6°C
   d. Temperatures were cooler
2. During this time, global average temperatures briefly spiked approximately _____ degrees from your answer in question #1 to 12°C
   a. 2°C
   b. 4°C
   c. 6°C
   d. 10°C

One way we can reconstruct past temperatures is by examining the presence of Oxygen-18 (^{18}O), a heavy isotope of Oxygen. The green line in Figure 9.1.4, used to detect temperature in the above questions, is actually a graph of the Ratio of Benthic (bottom-dwelling) Oxygen-18 to normal Oxygen-16 (the ratio is indicated by the Greek letter "δ") found in fossilized organisms in the sediment. A simple way to interpret this graph is that the larger the $\delta^{18}O$ value, the more Oxygen-18 is present in the sample. Because temperature is also being plotted on this figure, you need to use the scale on the far right of the graph to identify the amount of Oxygen-18 present, and the amount increases as you travel down the axis (you'll find out why in question 3).

3. Look at the small "blue" shaded box in the lower-right of the graph, which shows the difference in temperature from today vs. the time taken from the Vostok Ice Core data. The equivalent temperature difference is on the left side of the box, while the amount of Oxygen-18 is on the right. From this (just comparing the two scales), we can see that the more Oxygen-18 is present in the sample:
   a. The lower the temperature is believed to be
   b. The higher the temperature is believed to be

The sudden shock to the Earth system occurred over a period of approximately 1000-10,000 years – what may seem long to us, but in terms of geological time, is actually a very short period of time. The sudden increase was due to a sudden, rapid increase in greenhouse gases. There is still much debate about the exact cause of this spike in greenhouse gases, but this Carbon Brief article briefly discusses some possible causes, along with a more detailed description of PETM indicators. The PETM was the largest of a series of "Hyperthermals", periods when a sudden "burp" of greenhouse gases caused a short-lived spike in temperatures. During this time, the rate of Carbon Release was still significantly slower than it is now, but we can still look to this

period of rapid warming to see how human activity may affect our planet.

This page titled 9.1: Analog Forecasting is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

9.2: Emissions Scenarios

The IPCC Scenarios

The primary conclusions of the previous section are that, approximately 55 million years ago, a sudden spike in atmospheric carbon (in the form of Carbon Dioxide and Methane) led to a rapid rise in atmospheric temperature and a sudden die-off of deep-ocean organisms (by up to 40%). The sudden spike in Carbon concentrations and Global Average temperatures is only "sudden" in geological terms- thousands to tens of thousands of years- but it does provide us with a "slow-motion" scenario of what could happen to our planet if continued runaway greenhouse warming takes hold. In short, we can use the PETM as a warning sign to get our acts together!

However, there are many unpredictable variables involved in getting our act together. It's not as simple as assuming that current consumption trends will persist. For example, there was a noticeable decrease in fossil fuel consumption in both 2009 and 2020, driven by the 2008 Global Recession and the COVID-19 Pandemic, respectively. In both instances, there was a subsequent decrease in global Carbon emissions, though they quickly recovered. Neither the Recession nor the pandemic is an easily predictable event, but they had impacts on consumption. The same can be said of the onset of war, global natural catastrophes (such as asteroid collisions or major volcanic eruptions), or even the outcome of an election. All of these factors can impact global emissions by varying global growth and necessities. Thus, there is no convenient way to predict changes in Carbon emissions. Without the ability to predict emissions, we can't make meaningful projections about future climate. The solution is to create a series of Emissions Scenarios that present "what-ifs" for use as input to climate models.

To address this issue, the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) set up the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC is an intergovernmental body of the United Nations (UN). Its job is to "provide governments at all levels with scientific information that they can use to develop climate policies". The current set of future scenarios provided by the IPCC is in the form of Shared Socioeconomic Pathways (SSP's), which are five scenarios that climate scientists can use to provide a likely range of temperature increases and subsequent environmental impacts. The five scenarios are presented in Table 8.2.1, and Figure 8.2.1 shows total global carbon dioxide emissions (in billions of tons) for these scenarios.

Table 8.2.1: Shared-Socioeconomic Pathway Scenarios from the IPCC Sixth Assessment Report.

SSP Scenario	Description
SSP1-1.9	Very low greenhouse gas emissions; CO_2 emissions cut to net-zero around 2050.
SSP1-2.6	Low greenhouse gas emissions; CO_2 emissions cut to net-zero around 2075.
SSP2-4.5	Intermediate greenhouse gas emissions; CO_2 around current levels until 2050, then falling but not reaching net-zero by 2100.
SSP3-7.0 (SSP3's Baseline)	High greenhouse gas emissions. CO_2 emissions will double by 2100.
SSP5-8.5 (SSP5's Baseline)	Very high greenhouse gas emissions. CO_2 emissions will triple by 2075.

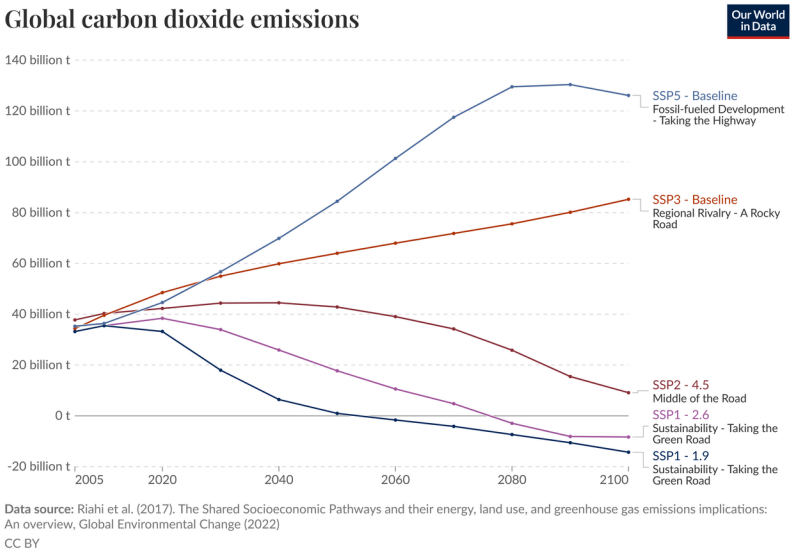


Figure 9.2.1: Carbon dioxide emissions under the five primary SSP emissions scenarios. (CC-BY 4.0; Riahi et al via Our World In Data). Alternative Description of Image.

4. Which of the following scenarios would be the "worst-case scenario" in terms of emissions?
   a. SSP1-1.9
   b. SSP2-4.5
   c. SSP3-7.0
   d. SSP5-8.5
5. Based on the knowledge that additional greenhouse gases will lead to additional warming, which scenario would result in the most warming?
   a. SSP1-1.9
   b. SSP2-4.5
   c. SSP3-7.0
   d. SSP5-8.5

Figure 8.2.2 shows how carbon dioxide concentrations will change in each of the scenarios between now and 2100.

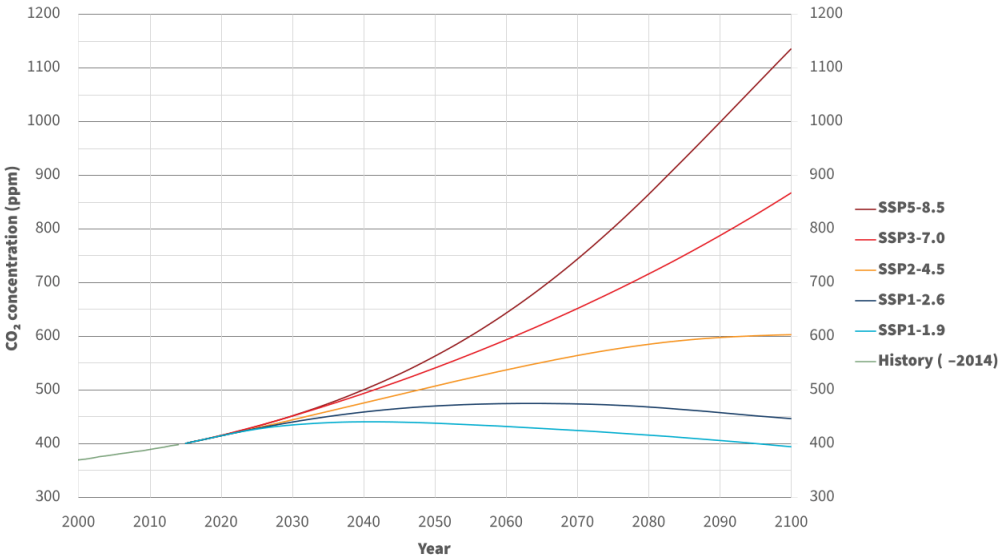


Figure 9.2.2: Shared Socioeconomic Pathways projected carbon dioxide concentrations. (CC-BY-SA 4.0; Sfdiversity via Wikimedia Commons). Alternative Description of Image.

6. Current Carbon Dioxide Concentrations are approximately 425 parts per million (ppm). According to Figure 9.2.2, which scenario is the only emissions scenario to show a decrease from 425 parts per million in carbon dioxide concentrations by 2100?
   a. SSP1-1.9
   b. SSP2-4.5
   c. SSP3-7.0
   d. SSP5-8.5
7. All other scenarios show at least some increase in Carbon Dioxide concentrations by 2100, with the SSP5-8.5 (Baseline) scenario showing:
   a. A decrease in carbon dioxide concentrations by 2100.
   b. A near-doubling in carbon dioxide concentrations by 2100.
   c. A near-tripling in carbon dioxide concentrations by 2100.
   d. A leveling-off in carbon dioxide by 2100.
8. Some of the "middle of the road" scenarios show Carbon Dioxide concentrations increasing, but then leveling off. Specifically, the SSP2-4.5 scenario shows a leveling off at _____ parts-per-million by 2100
   a. 450
   b. 600
   c. 900
   d. 1200

These emissions scenarios are not limited to Carbon Dioxide emissions. Methane, which is another potent greenhouse gas, is also projected in the SSP scenarios. These projections are shown in Figure 9.2.3.

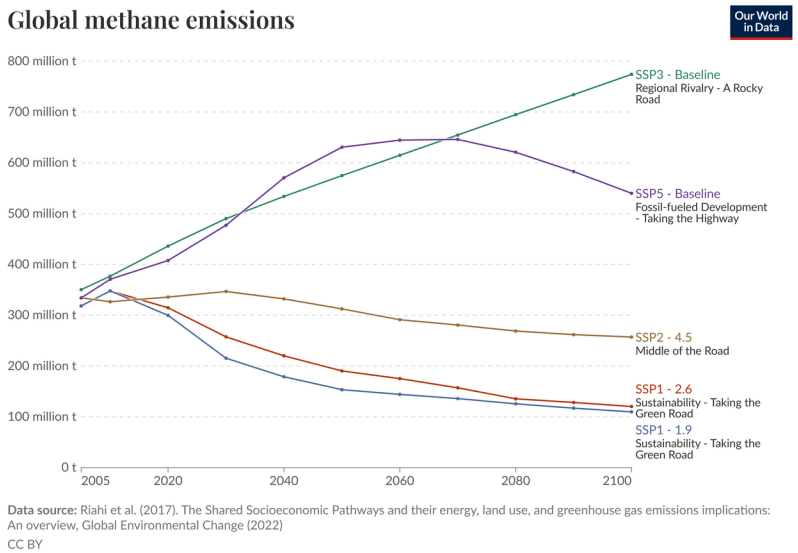


Figure 9.2.3: Methane Emissions under the five SSP scenarios. (CC-BY 4.0; Riahi et al via Our World In Data). Alternative Description of Image.

9. Interestingly, the SSP5 scenario doesn't show the greatest increase in Methane emissions. Instead, the _____ scenario shows the highest, steadily increasing methane emissions levels by 2100.
   a. SSP1-1.9
   b. SSP1-2.6
   c. SSP2-4.5
   d. SSP3-7.0 (Baseline)
10. On the other hand, all of the other emissions scenarios show:
   a. A leveling-off sometime during the 21st century, followed by a decline in methane emissions.
   b. A continued, sustained increase in methane emissions until 2050, and then a decline in methane emissions.
11. However, the SSP5-8.5 baseline scenario shows.
   a. An immediate (by 2020) decline in methane emissions.
   b. An increase in methane emissions until approximately 2060, followed by a decline until 2100.
   c. A continued, sustained increase in methane emissions until 2090, with only a slight decline in emissions by 2100.

This occurs because while the SSP5-8.5 scenario is the most fossil-fuel-intensive, it also assumes the global population will

decline to 7 billion by 2100. Comparatively, SSP3 shows the largest population increase, as the lack of a developed, globalized economy in many regions leads to higher birth rates in still-developing countries. Remember, the primary fossil fuel emissions by human activity are carbon dioxide. Since the population isn't increasing in SSP5-8.5, agricultural and land-use sources of methane are held constant into the next centuries. Because the atmospheric lifespan of methane is relatively short (about 12 years), actively cutting fossil/industrial sources while keeping agricultural rates flat drives a gradual decline in the global atmospheric concentration of methane. However, this is still offset by year-over-year increases in carbon dioxide emissions. All other emissions scenarios show some increase in population through the middle of the century, followed by an eventual decline by 2100. Thus, while it may look nice, the SSP5-8.5 scenario isn't a better emissions scenario. Figure 9.2.4 shows projected increases in global average temperature under each SSP scenario, relative to pre-industrial temperatures (year 1750 CE).

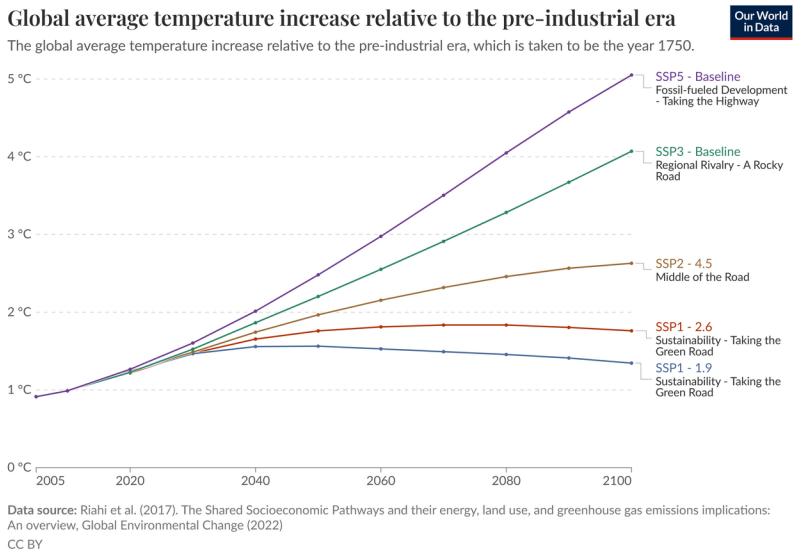


Figure 9.2.4: Global average temperature increase after 2005 for the five SSP scenarios. (CC-BY 4.0; Riahi et al via Our World In Data). Alternative Description of Image.

12. Regardless of the scenario, there has
    a. been almost 1°C of warming by 2005.
    b. been no warming by 2005.
13. Now examine the warming by 2100. Regardless of the scenario, there will be
    a. at least some additional warming (relative to 2005) by 2100.
    b. no warming at all by 2100.
    c. at least some cooling (relative to 2005) by 2100.
14. However, both SSP1 (1.9 and 2.6) scenarios project that temperatures will:
    a. Continue to sharply increase throughout the 21st century.
    b. Level off, and even begin decreasing by 2100.
15. Therefore, regardless of what we (as humans) do to reduce carbon emissions:
    a. We cannot limit warming by 2100.
    b. We can completely reverse warming to levels below 2005.
    c. There will be at least some additional warming, but we can limit it (meaning we can cause temperatures to stop increasing).
16. However, climate scientists argue (and the Paris Climate Agreement targets) that, if humans keep warming to below 1.5°C by 2100, we can avoid the most catastrophic impacts of climate change. Which scenario in Figure 9.2.4 has global temperature increases below 1.5°C by 2100?
    a. SSP3-7.0
    b. SSP2-4.5
    c. SSP1-2.6
    d. SSP1-1.9
17. Briefly return to Figure 9.2.1; the scenario you suggested in question 16 would require:
    a. No reductions in Carbon Dioxide Emissions
    b. Eventual (by 2060) reductions in Carbon Dioxide Emissions
    c. Immediate reduction in Carbon Dioxide Emissions
18. Therefore:

a. We (humanity) must work to reduce Carbon Dioxide Emissions immediately.
b. We (humanity) don't need to work on reducing Carbon Dioxide Emissions.

19. Which scenario shows the most warming by 2100?
    1. SSP1-1.9
    2. SSP2-4.5
    3. SSP3-7.0 (Baseline)
    4. SSP4-8.5 (Baseline)
20. This _____ with the conclusion we made in question 5.
    a. Agrees
    b. Does not agree
21. Recall the PETM, when temperatures increased significantly (by upwards of 4-8°C) in a 1,000-10,000 year time period, such a significant increase:
    a. Is possible by 2100 in these SSP scenarios
    b. Is not possible by 2100 in these SSP scenarios

With an increase in temperature comes a number of other major consequences, such as (but certainly not limited to) sea-level rise. Figure 8.2.5 is a graph of global sea-level increases, relative to the 1995-2014 average sea level.

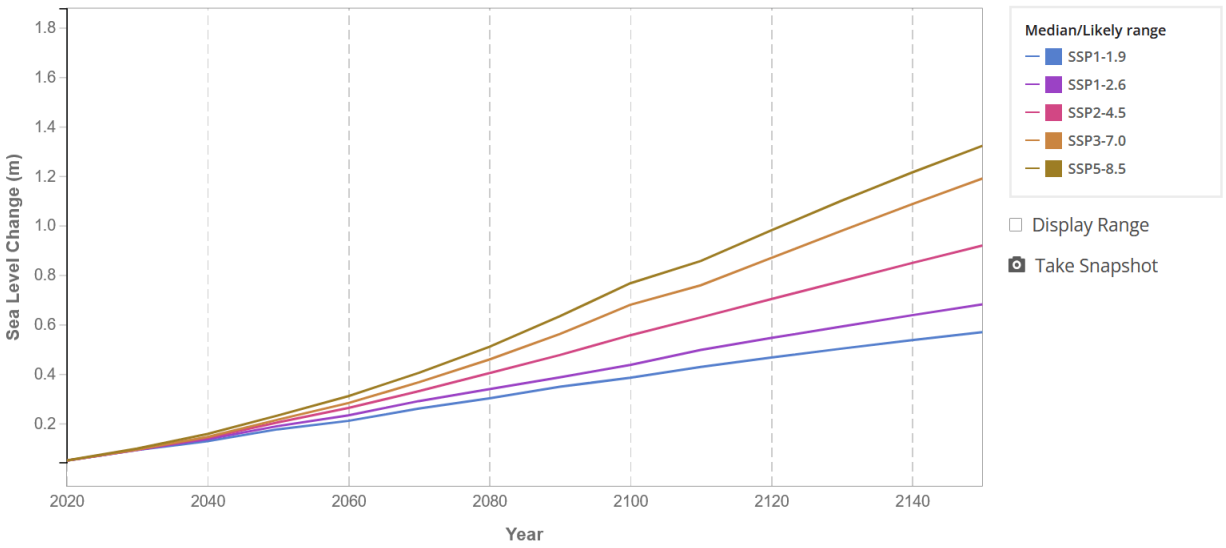


Figure 9.2.5: Global sea-level rise projections for each of the SSP scenarios. (Public Domain; NASA via Sea Level Projection Tool). Alternative Description of Image.

22. Regardless of scenario, there _____ by 2100.
    a. Will be at least some sea level rise.
    b. Will not necessarily be any sea-level rise.
23. Regardless of the scenario, all scenarios show a(n)
    a. Sustained increase in sea levels by 2100
    b. Leveling off of sea levels by 2100
    c. Sustained decrease in sea levels by 2100
24. The SSP5-8.5 scenario is the worst-case scenario, showing an approximately _____ increase in sea levels by 2100, with further increases beyond that.
    a. 0.2 meters
    b. 0.4 meters
    c. 0.8 meters
    d. 1.0 meter
25. Based on everything we have covered on this page:
    a. The warmer the temperatures get, the higher the sea levels will rise.
    b. There is no relationship between temperature increases and sea level rise.
    c. Warmer temperatures will cause sea levels to decrease.

Why does this matter? As sea levels rise, locations close to the ocean (including major airports such as San Francisco

International Airport) will become more exposed to storm waves, increasing the risk of inundation during storms and even of complete inundation under all conditions. For regions such as the San Francisco Bay, this can permanently submerge homes, businesses, and airports (as mentioned above), expose them to storm waves, or cause beach erosion. This isn't even getting into the ecological impacts that sea-level rise will have on local wetlands.

Sea-level rise is just one impact of a warming world explored in the 2021 IPCC Report, nor is it the only impact it will experience. Other impacts not explored in this lab manual but of significance include, but are not limited to, global decreases in sea and land ice, changes in precipitation patterns (including droughts), and ecological stresses (such as those affecting coral reefs). As mentioned elsewhere in this lab manual, these impacts are being studied in entire degree programs and beyond, with new research being published regularly.

This page titled 9.2: Emissions Scenarios is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

9.3: Accessible Descriptions

Figure 8.1.1: Sediment Core Section

Photograph of a sediment core collection displayed in a rectangular wooden storage tray. The tray contains eight horizontal core sections arranged in parallel rows. Each row holds cylindrical core samples that have been split lengthwise and laid flat for examination. Small labels at the ends of the rows indicate depth intervals, ranging approximately from 926.42 meters to 930.62 meters, suggesting the cores were recovered from a subsurface drilling project.

The core sections display variations in color, texture, composition, and structure. Most intervals consist of light-colored, fine-grained sedimentary material with visible layering and subtle banding. Several sections contain fractures, cracks, and breaks where the core has been fragmented during drilling or handling.

One interval in the upper half of the tray contains a markedly different zone of coarse, multicolored material composed of angular fragments embedded within a finer matrix. This interval contrasts sharply with the surrounding fine-grained layers and may represent a different depositional environment or a disturbed section.

Multiple gray markers and circular reference disks are placed on top of the cores at selected locations. These markers appear to identify features of interest, sample locations, fractures, or stratigraphic boundaries for analysis. The core segments vary in continuity, with some rows nearly intact and others broken into multiple pieces.

The image illustrates how sediment cores preserve a vertical record of subsurface geology, allowing researchers to study changes in sediment composition, depositional processes, environmental conditions, and geologic history through depth.

Figure 8.1.3: Ice Core

Photograph showing a long cylindrical ice core positioned horizontally on a metal measuring cradle inside a laboratory or cold-room research facility. The ice core appears nearly transparent to translucent white and has been extracted as a continuous cylinder from an ice sheet or glacier for scientific analysis.

The core rests in a metal channel mounted above a workbench. A ruler or measuring scale runs alongside the core, allowing researchers to determine its length and position during processing. Based on the visible scale and the portion shown in the image, the ice core section appears to be approximately 1 meter (about 3 feet) long, which is a common length for ice-core segments recovered during drilling operations.

The exposed circular end of the core reveals a smooth cross-section. Subtle bands, bubbles, and variations in transparency are visible within the ice, representing differences in snow accumulation, air content, dust concentration, and other environmental conditions preserved when the ice formed. The dark band
described in the figure caption is approximately 80 cm from the closest end of the core.

The surrounding laboratory contains equipment commonly associated with ice-core handling and storage, including metal shelving, cylindrical storage tubes, insulated containers, and processing surfaces. The environment appears organized for the measurement, logging, cutting, and sampling of ice cores.

Ice cores such as this are commonly collected from polar ice sheets in Antarctica and Greenland and can preserve records of past climate conditions. Scientists analyze trapped air bubbles, isotopes, dust particles, volcanic ash, and chemical compounds within the ice to reconstruct past temperatures, atmospheric composition, precipitation patterns, and greenhouse gas concentrations.

Figure 8.1.4: Past 65 Million Years of Climate Change

A multi-axis climate history figure titled "65 Million Years of Climate Change" traces climate evolution from approximately 65 million years ago to the present. Time runs from older on the left to the present on the right. Geological intervals labeled along the figure are the Paleocene (Pal), Eocene (Eo), Oligocene (Ol), Miocene (Mio), Pliocene (Pli), and Pleistocene (Plt).

The main jagged line represents benthic oxygen isotope composition, delta-18-O, using the right vertical axis from approximately 0 to 5 per mil. The scale is inverted, with 0 at the top and 5 at the bottom. In this record, increasing benthic delta-18-O generally corresponds to decreasing deep-ocean temperature and/or increasing global ice volume.

The large inset covering the Paleocene and Eocene converts the early isotope record to polar-ocean-equivalent temperature change, with values from approximately 4°C to 12°C. Temperatures begin near 7–8°C around 65 million years ago, increase through the Paleocene, and undergo the Paleocene-Eocene Thermal Maximum (PETM) near 56 million years ago. The record reaches its highest sustained values during the Eocene Optimum, at roughly 11–12°C around 52–50 million years ago. A pronounced long-term cooling follows: equivalent temperatures decline to approximately 8°C by 45 million years ago, 6–7°C around 40 million years ago, and approximately 4°C by 35 million years ago.

Near 34 million years ago, the figure labels Antarctic Glaciation, associated with an abrupt change toward larger delta-18-O values and the development of a major Antarctic ice sheet. The Oligocene remains substantially cooler than the early Eocene.

Around 23 million years ago, an event labeled Antarctic Thawing corresponds to a pronounced shift toward warmer conditions and/or reduced Antarctic ice. This is followed by renewed cooling and Antarctic Reglaciation around 14 million years ago.

A second inset over the most recent portion of the record expresses climate change as an equivalent Vostok Antarctic temperature anomaly, with a vertical scale from approximately +2°C to -8°C. The values trend downward toward the present, indicating substantial late-Cenozoic cooling.

The final few million years are labeled Rapid Glacial Cycles. Benthic delta-18-O reaches approximately 4–5 per mil, reflecting colder temperatures and larger global ice volumes associated with repeated Pleistocene glacial-interglacial cycles.

Overall, the figure depicts Earth's transition from the exceptionally warm early Cenozoic to a progressively colder climate with permanent Antarctic glaciation and, eventually, recurring large Northern Hemisphere ice sheets.

Table 8.4.1: Detailed information from the Paleocene-Eocene inset

Approx. age (million years ago)	Equivalent temperature change	Feature / interpretation
65	~7–8°C	Warm early Paleocene conditions
62	~8–9°C	Temperature rises with short-term fluctuations
60	~8–9°C	Warm Paleocene climate
58	~8°C	Brief cooling before major early Eocene warming
~56	~10–12°C	PETM; abrupt warming excursion
54	~10–11°C	Continued warming after PETM
52	~11–12°C	Approaching peak Eocene warmth
50	~11–12°C	Eocene Optimum; highest sustained temperatures in inset
48	~10–11°C	Beginning of long-term cooling
46	~9–10°C	Continued cooling
44	~8°C	Noticeable decline from Eocene maximum
42	~7–8°C	Cooling continues, with short-term fluctuations
40	~6–7°C	Substantially cooler than Eocene Optimum
38	~5–6°C	Approaching late Eocene cooling
35–36	~4°C	Lowest values in inset immediately before Antarctic glaciation

Table 8.4.2: Major climate events

Event	Approximate age	Significance shown
PETM	~56 Ma	Abrupt early Cenozoic warming
Eocene Optimum	~52–50 Ma	Highest sustained warmth shown
Long-term Eocene cooling	~50–35 Ma	Equivalent temperature declines by roughly 7–8°C
Antarctic Glaciation	~34 Ma	Major Antarctic ice-sheet expansion
Antarctic Thawing	~23 Ma	Temporary warming and/or ice retreat
Antarctic Reglaciation	~14 Ma	Renewed Antarctic ice expansion
Rapid Glacial Cycles	Last few Ma	Repeated glacial-interglacial cycles

Table 8.4.3: Geological intervals

Abbreviation	Geological interval
Pal	Paleocene
Eo	Eocene
Ol	Oligocene
Mio	Miocene
Pli	Pliocene
Plt	Pleistocene

Notes: The inset temperature values are approximate readings from the figure rather than direct observations. The main benthic delta-18-O record reflects a combination of deep-ocean temperature and global ice volume, so it should not be interpreted as a direct temperature curve throughout the entire 65-million-year interval.

Figure 8.2.1: Shared-Socioeconomic Pathway Carbon Dioxide Emissions Scenarios

Line graph showing historical and projected global carbon dioxide (CO_2) emissions from approximately 2005 to 2100 under five Shared Socioeconomic Pathway (SSP) scenarios. The horizontal axis represents year, and the vertical axis shows annual CO_2 emissions in billions of metric tons, ranging from approximately –20 billion tons to 140 billion tons per year.

All scenarios begin near 33–38 billion tons per year in the early 2000s and then diverge substantially through the twenty-first century. Positive values indicate net CO_2 emissions to the atmosphere, while negative values indicate net carbon removal from the atmosphere.

The SSP5-8.5 baseline scenario ("Fossil-fueled Development – Taking the Highway") shows the largest increase. Emissions rise from about 33 billion tons in 2005 to approximately 57 billion tons by 2030, 84 billion tons by 2050, 117 billion tons by 2070, and peak near 130 billion tons per year around 2080–2090. Emissions remain above 125 billion tons per year through 2100.

The SSP3-7.0 baseline scenario ("Regional Rivalry – A Rocky Road") shows continued growth but at a slower rate. Emissions increase from about 35 billion tons in 2005 to roughly 55 billion tons by 2030, 64 billion tons by 2050, 72 billion tons by 2070, and approximately 85 billion tons by 2100.

The SSP2-4.5 scenario ("Middle of the Road") rises slightly before declining. Emissions increase from about 38 billion tons in 2005 to approximately 44 billion tons by 2030–2040, then gradually fall to around 39 billion tons by 2060, 25 billion tons by 2080, and about 9 billion tons by 2100.

The SSP1-2.6 scenario ("Sustainability – Taking the Green Road") peaks early and declines substantially. Emissions rise slightly to approximately 38 billion tons around 2020, then decrease to about 26 billion tons by 2040, 10 billion tons by 2060, reach approximately 0 by the late 2070s, and become slightly negative by 2100 at around –8 billion tons per year.

The SSP1-1.9 scenario ("Sustainability – Taking the Green Road") shows the most aggressive emissions reductions. Emissions decline from approximately 35 billion tons in 2005 to about 18 billion tons by 2030, 1 billion ton by 2050, become negative shortly after 2050, and reach approximately –15 billion tons per year by 2100.

The graph illustrates that future emissions outcomes vary dramatically depending on socioeconomic development pathways and mitigation efforts. By 2100, the difference between the highest-emission and lowest-emission scenarios is approximately 145 billion tons of CO_2 per year.

Figure 8.2.2: Shared-Socioeconomic Pathway Carbon Dioxide Concentrations Scenarios

Line graph showing historical and projected atmospheric carbon dioxide (CO_2) concentrations from 2000 to 2100 under five Shared Socioeconomic Pathway (SSP) scenarios used in climate research. The horizontal axis represents year from 2000 to 2100, and the vertical axis shows atmospheric CO_2 concentration in parts per million (ppm), ranging from 300 ppm to 1200 ppm.

A historical line (green) shows CO_2 increasing from approximately 370 ppm in 2000 to about 395–400 ppm by 2014. After 2015, the graph branches into five future scenarios that diverge substantially over the twenty-first century.

All scenarios begin near 400 ppm around 2015–2020 and continue upward for at least several decades. The scenarios differ in the rate and magnitude of future emissions and resulting atmospheric CO_2 concentrations.

The SSP5-8.5 scenario (dark red) shows the most rapid increase. CO_2 rises from about 400 ppm in 2015 to approximately 560 ppm by 2050, 750 ppm by 2070, 1,000 ppm by 2090, and reaches roughly 1,130–1,140 ppm by 2100.

The SSP3-7.0 scenario (red) shows substantial growth but less than SSP5-8.5. CO_2 reaches approximately 540 ppm by 2050, 650 ppm by 2070, 780 ppm by 2090, and about 860–870 ppm by 2100.

The SSP2-4.5 scenario (orange) shows moderate growth. CO_2 increases to approximately 500 ppm by 2050, 560 ppm by 2070, and levels off near 600 ppm by 2100.

The SSP1-2.6 scenario (dark blue) rises more slowly, reaching about 470 ppm around 2050–2065, then gradually declining to approximately 445 ppm by 2100.

The SSP1-1.9 scenario (light blue) shows the strongest emissions reductions. CO_2 peaks near 440 ppm around 2040–2045 and then steadily declines to approximately 390–395 ppm by 2100, approaching current-day concentrations.

The figure demonstrates that future atmospheric CO_2 concentrations depend strongly on emissions pathways. By 2100, the difference between the highest and lowest scenarios exceeds 700 ppm, illustrating the large influence of future human activities on atmospheric composition.

Figure 8.2.3: Shared-Socioeconomic Pathway Methane Emissions Scenarios

Five colored lines on a white background track projected global methane emissions from 2005 to 2100. The horizontal axis shows year, and the vertical axis shows methane emissions in millions of metric tons per year, ranging from 0 to 800 million tons. Each line represents a different Shared Socioeconomic Pathway (SSP) scenario and is labeled near its endpoint on the right side of the figure.

The green SSP3-7.0 line rises steadily throughout the century, starting near 350 million tons in 2005 and reaching approximately 775 million tons by 2100, making it the highest trajectory shown. The purple SSP5-8.5 line also increases substantially, peaking near 645 million tons around the 2060s–2070s before declining to about 540 million tons by 2100.

The brown SSP2-4.5 line remains near current levels through the first half of the century and then gradually declines, ending near 255 million tons by 2100. Two lower trajectories show strong methane reductions: the orange SSP1-2.6 line declines from roughly 340 million tons in 2005 to about 120 million tons by 2100, while the blue SSP1-1.9 line falls from approximately 320 million tons to about 110 million tons by 2100, the lowest value shown.

The lines are close together near the beginning of the record but diverge widely after about 2030. By 2100, the gap between the highest pathway (SSP3-7.0) and the lowest pathway (SSP1-1.9) is approximately 665 million tons of methane per year.

The figure includes labels identifying the scenarios as:

- SSP3-7.0: Regional Rivalry – A Rocky Road
- SSP5-8.5: Fossil-fueled Development – Taking the Highway
- SSP2-4.5: Middle of the Road
- SSP1-2.6: Sustainability – Taking the Green Road
- SSP1-1.9: Sustainability – Taking the Green Road

Figure 8.2.4: Shared-Socioeconomic Pathway Temperature Increase Scenarios

Five colored lines on a white background show projected increases in global average temperature relative to the pre-industrial era (defined in the figure as approximately 1750). The horizontal axis shows years from 2005 to 2100, and the vertical axis shows temperature increase in degrees Celsius, ranging from 0°C to 5°C above pre-industrial levels.

All five lines begin near 0.9–1.0°C warming in 2005 and remain close together through about 2030. After that, the scenarios diverge substantially. Each line is labeled at its endpoint on the right side of the figure.

The purple SSP5-8.5 line ("Fossil-fueled Development – Taking the Highway") rises the fastest throughout the century. Warming reaches approximately 2.0°C by 2040, 3.0°C by 2060, 4.0°C by 2080, and slightly above 5.0°C by 2100, making it the highest trajectory shown.

The green SSP3-7.0 line ("Regional Rivalry – A Rocky Road") also increases steadily, reaching roughly 1.9°C by 2040, 2.6°C by 2060, 3.3°C by 2080, and approximately 4.1°C by 2100.

The brown SSP2-4.5 line ("Middle of the Road") shows moderate warming. Temperatures rise to approximately 1.8°C by 2040, 2.1°C by 2060, 2.5°C by 2080, and about 2.6°C by 2100.

The orange SSP1-2.6 line ("Sustainability – Taking the Green Road") increases more slowly. Warming reaches about 1.7°C by 2040, peaks near 1.8°C around 2070–2080, and then declines slightly to approximately 1.7–1.8°C by 2100.

The blue SSP1-1.9 line ("Sustainability – Taking the Green Road") shows the lowest warming. Temperatures rise to about 1.5–1.6°C around 2040–2050, then gradually decline to approximately 1.3–1.4°C by 2100.

The figure illustrates that future warming depends strongly on future emissions pathways. By 2100, projected warming ranges from approximately 1.35°C under SSP1-1.9 to slightly above 5°C under SSP5-8.5, a difference of about 3.7°C.

The title states: "Global average temperature increase relative to the pre-industrial era." A subtitle notes that the pre-industrial baseline is taken to be the year 1750.

Figure 8.2.5: Shared-Socioeconomic Pathway Sea Level Rise Scenarios

Five colored lines on a white background show projected global mean sea level change from 2020 to 2150 under five Shared Socioeconomic Pathway (SSP) scenarios. The horizontal axis shows year from 2020 to 2150, and the vertical axis shows sea level change in meters, ranging from approximately 0 to 1.8 meters. A legend on the right identifies the colored lines as SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The legend indicates that the plotted values represent median projections; uncertainty ranges are available but are not displayed.

All five curves begin near 0.05 meters of sea level rise around 2020 and increase throughout the period. The scenarios remain close together through the first few decades but diverge progressively after mid-century.

The SSP1-1.9 line (lowest-emissions scenario) rises most slowly. Sea level reaches approximately 0.20 m by 2060, 0.38 m by 2100, and about 0.57 m by 2150.

The SSP1-2.6 line rises slightly faster, reaching approximately 0.23 m by 2060, 0.44 m by 2100, and about 0.68 m by 2150.

The SSP2-4.5 line shows intermediate growth, reaching roughly 0.27 m by 2060, 0.56 m by 2100, and approximately 0.92 m by 2150.

The SSP3-7.0 line rises more rapidly after 2050, reaching approximately 0.29 m by 2060, 0.68 m by 2100, and about 1.19 m by 2150.

The SSP5-8.5 line (highest-emissions scenario) shows the greatest increase. Sea level reaches approximately 0.31 m by 2060, 0.77 m by 2100, exceeds 1 meter around the 2120s, and reaches approximately 1.32 m by 2150.

The separation among scenarios becomes increasingly large after 2100. By 2150, the difference between the highest and lowest projections is approximately 0.75 meters.

The image also includes a checkbox labeled "Display Range" and a camera icon labeled "Take Snapshot," suggesting the figure may be part of an interactive visualization.

This page titled 9.3: Accessible Descriptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

INDEX

A

American Meteorological Society
1: Orientation Lab
anthropogenic climate change
1.4: Global Warming vs. Climate Change
atmospheric conditions
1.4: Global Warming vs. Climate Change

C

carbon dioxide
1: Orientation Lab
1.4: Global Warming vs. Climate Change
climate
1.2: Maps and Geography
1.3: Longitude and Latitude
climate change
1: Orientation Lab
1.4: Global Warming vs. Climate Change
climate data
1.1: Lab Procedures
climate model
1.1: Lab Procedures
climate phenomena
1.3: Longitude and Latitude
climate science
1.4: Global Warming vs. Climate Change
continents
1.2: Maps and Geography
coordinate system
1.3: Longitude and Latitude
countries
1.2: Maps and Geography

D

distances
1.3: Longitude and Latitude

E

Earth
1.3: Longitude and Latitude

G

geography
1.2: Maps and Geography
1.3: Longitude and Latitude
global climate maps
1: Orientation Lab
global mean temperature
1.4: Global Warming vs. Climate Change
global warming
1: Orientation Lab
1.4: Global Warming vs. Climate Change
GPS
1.3: Longitude and Latitude

I

instructor
1.1: Lab Procedures
investigations
1: Orientation Lab

K

keeling curve
1: Orientation Lab

L

lab investigations
1.1: Lab Procedures
lab manual
1: Orientation Lab
latitude
1.3: Longitude and Latitude
longitude
1.3: Longitude and Latitude

M

manual
1.1: Lab Procedures
mapping
1.3: Longitude and Latitude
maps
1.2: Maps and Geography
methane concentrations
1.4: Global Warming vs. Climate Change
multiple choice
1.1: Lab Procedures

N

National Center for Atmospheric Research
1: Orientation Lab
National Weather Service
1: Orientation Lab

P

precipitation
1.2: Maps and Geography
problem solving
1.1: Lab Procedures

R

reading
1.2: Maps and Geography

S

scientific inquiry
1.1: Lab Procedures

T

temperature
1.2: Maps and Geography
temperature anomalies
1.4: Global Warming vs. Climate Change
temperature changes
1.4: Global Warming vs. Climate Change
tools
1.2: Maps and Geography

W

written questions
1.1: Lab Procedures

This page titled Index is shared under a Public Domain license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

GLOSSARY

S

Sample Word 1 | Sample Definition 1

This page titled Glossary is shared under a Public Domain license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.

DETAILED LICENSING

Overview

Title: Investigations in Climate Change

Webpages: 61

All licenses found:

- CC BY 4.0: 86.9% (53 pages)
- Public Domain: 9.8% (6 pages)
- Undeclared: 3.3% (2 pages)

By Page

- Investigations in Climate Change - *CC BY 4.0*
  - Front Matter - *Undeclared*
    - TitlePage - *CC BY 4.0*
    - InfoPage - *Public Domain*
    - Program Page - *CC BY 4.0*
    - Table of Contents - *Public Domain*
    - Licensing - *Public Domain*
    - Accessibility Statement - *CC BY 4.0*
    - About the Lab Manual - *CC BY 4.0*
    - About the Authors - *CC BY 4.0*
  - 1: Orientation Lab - *CC BY 4.0*
    - 1.1: Lab Procedures - *CC BY 4.0*
    - 1.2: Maps and Geography - *CC BY 4.0*
    - 1.3: Longitude and Latitude - *CC BY 4.0*
    - 1.4: Global Warming vs. Climate Change - *CC BY 4.0*
    - 1.5: Accessible Descriptions - *CC BY 4.0*
  - 2: Defining Earth's Climate - *CC BY 4.0*
    - 2.1: Factors affecting the Climate - *CC BY 4.0*
    - 2.2: Climate Zones - *CC BY 4.0*
    - 2.3: Precipitation - *CC BY 4.0*
    - 2.4: Accessible Descriptions - *CC BY 4.0*
  - 3: Records of Climate History - *CC BY 4.0*
    - 3.1: Climate Data - *CC BY 4.0*
    - 3.2: Local Climate Data - *CC BY 4.0*
    - 3.3: Annual Climate - *CC BY 4.0*
  - 4: Heat and the Greenhouse Effect - *CC BY 4.0*
    - 4.1: Heat Transfer - *CC BY 4.0*
    - 4.2: Radiation - *CC BY 4.0*
    - 4.3: Selective Absorbers and Greenhouse Gases - *CC BY 4.0*
    - 4.4: Atmospheric Carbon Dioxide measurements - *CC BY 4.0*
    - 4.5: The Greenhouse Effect - *CC BY 4.0*
    - 4.6: Accessible Descriptions - *CC BY 4.0*
  - 5: Earth's Energy Budget - *CC BY 4.0*
    - 5.1: Energy Balance - *CC BY 4.0*
    - 5.2: Global Energy Balance - *CC BY 4.0*
    - 5.3: Energy Budget and Climate Change - *CC BY 4.0*
    - 5.4: Other factors affecting Earth's Energy Budget - *CC BY 4.0*
    - 5.5: Accessible Descriptions - *CC BY 4.0*
  - 6: Water and the Climate - *CC BY 4.0*
    - 6.1: The Water Cycle - *CC BY 4.0*
    - 6.2: Ocean-Atmosphere Interaction - *CC BY 4.0*
    - 6.3: Accessible Descriptions - *CC BY 4.0*
  - 7: The Carbon Cycle - *CC BY 4.0*
    - 7.1: Components of the Carbon Cycle - *CC BY 4.0*
    - 7.2: Ocean Acidification and Short Term Carbon Cycle - *CC BY 4.0*
    - 7.3: Long Term Carbon Cycle - *CC BY 4.0*
    - 7.4: Accessible Descriptions - *CC BY 4.0*
  - 8: Global Circulation and El Niño - *CC BY 4.0*
    - 8.1: Why the wind blows - *CC BY 4.0*
    - 8.2: Other forces acting on the wind - *CC BY 4.0*
    - 8.3: Atmospheric Circulation - *CC BY 4.0*
    - 8.4: El Niño-Southern Oscillation - *CC BY 4.0*
    - 8.5: Accessible Descriptions - *CC BY 4.0*
  - 9: Predicting the Future - *CC BY 4.0*
    - 9.1: Analog Forecasting - *CC BY 4.0*
    - 9.2: Emissions Scenarios - *CC BY 4.0*
    - 9.3: Accessible Descriptions - *CC BY 4.0*
  - Back Matter - *Undeclared*
    - Index - *Public Domain*
    - Glossary - *Public Domain*
    - Detailed Licensing - *Public Domain*

This page titled Investigations in Climate Change is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Neel Desai and Alicia Mullens.