AMERICAN METEOROLOGICAL SOCIETY:

A COLDEX Center for Oldest Ice Exploration PARTNER

Project Ice

Introduction to Paleoclimatology

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TEACHER'S GUIDE

Project Ice

This guide is one of a series produced by Project Ice, a National Science Foundation sponsored initiative of the American Meteorological Society (AMS). AMS is a subawardee of Oregon State University on its NSF Science and Technology Center institutional award (OPP-2019719), Center for Oldest Ice Exploration (COLDEX). The purpose of COLDEX is to “explore Antarctica for the oldest possible ice core records of our planet’s climate and environmental history, and to help make polar science more inclusive and diverse.” Project Ice is the annual K-12 teacher focused activity within COLDEX, and is offered via hybrid delivery that includes a one-week residency at Oregon State University. The goal of Project Ice is to create and train a diverse network of master teachers prepared to integrate paleoclimatology and polar science in their classrooms and provide peer training sessions. To support these teachers' educational experience, Project Ice develops and produces teacher's guides, slide sets, and other educational materials.

For further information, and the names of the trained master teachers in your state or region, please contact:

Project Ice
American Meteorological Society
1200 New York Avenue, NW, Suite 450
Washington, DC 20005
amsedu@ametsoc.org

This material draws from U.S. Ice Drilling Program School of Ice work supported by the National Science Foundation under Award #1836328. Some content is also based on AMS DataStreme course investigations, developed with support from the National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA).

Module: Introduction to Paleoclimatology

Instructor: Project Ice Instructor or Project Ice Graduate
Audience/Grade Level: K-12 Educators

STANDARDS:

[Project Ice Objectives]

Understanding Climate Change and Paleoclimate:

1. Examine various proxy climate data sources and their contribution to understanding atmospheric and geologic variables at different temporal resolutions.

2. Investigate the Faint Young Sun Paradox and its role as an analog for future climate scenarios.

3. Analyze feedback mechanisms in the climate system, such as ice-albedo feedback, and their influence on Earth's climate system.

4. Explore the Milankovitch cycles and their roles in driving long-term climate variation.

5. Discuss the significance of the ocean and weathering in carbon cycling.

8. Understand the role of physical and chemical analysis of ice cores, including isotope analysis, in interpreting past atmospheric conditions based on air bubbles and other fragments preserved in ice cores.

9. Interpret ice core records to identify markers of climate variability and climate change over different time scales.

10. Describe how ice cores directly measure past atmospheric CO_2 levels and their importance in understanding natural climate cycles.

Climate Literacy Principles from: https://cleanet.org/clean/literacy/climate/index.html

1. The Sun is the primary source of energy for Earth's climate system. (a, b, c, d, e)

2. Climate is regulated by complex interactions among components of the Earth system. (a, b, c, d, e, f)

3. Life on Earth depends on, is shaped by, and affects climate. (b, c, d, e)

4. Climate varies over space and time through both natural and man-made processes. (d, e, g)

5. (a, b, c, e) Our understanding of the climate system is improved through observations, theoretical studies, and modeling.

Next Generation Science Standards (NGSS)

Performance Expectations

K-PS3-1. Make observations to determine the effect of sunlight on Earth’s surface.

2-ESS1-1. Use information from several sources to provide evidence that Earth events can occur quickly or slowly.

2-ESS2-3. Obtain information to identify where water is found on Earth and that it can be solid or liquid.

3-ESS2-2. Obtain and combine information to describe climates in different regions of the world.

4-ESS1-1. Identify evidence from patterns in rock formations and fossils in rock layers to support an explanation for changes in a landscape over time.

5-ESS2-1. Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.

5-ESS2-2. Describe and graph the amounts of saltwater and fresh water in various reservoirs to provide evidence about the distribution of water on Earth.

MS-ESS2-1. Develop a model to describe the cycling of Earth's materials and the flow of energy that drives this process.

MS-ESS2-2. Construct an explanation based on evidence for how geoscience processes have changed Earth's surface at varying time and spatial scales.

MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

HS-ESS2-2. Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems.

HS-ESS2-7. Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth.

Science and Engineering Practices

2. Developing and Using Models
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking
8. Obtaining, Evaluating, and Communicating Information

Disciplinary Core Ideas

- PS3.B: Conservation of Energy and Energy Transfer
- ESS1.C: The History of Planet Earth
- ESS2.A: Earth Materials and Systems
- ESS2.B: Plate Tectonics and Large-Scale System Interactions
- ESS2.C: The Roles of Water in Earth's Surface Processes
- ESS2.D: Weather and climate
- ESS2.E: Biogeology

Crosscutting Concepts

1. Patterns
2. Cause and Effect
3. Scale, Proportion, and Quantity
4. Systems and System Models
5. Energy and Matter
7. Stability and Change

Engage | Introduction to Earth's Climate

Earth's climate is always changing, but the current period of stable climate has allowed humans to flourish on this planet for the last hundreds of thousands of years. We now stand at about 8 BILLION people on our planet.

Our societal infrastructure to support this many people is based on the prediction that environmental conditions will remain largely the same in the future. We are far beyond the natural carrying capacity of the planet.

Humans have only been on this planet for 0.0001% of Earth's (and, accordingly, climate) history. The last 3 million years have been dominated by Ice Ages, but the last ten thousand years have been a relatively mild interlude between glacial periods.

The volume of CO_2 in the atmosphere in 2024 is the highest since roughly 55 million years ago. If our trend of burning fossil fuels continues, the climate will very likely warm beyond the limit of Earth's collective *adaptive* carrying capacity.[1] The concentration of atmospheric CO_2 has increased by 30% in the last 100 years alone, as shown in **Figure 1**.

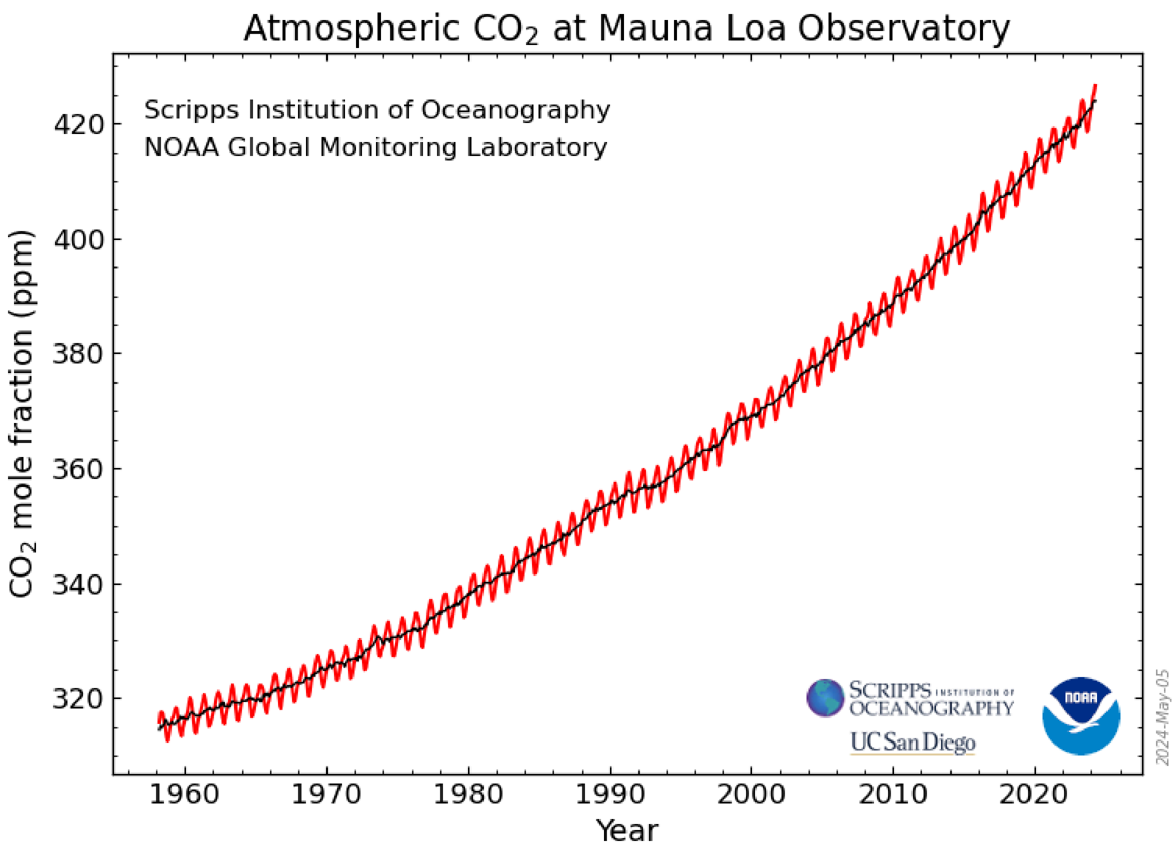

Figure 1. The 'Keeling Curve' from observations of CO_2 via the station at the Mauna Loa Observatory in Hawai'i identifies monthly mean concentrations (1958-2023). [NOAA MGL]

Explore | A Story of Early Climate "Influencers"

Any discussion of what controls our climate must ultimately begin with the Sun. To help understand the role the Sun plays in our climate, it's helpful to tell a story about how our climate evolved with the Sun as it "grew up" and became more luminous.

[1] the ability of a (human) system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. [Source: https://climate-adapt.eea.europa.eu/en/knowledge/tools/adaptation-support-tool/step-2-4-t/index_html]

In its younger days, the Sun shone at only about 75% of its current strength; it took multiple billions of years for its output to approach the current level of luminosity. An important question to ask at this point is, “How could the Earth be warm enough to sustain its earliest life forms while the Sun was still relatively weak?” The complex story that follows will help answer that question and also help explain the primary drivers of climate change.

The **Faint Young Sun Paradox**, first proposed by Carl Sagan and his colleagues, presents a unique hypothesis about Earth's early climate. Fossilized bacteria from about 3 billion years ago indicate that life was already thriving on our planet with a much weaker Sun. In theory, this reduced solar output should have left Earth as a frozen, uninhabitable ice ball, yet geological evidence suggests liquid water and relatively warm conditions prevailed.

To address this paradox, scientists turn to greenhouse gases like carbon dioxide (CO_2) and methane (CH_4). These gases “trap” heat in the atmosphere (i.e., the greenhouse effect), warming Earth’s climate. In Earth's early days, volcanic eruptions were more frequent than they are today, emitting extraordinary amounts of greenhouse gases such as CO_2, CH_4, and water vapor. Despite the faint young Sun, the volcanic-driven greenhouse effect likely kept the planet warm enough to sustain liquid water and life. Later on, eruptions from spreading continental plates likely emitted carbon dioxide that continued to help warm the Earth from about 250 to 50 million years ago.

Another unique contributor plays a critical role in our climate’s balancing act–one that combines the connections between geology and climatology. In short, atmospheric carbon can combine with water to form a weak acid—carbonic acid—that falls to the surface in rain. The acid dissolves rocks—a process called **chemical weathering**. These weathering processes break down rocks and minerals releasing elements like calcium, magnesium, potassium, or sodium ions. These ions then react with carbonate in water, flow with the fallen precipitation into rivers and ultimately into the ocean. These elements are then combined with carbon from ocean water to form carbonates that are deposited on the ocean bottom as limestone. This carbon capture contributes to the ocean’s ability to absorb carbon from the atmosphere.

The rise of the Himalayan Mountains around 50 million years ago, shown in **Figure 2**, intensified weathering through exposure of new rock surfaces. This large influx of sediments into the ocean acted as a giant CO_2 “scrubber,” channeling large amounts of greenhouse gases out of the atmosphere and contributing to global cooling.

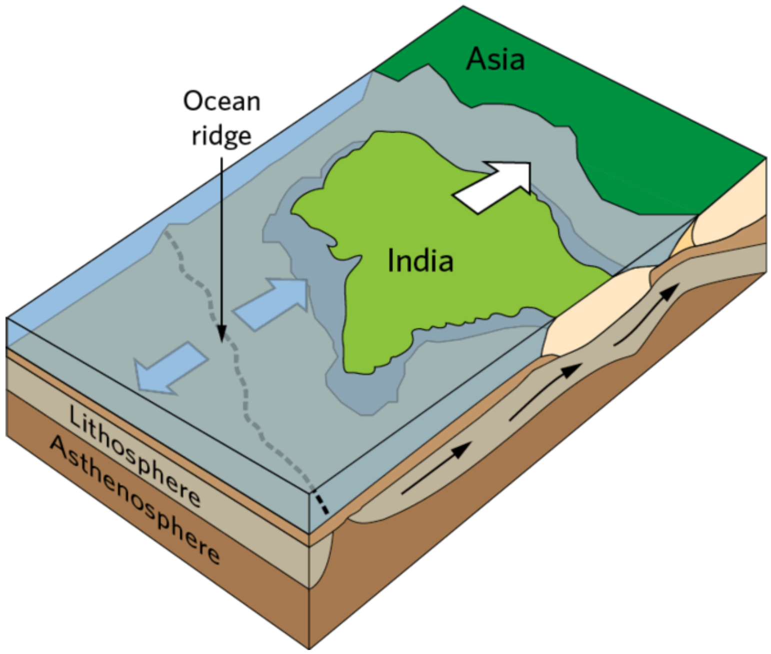

Figure 2. As the Indian subcontinent pushed into Asia, the Himalayan Mountains were "born," allowing for much more landmass exposure and, consequently, much more chemical weathering of rock. [Courtesy of R. Henson - *The Thinking Person's Guide to Climate Change*]

The interplay between these processes involves complex positive and negative feedbacks. For example, as volcanic activity released CO_2, the greenhouse effect increased, warming the planet. This warmth enhanced weathering, which in turn reduced atmospheric CO_2, providing a cooling effect. This dynamic system helped stabilize Earth's climate over geological timescales.

Earth's climate was also heavily influenced by the rise of plant life on land around 460 million years ago. Plants absorb CO_2 during photosynthesis, reducing greenhouse gases in the atmosphere. The spread of vegetation also accelerated weathering processes by breaking down rocks with their roots, enhancing the sequestration of CO_2. This biotic influence added a new layer of complexity to Earth's climate regulation.

The Faint Young Sun Paradox illustrates the intricate web of forcings and feedbacks between solar luminosity, greenhouse gases, volcanic activity, chemical weathering, and biological processes. These factors combined in a delicate balance that allowed early Earth to maintain warm conditions conducive to life, despite a fainter Sun. Understanding these ancient mechanisms not only helps us unravel Earth's climatic history but also provides insights into current and future changes.

Explain | Climate Forcings

Cycles in Earth's Orbit

Changes in Earth's orbit have caused fluctuations in both regional and global temperatures throughout Earth's history. The collective effects of changes in Earth's position relative to the Sun affect how much solar radiation reaches Earth. The cycles in Earth's orbit drive Earth's long-term climate and trigger glacial and interglacial periods that can endure for tens of thousands to hundreds of thousands of years. These Earth-Sun orbital variations, called **Milankovitch Cycles**, can alter up to 25% of the radiation that is received in Earth's middle latitudes (30–60°) and, most importantly, *where* that radiation is received on Earth. Milankovitch Cycles include three main oscillations in Earth's orbital movements, as shown in **Figure 3**.

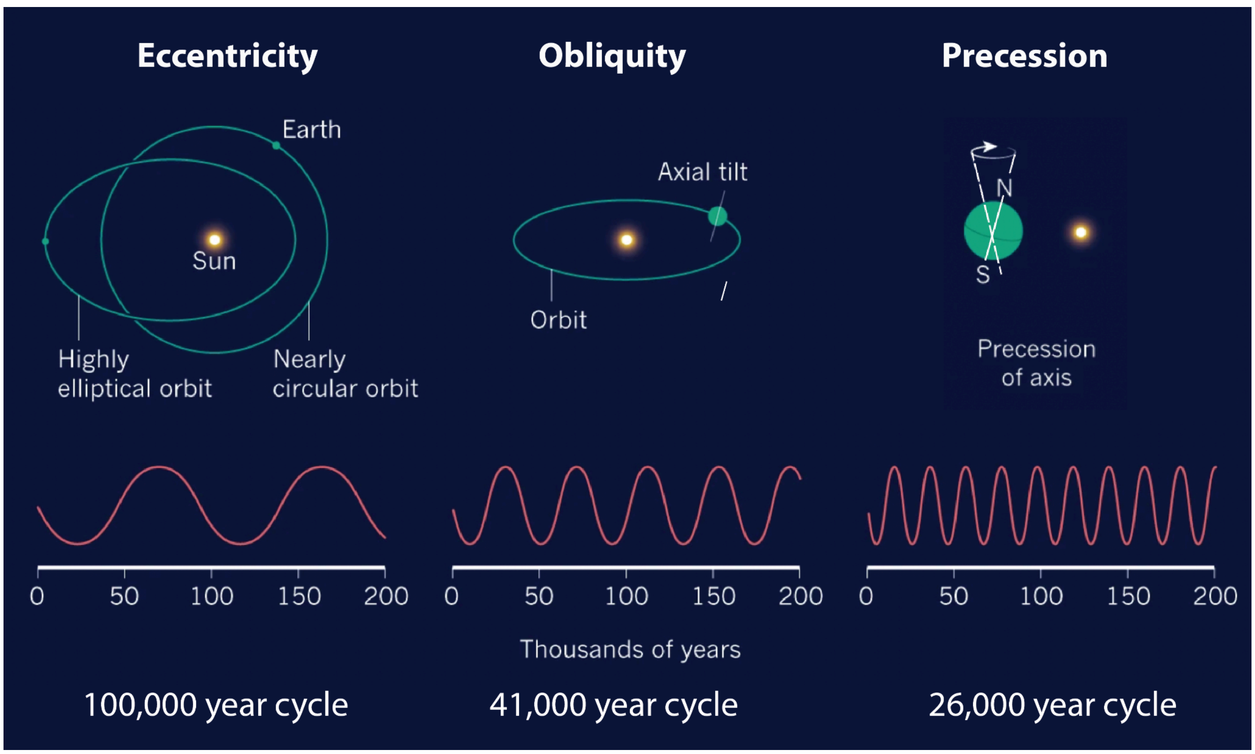

Figure 3. Illustration of the three Milankovitch Cycles and the frequency of each cycle. [Adapted from Maslin, M., 2016]

First, Earth's orbit around the sun is not perfectly circular and changes over a 100,000-year cycle from nearly circular to slightly more elliptical because of the pull of Jupiter and Saturn on Earth. This variation in Earth's orbit around the Sun is called *eccentricity*, and the change that it causes in incoming solar radiation is relatively small in the short term but affects Earth's climate more significantly on a longer time scale.

Eccentricity is measured from 0 for completely circular to 1, where an ellipse turns into a straight line. Examples of eccentricity are shown in **Figure 4**. The eccentricity of Earth's orbit around the sun varies from nearly circular to a maximum ellipticity of 0.068, which is still just barely elliptical.

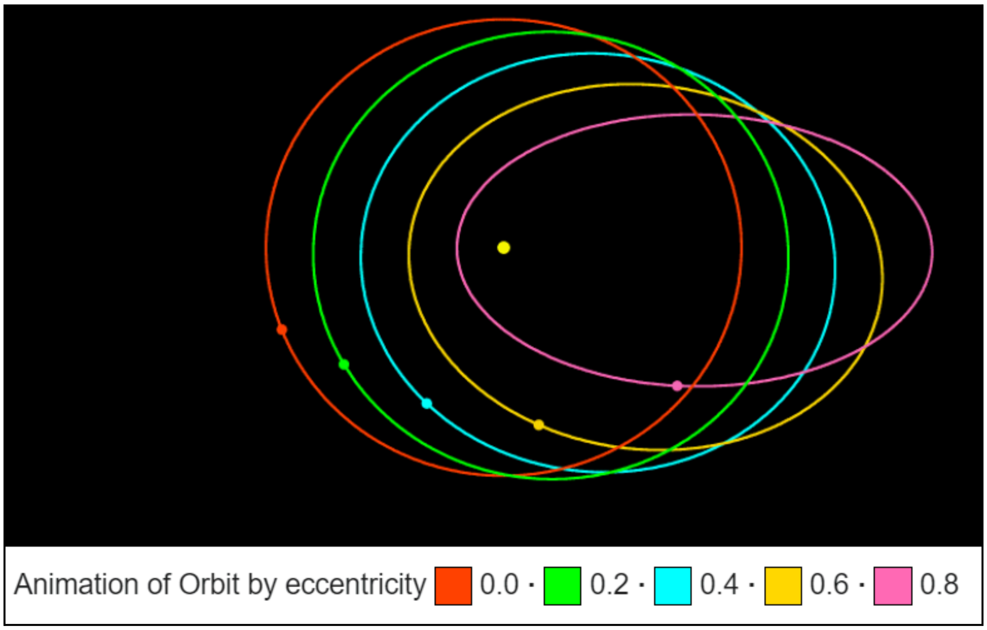

Figure 4. Example eccentricities of planetary orbits show the change in shape. [Phoenix7777/CC BY-SA 4.0]

Next, it is generally taught that Earth's axis is tilted at 23.5°. In actuality, it has varied between 22.1° and 24.5° with respect to Earth's orbital plane, as shown in **Figure 5**. This variation is called *obliquity* and varies over 41,000 years from the most extreme tilt to the least extreme and back to the most extreme. When the tilt is more inclined, seasons are more extreme because the total solar radiation received has greater variation at higher latitudes. In other words, instead of only migrating to 23.5°N latitude in the Northern Hemisphere's summer, the Sun's most direct rays would migrate even further north to 24.5°N.

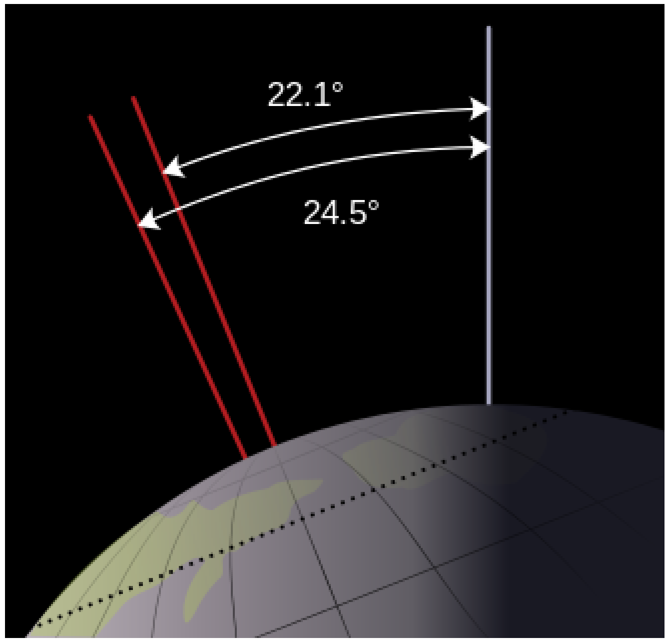

Figure 5. Earth's obliquity cycles from 22.1° to 24.5°. [Energy Education]

Finally, as Earth rotates on its axis, it wobbles slightly in a circle like an off-center, spinning top. This is due mainly to tidal forces that cause Earth to bulge at its equator. This wobble is called *axial precession* and affects the direction of Earth's tilt at various points in its orbit around the Sun as seen in this animation.

Axial precession determines whether the Northern Hemisphere or Southern Hemisphere is pointed *toward* the Sun in January when the Earth's orbit places it closest to the Sun, making seasons potentially more extreme in one hemisphere and less extreme in the other. The entire circular wobble cycle takes about 26,000 years. Currently, Earth's axis is pointed toward Polaris, the North Star, which puts the Southern Hemisphere in a tilt toward the sun at perihelion (closer to the sun) and the Northern Hemisphere tilted away from the sun at aphelion (further away from the sun). This means that solar insolation in the summertime of the Northern Hemisphere is somewhat moderated compared to other points in the Milankovitch Cycles.

Plate Tectonics

The locations of Earth's continents are crucial in determining climate. Back in 1620, Francis Bacon noticed how South America and Africa fit together like puzzle pieces. Even kids can see this before ever learning about continental drift, Alfred Wegener's 1915 theory that continents slowly moved to their current spots. The theory of continental drift was based on the shapes of South America and Africa, and similarities in rocks and fossils on different continents. The theory of continental drift later evolved into the theory of **plate tectonics**, the uniting theory of geology. Today, satellites track tiny land movements to monitor this drift. Scientists also use techniques like analyzing ancient magnetism in volcanic rocks to figure out where continents used to be.

These clues reveal that Earth's land once formed supercontinents. The first, Rodinia, formed over a billion years ago and broke apart into pieces. These separated pieces reformed into another supercontinent, Gondwana, which drifted across the South Pole around 400–300 million years ago. Gondwana then became part of Pangaea, a supercontinent that incorporated nearly all landmasses on Earth. About 200 million years ago, Pangaea began to split into continents similar to the ones we have today. **Figure 6** shows the supercontinents Rodinia, Gondwana, and Pangaea, as well as the current configuration of the continents. Pink shows land that now belongs to Africa, light blue is Antarctica, dark purple is Australia and Oceania, light purple is Eurasia, green is North America, and yellow is South America.

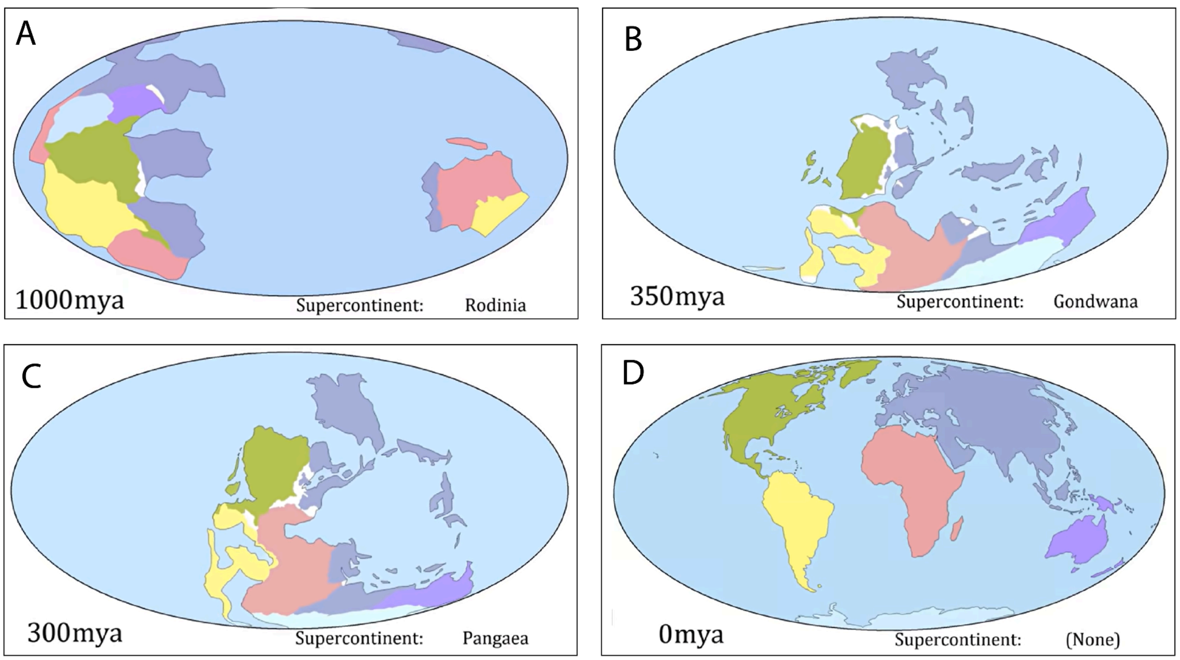

Figure 6. Supercontinents (A) Rodinia, (B) Gondwana, (C) Pangaea, and the (D) current continental configuration. [Modified from AlgolZ]

The positions of these ancient continents as they shifted over Earth's surface shaped ocean currents and set the stage for ice ages. Large landmasses near the poles, like Gondwana in the past or Russia, Canada, Greenland, and Antarctica today, allow major ice sheets to develop. But just having land near the poles isn't enough. From 250 to 50 million years ago, continents were situated near the southern pole, but there was little to no glaciation. This was likely because orbital cycles, tectonic plate configurations, atmospheric greenhouse gas concentrations, or a combination of these made the planet warmer than it is today.

Volcanoes

Volcanoes are like Earth's dramatic climatic disruptors, throwing massive amounts of ash and gases (e.g., CO_2 and SO_2) into the atmosphere when they erupt.[2] A single large eruption, like Mount Pinatubo's spectacular blast in 1991, can eject Sun-blocking particles all the way into the stratosphere. When this happens, these particles block out a portion of the sunlight from reaching Earth's surface and can cool the planet by over 1°C (1.8°F) for a year or more until gravity gradually brings them back down toward the surface. Tropical volcanoes like the ones in the Philippines (**Figure 7**) are especially effective at cooling the planet because their debris spreads easily across both hemispheres. Multiple smaller eruptions may not be as high-profile, but together they can still make a difference in Earth's climate.

Figure 7. Volcanic ash and gases rise above Mount Pinatubo, Philippines, on June 12, 1991. [USGS]

The 2013 IPCC report established that a string of minor eruptions after 2000 helped slow down the warming trend during the late 1990s into the early 2010s. Over longer time scales, volcanoes also contribute to warming by adding 0.1–0.3 metric gigatons of carbon to the atmosphere each year on average. That's a large amount but is still less

[2] Aerosols form after an eruption as SO_2 can combine with water to form sulfate aerosols.

than 1% of the current human emissions. The amount of carbon produced by volcanic eruptions is part of the natural carbon cycle on Earth and is balanced by other natural carbon sinks.

Asteroids

Asteroids sometimes make surprise appearances in Earth's climate story. Most are very minor players, but the rare giant asteroid hits Earth about once every million years. These can have effects similar to a major volcanic eruption, cooling the climate for a year or two by blasting dust and soot into the stratosphere. However, a big enough asteroid can also create an explosive wave of heat as it enters the atmosphere, setting much of Earth's vegetation on fire. These fires would release enough CO_2 to cause global warming lasting centuries, much longer than the brief cooling after the collision. This dramatic scenario happened at the end of the Triassic, around 66 million years ago, when a massive asteroid hit Earth ending the age of the dinosaurs.

This asteroid likely impacted Earth on the north end of Mexico’s Yucatán Peninsula, which is now a giant crater containing pressure-altered metamorphic rock. Iridium and other substances more common in asteroids than on Earth have been found in rocks formed during that time from all over the planet. There are also layers of coal and oil, suggesting widespread fires. More than half of all species, including most dinosaurs, are thought to have died in this natural disaster. Some surviving species may be the ancestors of today’s birds and crocodiles.

Group Review and Discussion:

1.) What are the natural processes that affect Earth’s climate?

2.) Which of these forcings could potentially have the greatest impact on climate? The least?

3.) Which of these forcings change in predictable cycles?

4.) How much do you think each of these forcings might affect cycles of cold (re: glacial) and warm (interglacial) periods?

Elaborate | Proxy Data Sources

Historical Observations

Written human records play a crucial role in paleoclimate studies, serving as valuable proxies that bridge the gap between natural archives and modern instrumental data. These records, meticulously kept in various forms such as chronicles, ship logs, agricultural records, and personal diaries, allow us to reconstruct the recent past climate regime with remarkable precision. By interrogating these narratives, we can identify patterns of climatic variability, understand the impacts of climate on human societies, and enhance our numerical models for predicting future climate scenarios. The integration of written records into paleoclimate research not only enriches our understanding of historical climate dynamics but also underscores the importance of interdisciplinary approaches in studying Earth's climatic history.

In places like Europe and Japan, these written records are like time machines, taking us back hundreds of years, often with almost daily exactitude. It’s like having a backstage pass to history, where you can see how early blooms signaled the start of spring or how certain animals moved a bit closer to the poles as temperatures shifted. For example, in Japan, the cherry blossom festivals, known as Hanami, have been celebrated for centuries, and the meticulous records of when these trees bloomed each year tell a fascinating story about climate trends over time. An example of a written record of atmospheric phenomena from the early 19th century is shown in **Figure 8**.

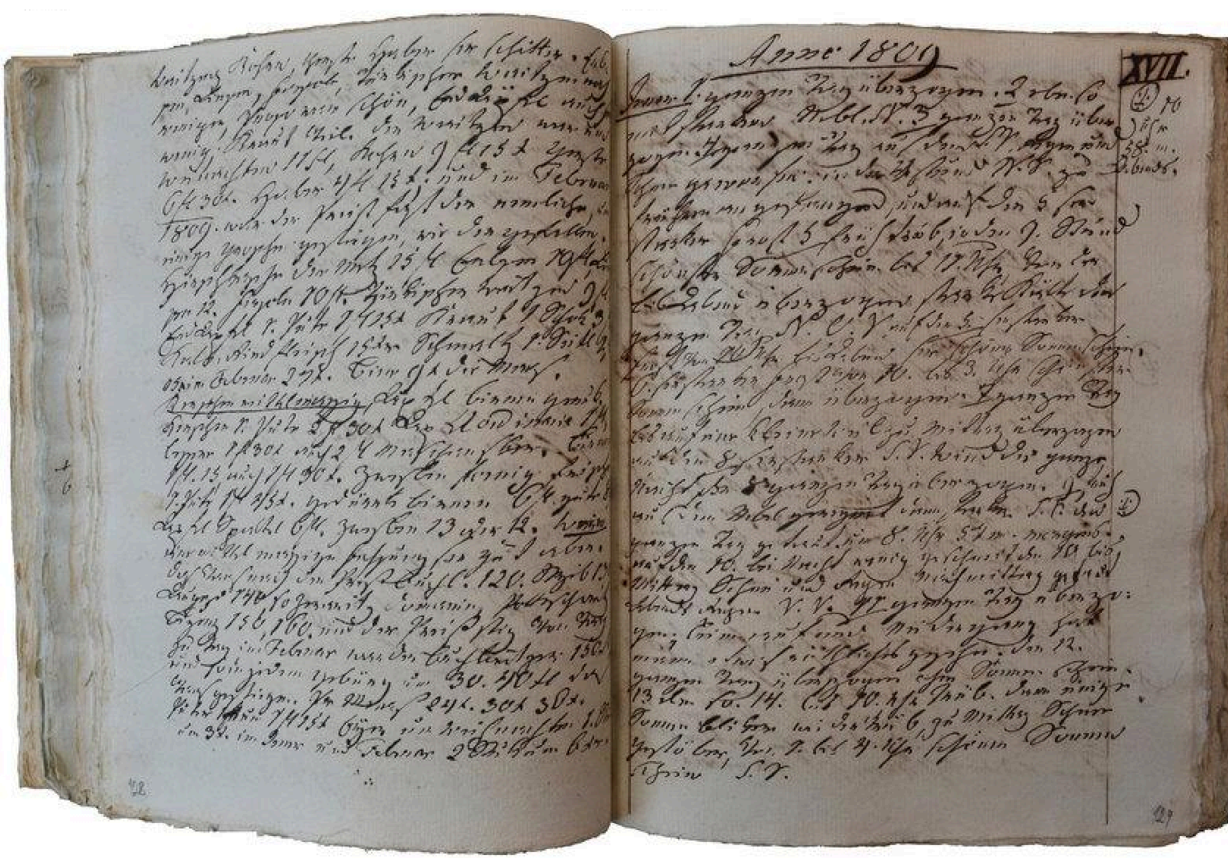

Figure 8. The climate in south-east Moravia, Czech Republic, 1803–1830, based on daily weather records kept by the Reverend Šimon Hausner. Climate of the Past. [Brázdil, R. et al., 2019]

In medieval England, monks and scholars kept detailed chronicles of weather patterns, which were crucial for agriculture and daily life. The meticulous weather diaries of the 17th-century polymath, Robert Hooke, provide insights into the Little Ice Age, a period of cooler climate that affected much of Europe. Similarly, in Japan, historical records of rice harvests, which are highly sensitive to weather conditions, offer clues about past climate variability and its impact on food security. These written records are more than just old notes; they are part of unlocking our planet's climate secrets.

The longest observed records of *global* temperature date back only to about 1850, and in many places, they are even shorter. When we have no observational data, we can use **proxy data**, which are data collected from a source that we can apply to determine another factor, often via models. For example, if we measure the amount of CO_2 in the atmosphere, then we also have indirect knowledge of whether global temperatures were warmer or cooler. The scientific study of proxy data to extract information about the past climate is called **paleoclimatology**. From this point forward in this module, we will explore the process of collecting proxy data and creating models to relate it to past climate.

1. What is a proxy data source?
    a. Direct measurements of current climate conditions
    b. Indirect evidence used to infer past climate conditions*
    c. Data collected from outer space
    d. Observations of animal behavior

Biological

Former living organisms can serve as an archival record of past climates, if appropriately studied. One specific method of investigation, **dendrochronology**, is the scientific method of dating tree rings to the exact year they were formed. This technique allows paleoclimatologists to reconstruct past climate conditions by analyzing the growth patterns of trees, which are influenced by environmental factors such as temperature and precipitation. By examining these patterns, researchers can gain insights into historical climate variations and events.

Some trees are hundreds or even thousands of years old, and their growth records the climate in which they lived. Each year, a tree grows a new ring, the thickness of which varies by the weather, especially temperature and precipitation. Spring growth is lighter in color followed by darker late-summer growth, so together, a light wood and dark wood ring record one year. During wet years, trees grow more than in dry years, producing a wider ring. If this is coupled with enough sun, that isn't too hot, the tree will grow more. Additionally, inner rings, when a sapling is growing fastest, tend to be wider than outer rings and are corrected for in studies. Variations in age and conditions make it important to gather data from many trees in a region to get a better picture of the climate.

Trees only record information about the climate during their lifetime, making tree rings a very limited source of proxy data. However, sometimes trees are fossilized, which allows scientists to investigate tree rings that are much older than any tree living today. A fossilized tree was even found in Antarctica as pictured in **Figure 9**.

Figure 9. A piece of fossilized wood from the Jurassic more than 150 million years ago. It is a very rare specimen, as only two or three other pieces of fossilized wood have been found from this era in Antarctica. The specimen was collected by a team of paleontologists based at the Allan Hills on the edge of the McMurdo Dry Valleys. [Photo by Peter Rejcek, NSF]

Counting tree rings and measuring their widths allows scientists to better understand large-scale climate changes and make conclusions about the local or regional changes in the precipitation from year to year. Computer analysis of tree rings allows for even greater precision in measurements, and paleoclimatologists can compare thousands of measurements to reveal when, where, and how quickly climate has changed in the past.

2. What can be inferred from the presence of fossilized wood in Antarctic ice?
    a. The exact location of the original tree
    b. The historical presence of forests in Antarctica
    c. The current average temperature of Antarctica
    d. The specific cause of the current Antarctic ice sheet

Corals

Brightly-colored corals grow in the warm, shallow waters of the tropics and subtropics. Made up of tiny organisms called polyps, they have a symbiotic relationship with photosynthesizing phytoplankton that nourish them. The resulting growth of corals is due to the deposition of calcium carbonate by those polyps.

Like trees, corals grow faster when there is ample sunlight and nutrients. They also add seasonal layers that appear as bands in their calcium carbonate shells. The density of these bands is visible under an X-ray, as shown in **Figure 10**. Corals are sensitive to seasonal changes, and they are sensitive to even the slightest shifts in temperature, precipitation, and water clarity. They can register these changes within a matter of months, which makes corals a uniquely responsive indicator of climate variations and environmental conditions.

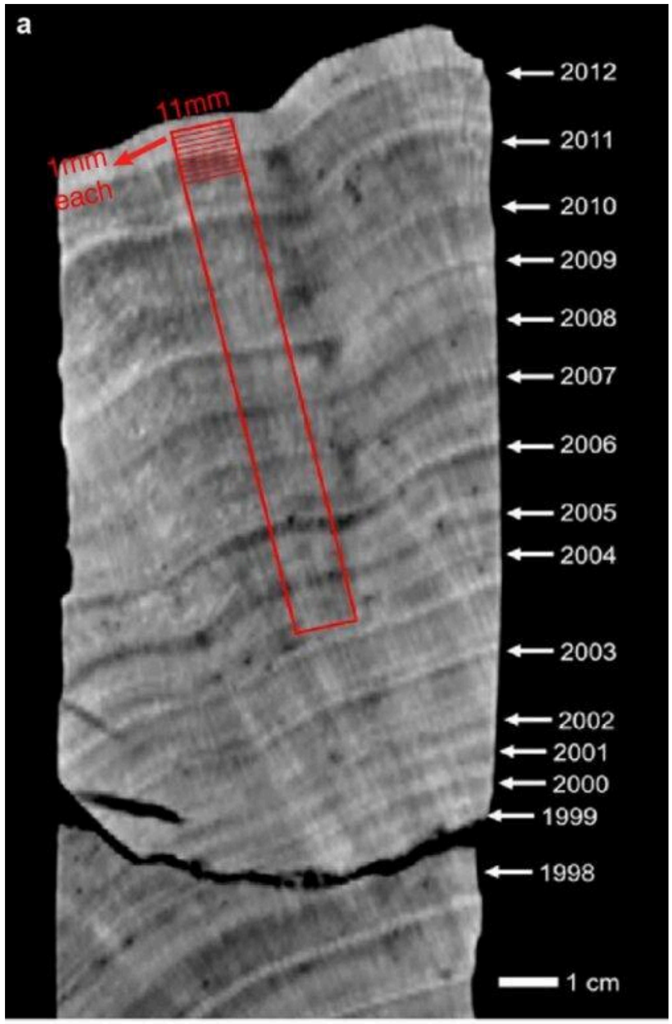

Figure 10. A CT scan cross-section of a coral core, with the oldest growth at the bottom and the surface of the coral, grown most recently, at the top. Each light and dark band coupling is a year of growth. [Chen et al., 2023]

Seasonal temperature changes create alternating bands of high- and low-density calcification. High-density, dark bands, also called *stress bands*, may occur inter-annually as a result of stress due to extreme conditions like heat or cold. Corals grow best at a water temperature between 26–27°C (78.8–80.6°F), and while some species of corals can handle temperatures outside that range, cooler or warmer temperatures inhibit new growth, creating the stress bands.

A study of Bermuda corals found that temperature is the most important factor in coral growth patterns. Warmer water temperatures increase the rate of growth until they become too warm. The coral bleaches and will die if ocean temperatures are above that temperature for too long.

The climate record found in coral is detailed but limited by temperature and ocean depth. Also, corals only live a few hundred years, which allows us to reconstruct climate in that specific timeframe, but piecing together a continuous timeline with only coral samples can be a challenge.

3. Corals and trees both record the climate at what temporal resolution?
    a. Daily
    b. Monthly
    c. Seasonal
    d. Decadal

Other Biological Proxy Records

The ocean is a trove of proxy climate records. In addition to corals, ocean sediments contain the remnants of carbonate shells built by Coccolithophores, a group of microscopic planktonic organisms the size of a grain of sand, including bottom-dwelling foraminifera. The quantity, composition, and type of these shells can reveal a great deal about the amount of carbon or other elements that the ocean contains at various points in time.

Diatoms, microscopic algae with silica shells, are another particularly valuable climate proxy source. These tiny organisms reside in almost all aquatic habitats and are sensitive to changes in water temperature, pH, and nutrient levels, making their fossilized remains excellent indicators of past climatic conditions. For example, scientists can infer historical changes in lake conditions and regional climates by analyzing the species composition and abundance of diatom fossils in lake sediments.

Other fossils found in water environments also contribute to our understanding of past climates. Plant fossils, such as pollen grains and leaf imprints, reveal information about historical vegetation and, by extension, the climate conditions that supported them. Insect fossils, including those of beetles and mosquitoes, offer clues about past temperatures and moisture levels, as different species thrive in specific climatic conditions. Animal fossils, like those of amphibians and fish, further complement this data by indicating the past water temperatures and ecological conditions of the lakes they inhabited.

By comparing and integrating these diverse fossil records, paleoclimatologists can construct a comprehensive picture of past climatic changes, providing valuable insights into how Earth's climate has evolved over time.

Cryological

Ice cores provide a continuous record that goes back 740,000 years in Antarctica and 130,000 years in Greenland. These ice cores like the one shown in **Figure 11** are an important source of information about past climate changes because they provide high-resolution direct measurements of gas concentrations and chemical compositions from the ancient atmosphere. Nowhere on Earth is there a larger resource for direct measurements of past atmospheric gas concentrations as in the polar ice sheets.

Figure 11. An ice core can reveal a great deal about the prior climate. The bubbles in ice are trapped atmospheric gases that will be sent to various laboratories for analysis. These samples are from Beacon Valley, Dry Valleys, Antarctica. [Photo by Jacquelyn Hams (PolarTREC 2008), Courtesy of ARCUS]

In addition to samples of the past atmosphere, ice cores also contain ancient water, volcanic ash, and dust. These many sources of information in one location make ice cores the gold standard of proxy climate data.

Ice cores also contain stable isotopes like oxygen-18, or ^{18}O, which offer another source of information about past climates. Isotopes are a form of the same element that contains the same number of protons and electrons, but a different number of neutrons, hence they have different mass numbers (e.g., 16 and 18). ^{18}O is heavier than regular oxygen, so it condenses more easily and evaporates more slowly. In ice cores, the ratio of ^{18}O to regular oxygen (^{16}O) helps reveal ancient temperatures, seasonal changes, and glacial cycles. The discussion of isotopes will be addressed in much greater detail in succeeding modules of this course.

4. What do ice cores provide scientists with that other climate proxy data sources do not?
    a. Records of regional solar energy and precipitation
    b. Measurements of past atmospheric gas concentrations
    c. Details of planetary and celestial movements
    d. Records of past plant and animal life

Geological

The rock record also records information about the past climate. Rocks, particularly sedimentary rocks, tell the story of how conditions and landscapes changed in that location. These records include information about changes in climate, biology, and even the location of the continents. There are often distinct markers of catastrophic events like a large asteroid hitting Earth or ash deposits from an especially large volcanic eruption. These layers allow scientists to correlate sedimentary sections from across a region and sometimes the world.

Three types of sedimentary rocks—clastic, chemical, and organic, record different information about regional environmental conditions.

Clastic sedimentary rocks are made of pieces of other rocks that are cemented together. The properties of these fragments or clasts can tell us about both the source rocks and the conditions under which they were deposited. Sediments are deposited in basins, comparatively low areas, such as oceans and lakes. The oldest sediments are deposited at the bottom of the sediment record with more recent sediments piled on top (**Figure 12**). Other elements like organisms and pollen are included in sedimentary rocks that can tell us about the plant and animal life during that time. Fossils of certain plants and animals, index fossils, can help correlate the age of sedimentary rocks formed during that time period.

Figure 12. A sedimentary cross-section has older sediments and fossils at the bottom of the section and younger ones at the top. [James St. John/CC BY 2.0]

Glaciers form distinctive sediments that are either of many mixed sizes or very fine dust. They also create specific geographical features and scrape existing rocks in recognizable ways. These traces help scientists to determine when there were glacial periods and how extensive the glaciers were.

Chemical sedimentary rocks result from chemical reactions that precipitate solids out of a solution. Limestone is formed in warm, shallow waters and often includes shells of phytoplanktonic organisms, such as foraminifera and diatoms, that can tell us about the composition of the water that they lived in. Formations in caves (e.g., stalagmites and stalactites) are a special case of chemical sedimentary rocks that form layers over a long period that record the conditions in which they were formed.

Organic sedimentary rocks like coal tell scientists where and when there were large, highly productive regions such as rainforests or peat bogs. They can also be formed during a mass extinction event, like the end of the Jurassic period.

To turn sediments into sedimentary rocks, they must experience very high pressures to compress and cement the clasts and layers together. This occurs deep underground as the sediments are buried. We only get to see sedimentary rocks long after they were formed as the material above them is eroded away, and the rocks are located at or near the surface. In some places like ocean and lake bottoms, scientists core the sediments before they are compressed into rock providing a much more recent sedimentary record.

5. Scientists can tell how old a sedimentary rock is based on its position compared to other layers. What cannot be found using this method?
    a. The actual time the rock was formed
    b. The source of the clasts
    c. How that rock compares to rocks in other locations
    d. All of the above

Absolute Dating

In the 1950s, a revolution in paleoclimatology began. Radiometric dating using unstable isotopes of different elements provided a way to determine the absolute age of paleoclimatic proxies with high precision, transforming our understanding of Earth's history. These "benchmarks" provide a timestamp for when a particular proxy record was formed, enabling the reconstruction of Earth's climate history with much more certainty far beyond the reach of historical observations. By dating the chemical elements in rocks and fossils, radiometric dating helps scientists identify and understand the timing and sequence of events that drove climate changes in the past.

So, how do scientists extrapolate these benchmarks? Elements like carbon and uranium have different forms, or isotopes, with varying numbers of neutrons. Some isotopes are unstable and decay over time at predictable rates. There are many unstable isotopes, but three are particularly useful for paleoclimatology: Carbon-14, Uranium-235, and Uranium-238.

The unstable isotope carbon-14, or ^{14}C, is formed when cosmic rays in the upper atmosphere collide with an atom of nitrogen turning it into ^{14}C.[3] That ^{14}C is then pulled into the rest of the atmosphere by gravity and is often absorbed by living things through photosynthesis and then through the food chain. When these organisms die, ^{14}C starts

[3] This process of shattering a nucleus into smaller pieces, including neutrons is called *spallation*.

to decay back into nitrogen at a known rate. After about 5700 years, half of the ^{14}C will have decayed—this is its half-life. Scientists can determine the age of a deceased or fossilized organism by measuring the remaining ^{14}C. This method provides a means of dating things up to about 50,000 years old, like ancient air bubbles in ice cores, marine shells, or relatively recent fossils.

Another element with unstable isotopes is uranium, which has a much longer half-life than ^{14}C making it very useful for long-term dating. Uranium-235 has a half-life of 700 million years, while uranium-238 has a half-life of a whopping 4.5 billion years—the age of Earth itself! Uranium-235 and uranium-238 atoms decay to thorium by ejecting 2 neutrons and 2 protons as shown in **Figure 13**. Scientists measure the concentrations of these isotopes and their daughter elements to date rocks and older fossils through mass spectrometry.

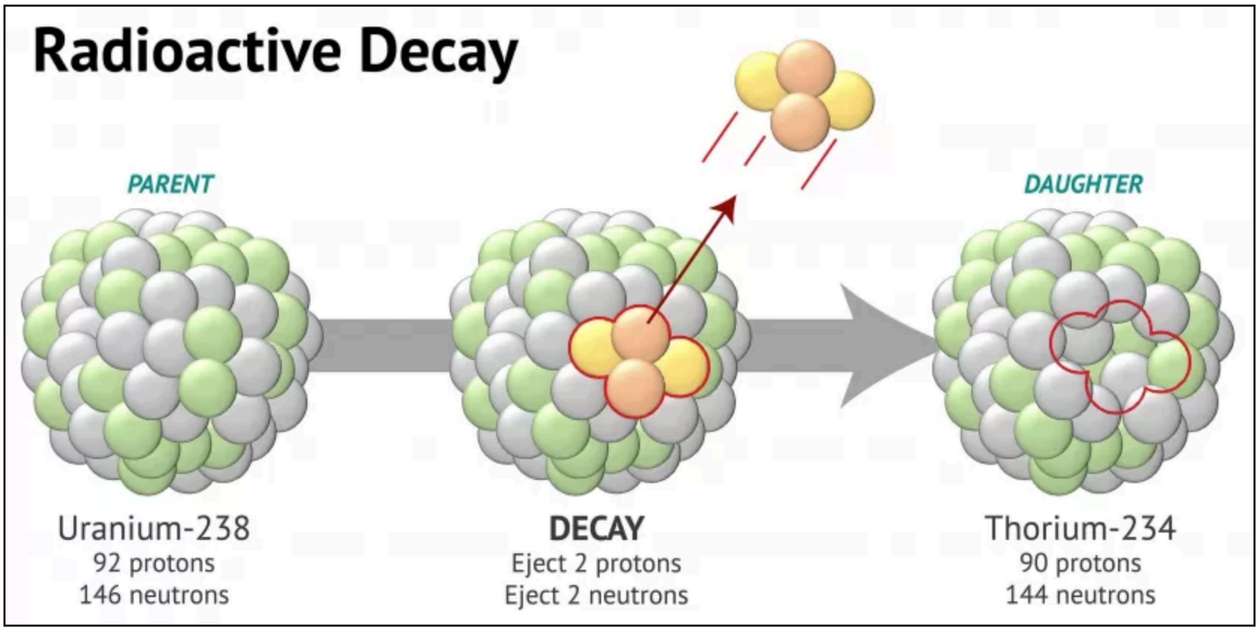

Figure 13. Uranium-238 decays radioactively to thorium-234 by ejecting a particle containing 2 protons and 2 neutrons. [Human Origins Program, NMNH, Smithsonian Institution]

Of course, no technique is perfect. Sometimes, contamination from other materials can change the concentrations of the elements used in radiometric dating. Testing multiple samples from different locations helps to minimize errors.

6. A sedimentary rock is found to be between 500 and 600 million years old based on fossils around it. Which unstable isotope would be most appropriate for determining its age more precisely?
    a. Carbon-14
    b. Uranium-235
    c. Uranium-238

Computer Modeling

Numerical modeling techniques are essential tools in incorporating and extrapolating the data from proxy sources. Scientists have created models to predict future climate based on current data. To test these models, scientists have them recreate the climate conditions for the last century for which we have historical information. Versions of these models are also used to reconstruct past climate using proxy data. Models certainly have limitations and aren't the primary tool for paleoclimatologists, but they're a critical part of the toolkit.

Another helpful attribute of modeling is to see how well these models handle the changes we see every year. For example, the seasonal cycle in the midlatitudes (the areas between the tropics and polar regions) serves as a mini-version of long-term climate shifts. If our models can identify these seasonal transitions, it's a good sign they're on the right track.

When it comes to prehistoric times, it's a bit trickier. We don't have as much data to check against—no ancient weather stations, unfortunately. But even here, simpler models can still be very helpful. They allow scientists to explore what kinds of ancient climates might have been possible, even if we can't know all the details.

Figure 14 identifies some critical concepts used in climate models. Each of the thousands of 3-dimensional grid cells can be represented by mathematical equations that describe the constituents in that sample area and the way energy moves through it. The advanced equations are based on the fundamental laws of physics, fluid mechanics, and chemistry. To "run" a model, scientists specify the climate forcing (for instance, setting variables to represent the amount of greenhouse gases in the atmosphere) and have supercomputers solve the equations in each cell. Results from each grid cell are passed to neighboring cells, and the equations are solved again. Repeating the process through many time steps represents the passage of time.

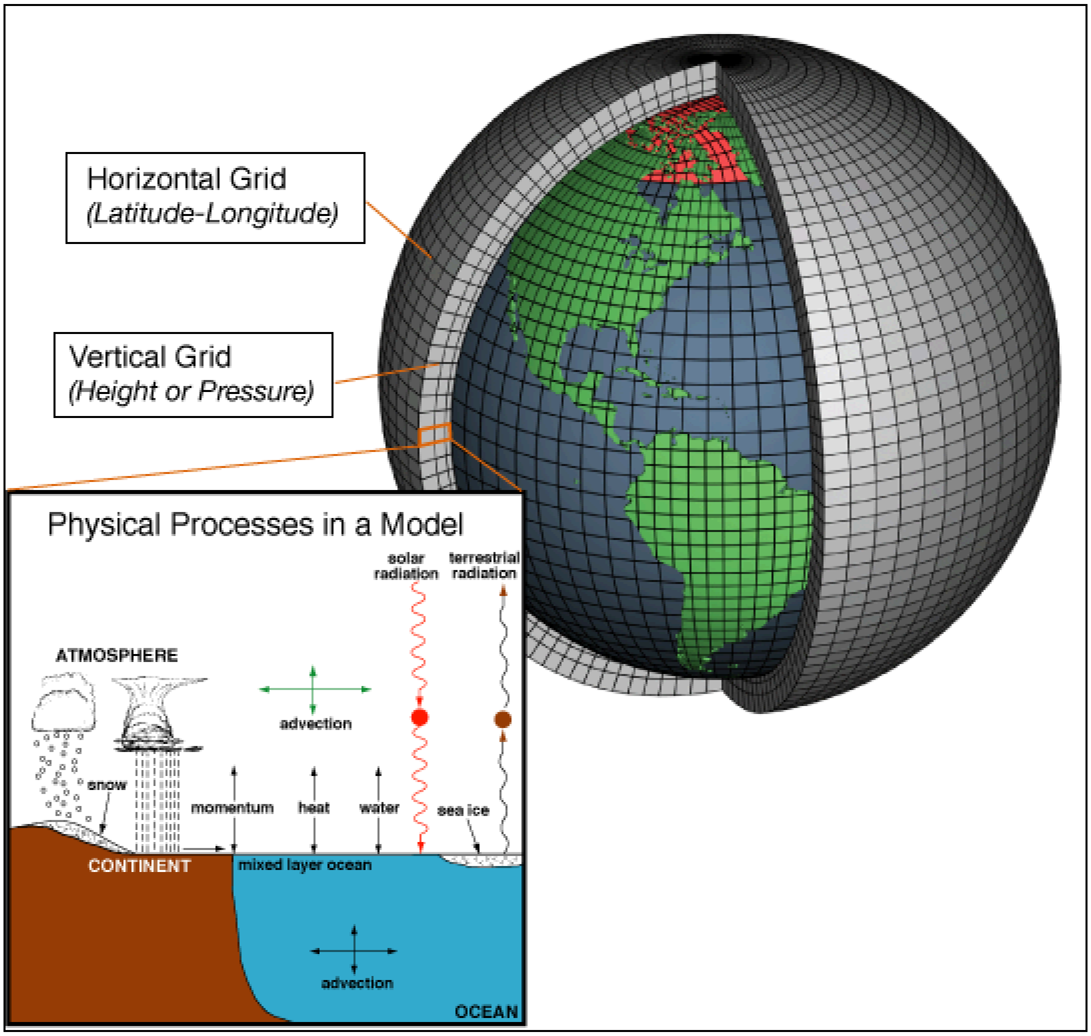

Figure 14. A complex temporal and spatial model can be used to determine possible past and future climates based on multiple physical processes and corresponding equations. [NOAA]

Conclusions

Paleoclimatologists have found with increasing certainty that greenhouse gas concentrations are intimately linked with the rise and fall of global temperature. Ice cores and other records confirm this strong linkage over the last million years, and there is no reason to think it should not be a consistent pattern. Because CO_2 changes are so closely coupled in time to the growth and decay of ice sheets, it is hard to tell exactly which came first and when. Sorting out these chains of events and patterns is *the job of a paleoclimatologist*.

Studies of past climate and the circumstances that allowed humans to populate the planet allow us to understand two paradoxical realities: A tipping point of possible societal debasement may be at hand. We also know enough about Earth's past climate patterns to rebalance Earth's climate. This knowledge is based on known and extrapolated information as well as understanding uncertainties in research and scientific investigations.

The clues paleoclimatologists uncover and the answers they portend aren't always clear, but we must embrace this nuance, keep an open mind to new findings, and allow better understanding and knowledge gained to further inform policy and potential solutions. To do these things, we need to appreciate the complexity of what the proxy markers in paleoclimate tell us. One very clear and important message from what we have learned so far is that changes in climate are often extremely abrupt, and often intense and rapid over geologic time.

In addition, analogs of the past must be carefully considered and reviewed. One important reason is because past climate was influenced by the differing location of the continents. In other words, 200 million years ago the continents were not oriented the way they are today. Even 10 million years ago India had not yet connected to Eurasia and North and South America were not yet joined. These features alone have massive implications for oceanic circulation patterns.

Digital media and popular "influencers" tend to portray science as "never getting it right," but this is a skewed view of scientific principles. Dire headlines portend doomsday glaciers melting. The nuance is *much more* complex and a bit more hopeful. The answer lies with us and our actions. But we must make informed decisions, using the best science, and robust data sets. The climate history of our planet gives us ample evidence about past climate changes. We are lucky to live in a time when technology allows us to have the ability to deduce clues from our paleoclimatic records.

Evaluate | Paleoclimatology

To review what has been presented and investigated during this module:

7. What is paleoclimatology?
    a. The study of ancient human civilizations
    b. The study of Earth's past climates
    c. The study of fossils
    d. The study of ocean currents

8. Which gas below had a strong role in enhancing the greenhouse effect of Earth's early climate history?
    a. Oxygen
    b. Nitrogen
    c. Carbon dioxide
    d. Argon
9. What is the 'Faint Young Sun Paradox'?
    a. The theory that the Sun was much hotter & brighter in its early days
    b. The hypothesis that early Earth was cold and uninhabitable
    c. The idea that the Sun has always been at its current strength
    d. The observation that early Earth was warm despite the Sun being weaker
10. What is the significance of the Keeling Curve?
    a. It shows the historical temperature fluctuations
    b. It records daily atmospheric CO_2 concentrations since 1958
    c. It tracks the growth rate of trees
    d. It measures sea level changes
11. What are Milankovitch Cycles?
    a. Variations in the Earth's orbit that can affect climate
    b. Changes in solar radiation due to sunspot activity
    c. Cycles of volcanic eruptions
    d. Fluctuations in ocean currents
12. What does the term 'eccentricity' refer to in the context of Earth's orbit?
    a. The shape of Earth's orbit around the Sun
    b. The wobble in Earth's rotation
    c. The tilt of Earth's axis
    d. The intensity of solar radiation
13. Which process is described by the chemical breakdown of rocks and the removal of CO_2 from the atmosphere?
    a. Photosynthesis
    b. Respiration
    c. Chemical weathering
    d. Combustion
14. What proxy does dendrochronology study?
    a. Coral growth patterns
    b. Ice core layers
    c. Tree ring data
    d. Sedimentary and igneous rock formations

15. Which of these elements' isotopes below are commonly used in radiometric dating to determine the age of ancient samples?
    a. Hydrogen
    b. Oxygen
    c. Carbon
    d. Nitrogen
16. What role do volcanic eruptions play in a changing change?
    a. They have little to no effect on climate
    b. They only warm the planet
    c. They have the potential to both cool and warm the planet
    d. They only cool the planet
17. What is the primary cause of seasonal variations on Earth?
    a. Changes in Earth's distance from the sun
    b. Variations in solar radiation intensity
    c. Changes in ocean currents
    d. The tilt of Earth's axis
18. What is one effect of increased atmospheric CO_2 levels?
    a. Decreased plant growth
    b. Stabilized climate conditions
    c. Enhanced greenhouse effect
    d. Reduced solar radiation
19. How do corals serve as a climate proxy?
    a. By recording temperature and ocean conditions in their growth layers
    b. By trapping air bubbles in their structure
    c. By storing atmospheric dust
    d. By measuring the salinity of ocean water
20. What is axial precession?
    a. The variation in the tilt of Earth's axis
    b. The wobble in Earth's rotational axis
    c. The elliptical shape of Earth's orbit
    d. The distance between Earth and the sun
21. Which event is associated with a dramatic climate shift caused by an asteroid impact?
    a. The rise of the Himalayan Mountains
    b. The extinction of the dinosaurs
    c. The Little Ice Age
    d. The formation of Pangaea

22. What substance below is Uranium-235 primarily used as a dating method?
    a. Plants and animals
    b. Fossils
    c. Very old rocks
    d. Recent volcanic ash
23. Why is it important to study past climates?
    a. To understand natural climate variability
    b. To predict future climate scenarios
    c. To distinguish between natural and human-induced changes
    d. All of the above