AMERICAN METEOROLOGICAL SOCIETY:

A COLDEX Center for Oldest Ice Exploration PARTNER

Project Ice

Ice Core Analysis and 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:

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Figure i. The bottom of an ice core drilled in Alaska shows pebbles and dingy ice, indicating the presence of nearby bedrock. [Photo by Mike Waszkiewcz]

“The paleoclimate record shouts to us that, far from being self-stabilizing, the Earth's climate system is an ornery beast which overreacts even to small nudges.”

Wallace “Wally” Broecker, Geochemist (1931-2019)

"Nothing in life is to be feared. It is only to be understood. Now is the time to understand more, so that we may fear less."

Marie Curie, Physicist (1867-1934)

Module: Ice Core Analysis and Paleoclimatology
Instructor: Project Ice Instructor or Project Ice Graduate
Audience/Grade Level: K-12 Educators

STANDARDS:

[Project Ice Objectives]
Understanding Climate Change and Paleoclimate:

6. Analyze the evidence of past atmospheric composition and climate evolution preserved in ice sheets
7. Examine the components and dynamics of Earth's climate system at local, regional, hemispheric, and global scales.
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.
11. Compare historical CO_2 levels with contemporary levels to assess the impact of human activities on atmospheric CO_2 concentrations.

Studying Ice Dynamics and Glacial History:

6. Examine evidence from ice cores to evaluate the natural variability in ice, ocean, and atmospheric dynamics.

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

2. Climate is regulated by complex interactions among components of the Earth system. (c, f)
4. Climate varies over space and time through both natural and man-made processes. (a, d, e, f, g)
5. Our understanding of the climate system is improved through observations, theoretical studies, and modeling. (a, b, c, d)

Next Generation Science Standards

Performance Expectations

- 2-ESS1-1. Use information from several sources to provide evidence that Earth events can occur quickly or slowly.
- 5-ESS2-1. Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.
- 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-ESS2-4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.
- 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-ESS2-5. Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes.

Science and Engineering Practices

1. Asking Questions and Defining Problems
2. Developing and Using Models
3. Planning and Carrying Out Investigations
4. Analyzing and Interpreting Data

Disciplinary Core Ideas

- 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
- ESS3.C: Human Impacts on Earth Systems

Crosscutting Concepts

1. Patterns
2. Cause and Effect
4. Systems and System Models
5. Energy and Matter
7. Stability and Change

Engage | Why do we focus on climate?

As the American author Mark Twain said, “Climate is what you expect, weather is what you get.” Climate has been historically defined as the average of weather plus information on extremes at a particular location over a period of time. Now, it characterizes the overall condition of Earth’s climate system, composed of the atmosphere, hydrosphere (including the cryosphere, the frozen water portion of Earth), lithosphere, and biosphere, resulting from internal and external influences, mutual interactions, and feedbacks.

Climate change is the systemic change in climate elements sustained over several decades or more and can be caused by natural external forcings, human-caused forcings, or natural internal processes. Climate is inherently variable but is currently changing at rates unprecedented in recent Earth history, due to fossil fuel burning and altering of Earth’s surface characteristics. In this module, we are focusing on using ice cores to identify changing conditions in Earth’s past climate, or paleoclimate. Studying past changes helps scientists discern the climate system's response to current and future changes.

Ice cores allow us to make either direct or proxy measurements of the atmosphere’s temperature, composition, precipitation, and wind patterns on regional and global scales. These measurements help us understand changing interactions between terrestrial, marine, cryospheric (pertaining to snow and ice-covered regions), and atmospheric systems. **Figure 1** is a cut plan for an ice core. After the ice cores are cut, each ice sample will be sent to a scientific laboratory for chemical and physical measurements. In this way, scientists collaborate by making individual measurements that then contribute to the overall understanding of paleoclimatology.

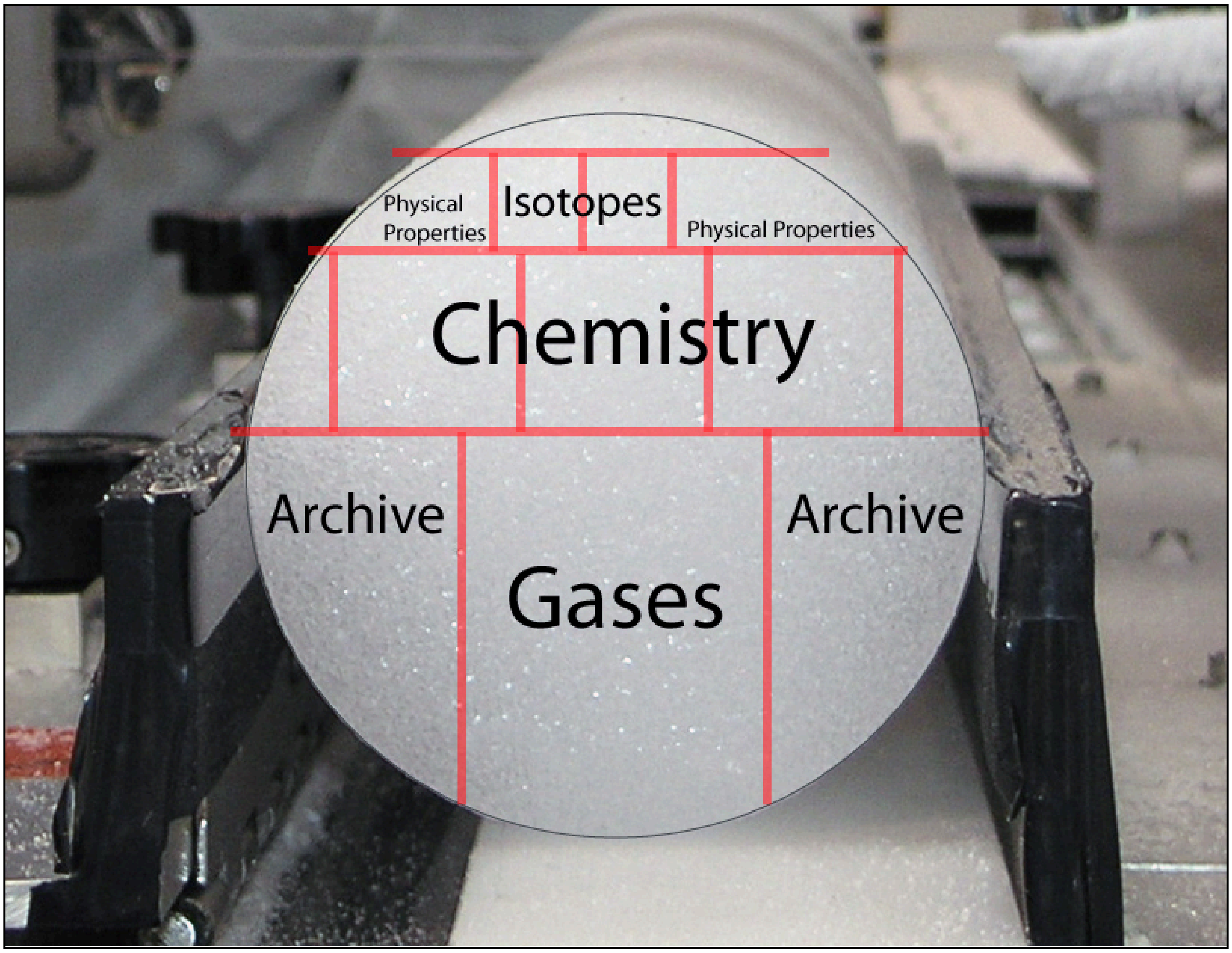

Figure 1. Cut plan of an ice core with labels to identify the analysis each section of ice core will undergo. The archive pieces are also set aside and stored for future research. [NSF-ICF]

In this module, we will learn how scientists analyze ice cores and as well as what the measurements tell us about Earth's climate history. We examine how a better understanding of paleoclimate helps us predict our future climate and even look at human impacts seen in the ice core record.

Group Review and Discussion:

1.) What does Earth's climate system encompass?

2.) What is climate change?

3.) Has the Earth's climate remained constant over time?

4.) What were the major controls of Earth's climate before human impacts?

Explore | The paleoclimate record from ice cores

The NSF-supported Center for Oldest Ice Exploration (COLDEX) has nine analytical labs across the United States, each with its own specialized procedures and equipment to analyze different properties of the ice. **Figure 2** displays the results of ice core analysis for carbon dioxide, methane, and dust, all direct measurements from the ice itself, from the air bubbles, or the dust trapped in the ice, while temperature is calculated from proxy data. These measurements are similar to the ones currently being conducted on COLDEX-drilled ice cores. The variables shown in Figure 2 are strongly correlated with one another. The age of the samples extends from 800,000 years, on the left of the horizontal axis, to today, on the right. Each property reveals details of Earth's climate over the past 800,000 years.

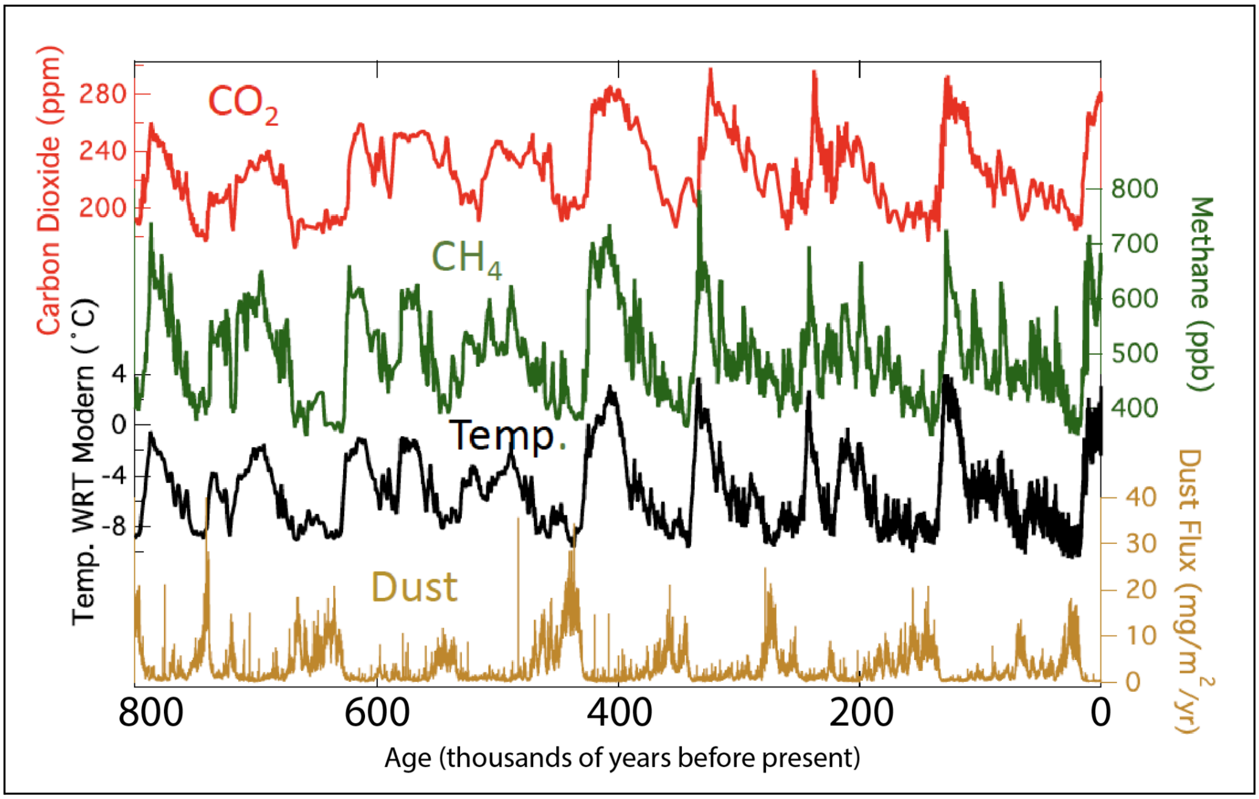

Figure 2. A record of paleoclimate data recovered from ice cores over the past 800,000 years: carbon dioxide concentration (parts per million, ppm), methane concentration (parts per billion, ppb), dust flux (milligrams of dust per square meters per year), and temperature with respect to (WRT) modern temperature. [Adapted from Bereiter et al., 2015; Loulergue et al., 2008; Lambert et al., 2008; Jouzel et al., 2007]

While Figure 2 extends back 800,000 years, COLDEX intends to extend that continuous record back to 1.5 million years and find individual samples of ice that are up to 5 million years old. As described in the *Ice Core Science and Engineering* (#4) module, these older ice samples can be folded up into younger layers.

Data in Figure 2 allows us to find patterns for the variables across 800,000 years of Earth's history. An individual variable (such as CO_2 concentration) can either be positively or negatively correlated to another variable (such as temperature). *Positively correlated* variables change in similar directions over time while *negatively correlated* variables change in opposite directions over time.

Group Review and Discussion:

1.) Pick one of the variables in Figure 2. Why do you think scientists want to measure this variable in ice cores?

2.) Which variables are positively correlated over the 800,000-year ice core record?

3.) Which variables are negatively correlated over the 800,000-year ice core record?

4.) What is the approximate range of CO_2 concentrations (given in parts per million, or ppm) over the 800,000 years of the ice core record?

5.) How have paleoclimate records from ice cores contributed to our understanding of paleoclimate and climate change?

***Explain* | Ice core analysis and paleoclimate**

Positively correlated variables in the paleoclimate record help us draw conclusions about how different aspects of the climate system interact with each other. For example, in Figure 2, the concentration of the two greenhouse gases, carbon dioxide (CO_2) and methane (CH_4), increase and decrease along with temperature. Meanwhile, the dust flux, or change in dust concentration over time, is negatively correlated with temperature. Dust, as well as volcanic ash, in ice cores provides information about the complex nature of the climate system.

The processes in past climate systems resulting in these positive or negative correlations and the speed of the changes they cause are highly complex topics, and the details are still debated among climatologists. However, understanding the basics is important to understanding how anthropogenic greenhouse gas concentrations play a role in our warming climate today.

Air bubbles in ice cores

An ice sheet grows when there is more snowfall than ice melt. Older snow that has not melted for at least one year after it first fell is called **firn**. In order for firn to become ice, there has to be enough force from snow above the layer to compress the firn. Over time, snow is compressed and forms ice, and the air spaces between individual flakes are preserved, along with atmospheric dust, volcanic ash, and everything else in the snow. In glaciers with high rates of snow accumulation, such as those on mountains in more temperate climates, firn can take as little as a few years to turn into ice. In Antarctica, the climate is exceptionally dry, and firn can take 100–300 years to turn into ice at depths of up to approximately 80 m (262.5 ft.) below the surface of the ice sheet.

As firn is formed and ice sheets expand, air bubbles are encapsulated in the ice at the *firn-ice transition zone*, where snow is compressed until there is no open pore space between crystals. This is an extremely important process as the air in this zone no longer interacts with atmospheric air, creating a protected capsule of ancient air. The depth at which the air bubbles are closed off is called the *bubble closeoff zone* (**Figure 4**). The bubble closeoff zone can be large—the Vostok ice core from Antarctica has a bubble closeoff zone that is about 8 meters thick, comprising about 300 years of ice within the record. Because the bubbles are isolated after the snow falls, the air sample in the bubble is younger than the ice it is surrounded by. Ice core scientists must account for this difference in age when reporting the concentration of gases in the air bubbles.

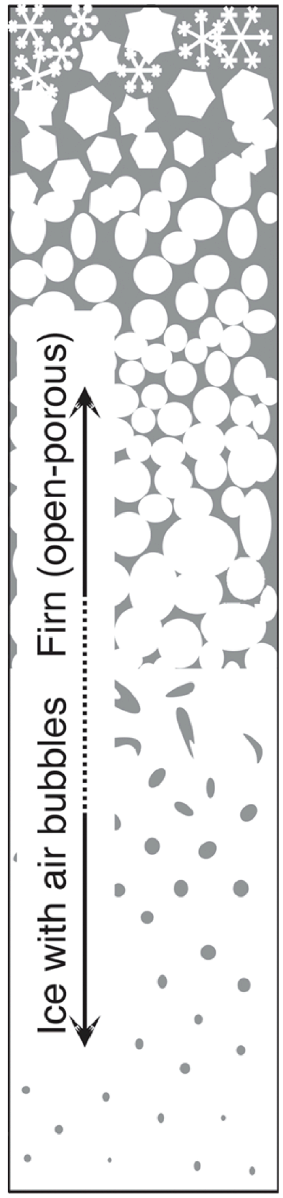

Figure 4. The transition from snow at the top to firn to ice near the bottom, showing the change from open pore spaces in the snow and firn to closed-off air bubbles in the ice as it is compressed. The dashed part of the arrow in the firn-ice transition zone represents the bubble closeoff zone. [Modified from Schüpbach et al., 2016.]

Ice core dating

Scientists use various techniques to date ice cores based on their depth and characteristics. Techniques include relative dating (including layer counting), isotope analysis, radiometric dating, and the use of volcanic events or other chronological markers. Counting annual layers is most practical in more recent ice and is only possible when the snow accumulation rate is at least 4 cm (1.6 in.) per year. A year is made up of both summer snow layers, which are less dense and lighter in color, and winter snow layers, which are denser and darker in color. As snow accumulates on top, the yearly layers are compressed and become indistinguishable as individual layers at a certain depth in the core. This is why additional methods are needed to date most ice cores.

Measuring the gases in ice core bubbles

Chemically analyzing the gases in ice core bubbles is a primary goal of COLDEX. Bubbles in ice cores provide direct samples of air from the time the bubble was encapsulated in the ice. Individual air bubbles are small, and bubbles comprise about 10% of the volume of an ice core. The gases that are trapped in the bubbles when firn becomes ice include oxygen (O_2), nitrogen (N_2), argon (Ar), carbon dioxide (CO_2), and methane (CH_4). Some of these gases shed light on Earth's past climates.

There are two types of measurements made on the gases in ice core bubbles: the gas's concentration and the gas's isotope composition. The **concentration** of a gas tells us the relative proportion of that gas within the atmosphere. For example, the concentration of carbon dioxide has varied from around 170 parts per million (ppm) to 300 ppm in the ice core record. This means that, for every million parts or units of a solution (in this case, the gas molecules in the sample), 170 to 300 of them were carbon dioxide molecules.

Scientists are particularly interested in how the concentration of greenhouse gases in the atmosphere has changed over Earth's history. Greenhouse gases, including CO_2, CH_4, and nitrous oxide (N_2O), absorb infrared energy (heat) and warm the planet. Burning of fossil fuels and other human activities have resulted in an excess of greenhouse gases in the atmosphere. We can point to these activities as the cause of global warming today, but what were greenhouse gas concentrations before human activities? **Figure 5** shows the CO_2 and CH_4 concentrations for the past 800,000 years.

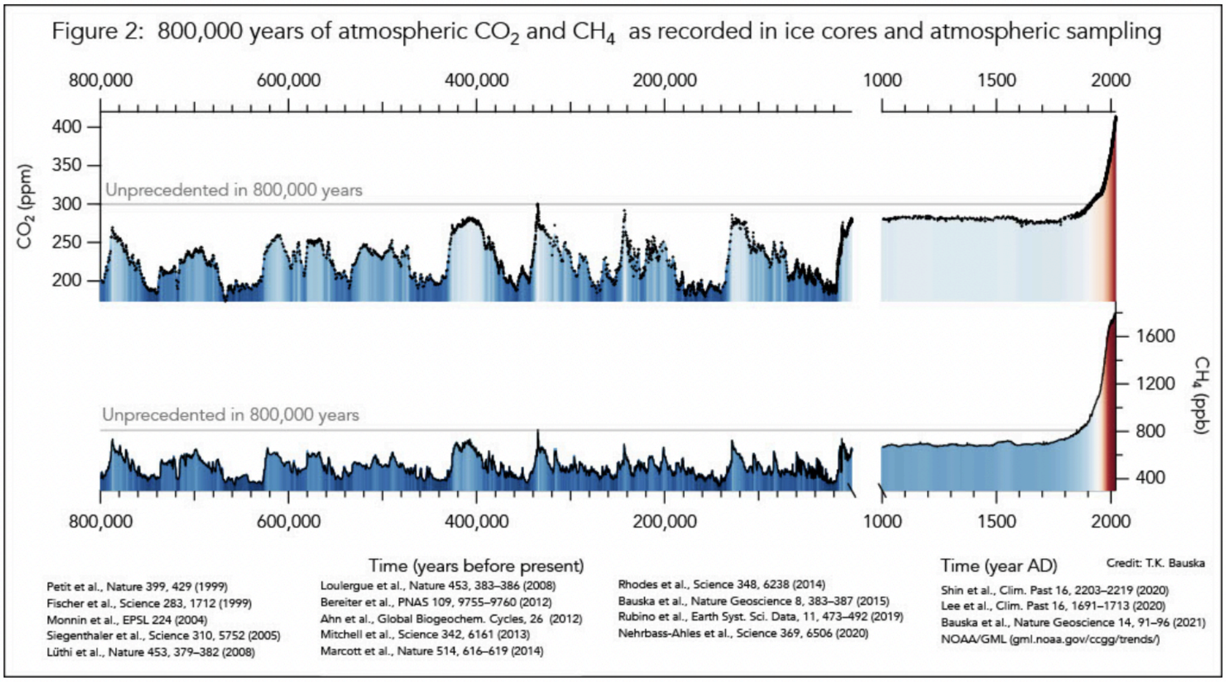

Figure 5. CO_2 and CH_4 measured in ice core bubbles show that cycles of higher and lower concentrations are normal over the past 800,000 years of Earth's history. [The British Antarctic Survey]

Figure 5 shows the changes in CO_2 and CH_4 concentrations over time based on the ice core record and instrumental measurements. Notice that never during the 800,000 year record have the concentrations of atmospheric CO_2 or CH_4 approached the concentrations we see today, 427 parts per million (ppm) of CO_2 as of April 2024 and 1932 parts per billion (ppb) of CH_4 as of December 2023 (NASA Vital Signs). This shows us that the current CO_2 and CH_4 concentrations are outside the range of normal, cyclical values characterizing Earth's past atmosphere. Human activities began more significantly impacting the Earth's climate in the late 19th century during the Industrial Revolution. However, what caused the cyclical changes in CO_2 and CH_4 concentrations before that?

Carbon Isotopes

Using highly sensitive mass spectrometers, scientists can measure the proportion of isotopes making up the gas in ice core bubbles. **Isotopes** are atoms of the same element that have different numbers of neutrons in their nucleus. This results in small differences in the mass of these atoms, which can be measured. For example, carbon has three isotopes: carbon-12 (6 protons, 6 neutrons), carbon-13 (6 protons, 7 neutrons), and carbon-14 (6 protons, 8 neutrons), notated as ^{12}C, ^{13}C, and ^{14}C. ^{12}C and ^{13}C are stable isotopes of carbon, meaning these atoms will not decay and form different elements over time. ^{14}C is the radioactive isotope of carbon: over time, ^{14}C

decays into nitrogen-14 (^{14}N) and is the basis of radiocarbon dating. There are many carbon sources, which produce more carbon than they absorb, and sinks, which absorb more carbon than they produce. Each of these sinks and sources preferentially absorbs or produces a specific ratio of the stable carbon isotopes. This allows scientists to use isotopes to identify the balance of sources and sinks present on Earth when the ice core bubble becomes encapsulated in the ice.

Scientists compare the ratio of $^{13}C/^{12}C$ to a standard value and use delta notation, $\delta^{13}C$, to refer to it. These values can be used to infer changes in sources and sinks of carbon through time. The following is the formula for calculating $\delta^{13}C$. Notice that the entire formula is multiplied by 1000 (rather than 100), meaning that $\delta^{13}C$ values are given in units of per thousand ("per mil") rather than percent.

$$\delta^{13}\mathrm{C} = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}}{(^{13}C/^{12}C)_{standard}} \times 1000$$

If a carbon source or sink results in an increase in the ^{13}C isotope relative to the ^{12}C isotope, the $\delta^{13}C$ value will become higher or less negative. If the carbon source or sink results in an increase in the ^{12}C isotope relative to the ^{13}C isotope, the $\delta^{13}C$ value will become lower or more negative. The standard has a $\delta^{13}C$ value of zero.

Figure 6 shows the concentration (red) and carbon isotope composition of CO_2 (green) in ice core bubbles over the past 25,000 years, with the oldest ice on the right and younger ice to the left along the x-axis.

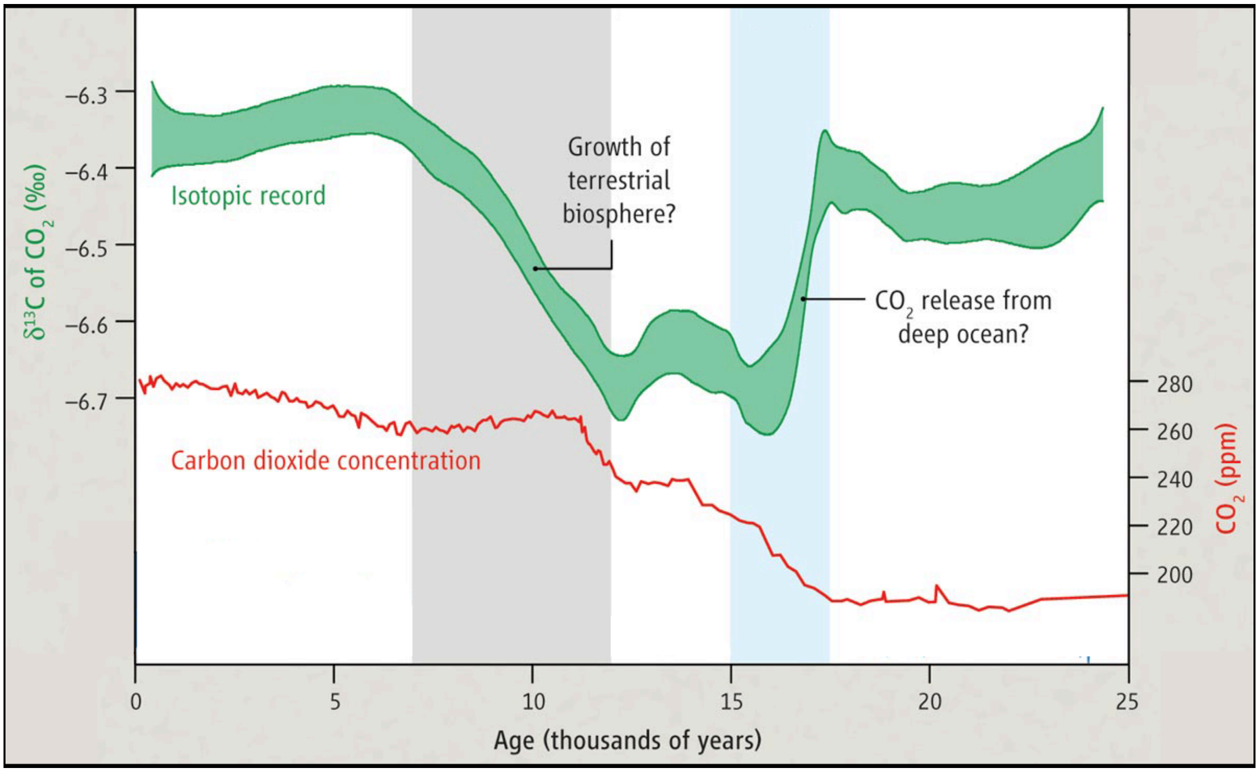

Figure 6. CO_2 concentrations in red and carbon isotopic composition of CO_2 in green from ice core bubbles over the past 25,000 years. Isotope measurements are given as $\delta^{13}C$ values of CO_2. The width of the green line represents the uncertainty. [Modified from Brook, E., 2012]

In Figure 6, the CO_2 concentration increased from less than 200 ppm to approximately 275 ppm over 25,000 years, mostly between 17,000 and 11,000 years ago.

The changes in $\delta^{13}C$ values help us better interpret the possible causes of the change in CO_2 concentrations during these times. There was a decrease in the $\delta^{13}C$ values from around 17,000 to 15,000 years ago (blue-shaded region). A release of CO_2 from a reservoir of organic carbon, rich in the ^{12}C isotope from the bottom of the deep ocean was likely the cause of the decrease in the $\delta^{13}C$ values.

From 12,000 to 7,000 years ago, the CO_2 concentration stabilized. The carbon isotope composition of the CO_2 tells us that the amount of ^{12}C isotopes in the atmosphere decreased. These changes were probably caused by an increase in land plants, which take in CO_2 during photosynthesis and preferentially absorb the ^{12}C isotope, removing it from the atmosphere. These 'new' organisms slowed the rate CO_2 concentration increased while increasing the $\delta^{13}C$ value of that CO_2.

Using ice to determine past temperatures

The isotopes of water (H_2O) from melted ice cores can be used as a proxy for paleotemperature. The isotopes needed for this temperature proxy are ^{16}O, ^{18}O, ^{1}H, and ^{2}H (called deuterium). In this section, we will focus on oxygen isotopes, but hydrogen isotopes work in a similar fashion. Similar to carbon isotopes, water isotopes are compared to a standard, standard mean ocean water. This allows us to use delta notation of $\delta^{18}O$ for oxygen and $\delta^{2}H$ (often written as δD for deuterium) for hydrogen. Here is the formula to calculate $\delta^{18}O$:

$$\delta^{18}\mathrm{O} = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} \times 1000$$

In general, ice formed during colder temperatures has more of the lighter ^{16}O isotopes compared to ice formed during warmer temperatures. The lighter oxygen isotopes are the first to evaporate from ocean water into water vapor in the atmosphere. This means that precipitation formed when this water vapor condenses will be rich in the ^{16}O isotope. During extended periods of warmer global temperatures (interglacial periods), much of the ^{16}O-rich precipitation that falls on land will return to the ocean water as runoff. During extended periods of colder global temperatures (glacial periods), more of the precipitation will fall as snow, which can eventually freeze into ice. During glacial periods, more of the ^{16}O isotope will be “locked up” in glaciers and ice sheets. Ice formed during these colder glacial periods is richer in the ^{16}O isotope, with lower (or more negative) $\delta^{18}O$ values. This also means that ocean water during glacial periods is richer in the ^{18}O isotopes compared to interglacial periods, resulting in ocean water having a higher (or less negative) $\delta^{18}O$ value. This process is shown in **Figure 7**.

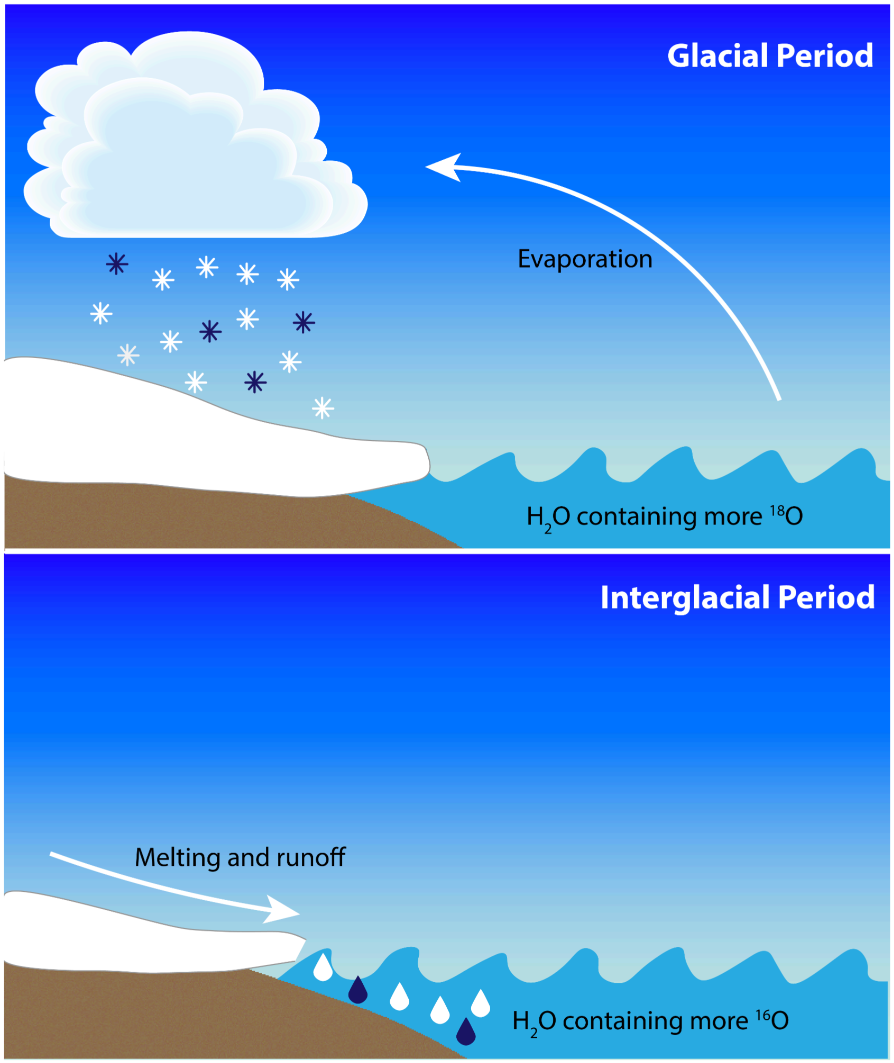

Figure 7. Diagram of how heavy and light isotopes are distributed by snow during glacial and interglacial periods. ^{16}O isotopes are white snow and droplets, and ^{18}O are dark blue.

As shown in Figure 7, during glacial periods, more ^{16}O is stored in ice sheets while during interglacials the ^{16}O runs back off into the ocean. Accordingly, the $\delta^{18}O$ values from ice cores provide a proxy for temperature at the time the snow was formed. This relationship between water isotopes and temperature allows us to use the direct measurements of $\delta^{18}O$ from the ice as a proxy for past temperature as shown in the figure below. Increasing (less negative) $\delta^{18}O$ values in **Figure 8** indicate warming temperatures and decreasing (more negative) $\delta^{18}O$ values indicate cooling temperatures. The oldest records are on the left.

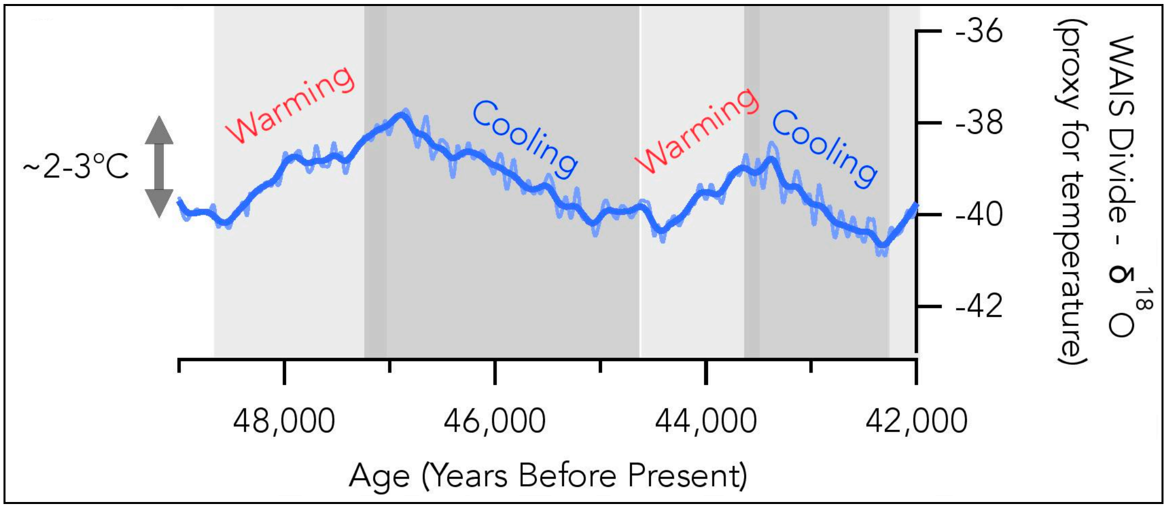

Figure 8. $\delta^{18}O$ values for ice in the West Antarctic Ice Sheet (WAIS) Divide ice core from approximately 49,000 to 42,000 years before present. $\delta^{18}O$ values are used as a proxy for temperature, showing a range of 2–3°C. [Modified from British Antarctic Survey]

Atmospheric dust in the ice core

Atmospheric dust and volcanic ash, along with other particles, like sea salt are often trapped between layers and preserved when the snow becomes ice. Dust, in particular, has important global climate impacts. Increased dust in the atmosphere reflects more of the incoming solar radiation, decreasing the amount of solar radiation that reaches Earth's surface. However, dust on the surface of glaciers and ice sheets has the opposite effect by decreasing the reflectivity of these surfaces and absorbing more solar radiation. Dust that is rich in iron can cause an increase in the amount of primary producers (such as phytoplankton) in the oceans, causing a decrease in atmospheric carbon dioxide as these organisms use CO_2 to make their own food.

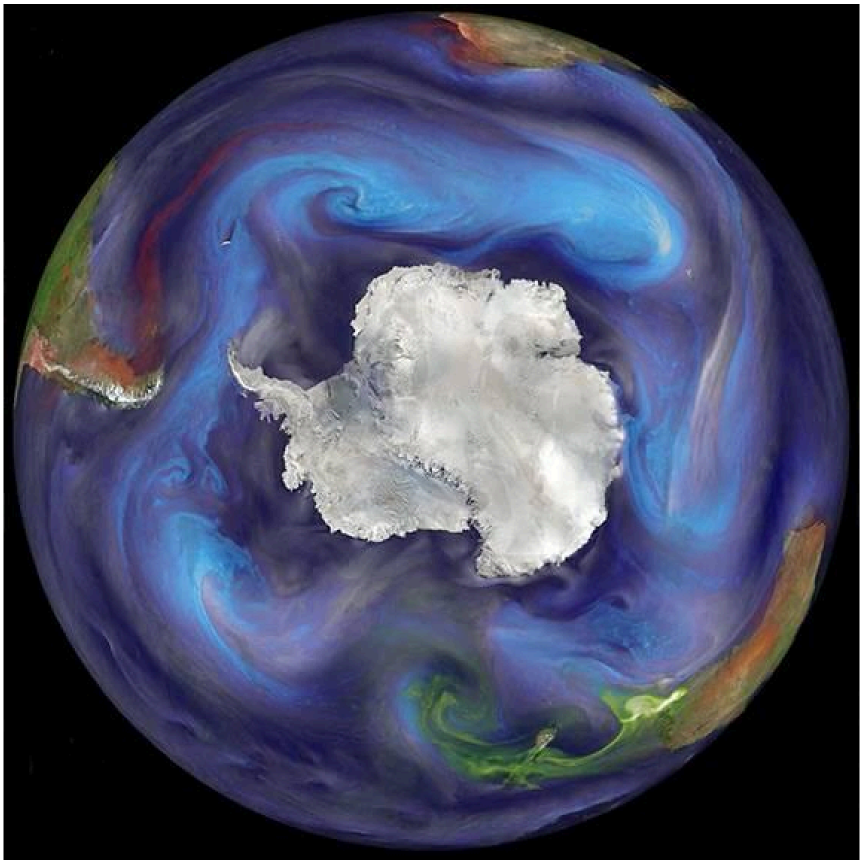

Figure 9. Satellite image from December 2006 of aerosols (solid particles suspended in air) swirling in wind currents around Antarctica. The red-orange colors are dust, blue colors are sea salt, green-yellow colors are organic and black carbon (likely from fossil fuel burning), and white and brown colors are sulfate-rich ash (from volcanoes or human-caused pollution). [NASA/GISS]

To measure the chemical properties of dust in ice cores, the ice is first melted, releasing the dust particles, as shown in Figure 10. Generally, scientists want to analyze the dust's chemistry to determine its age and source.

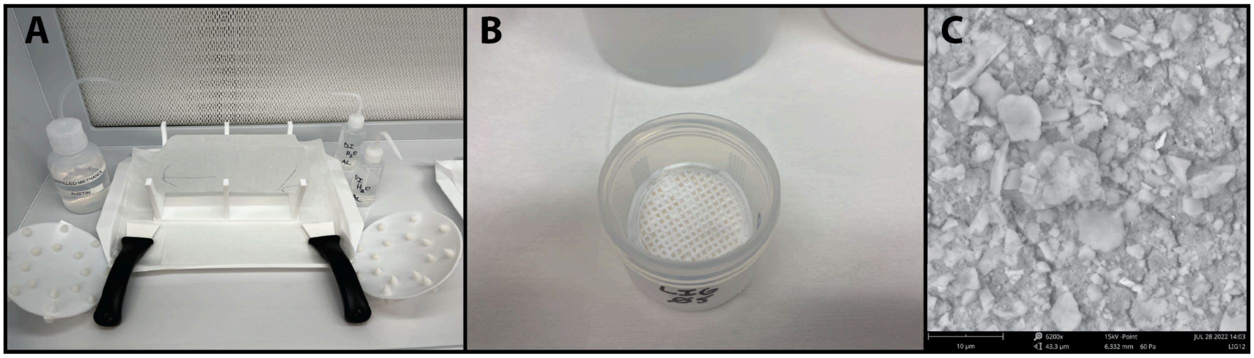

Figure 10. (A) A sample of ice is prepared, with chisels to scrape off the outer layer of the ice, then it is washed with pure water and methanol. (B) Once melted it is filtered and the dust particles are collected in the bottom of a jar. (C) Dust particles are examined using a scanning electron microscope. It was determined this dust is 140,000 years old. [Photos by Austin Carter/COLDEX]

Scientists specifically measure unstable radiogenic isotopes, covered in Module 1: Introduction to Paleoclimatology, in the dust to estimate its age. Radiogenic isotopes and mineral chemistry, among other tests, identify the origin of the dust, which assists in determining changes to land surface and global atmospheric circulation patterns. Most of the dust in Antarctica came from southern South America, but has also been found from other regions.

COLDEX is partnering with the University of Washington Applied Physics Laboratory to develop a rapidly melting probe called an ice diver (**Figure 11**). This probe includes a sensor to measure the chemical properties of dust within the ice sheet, which provides information about whether the ice was deposited during a glacial or interglacial period before drilling a core. By counting up the number of glacial and interglacial cycles going back in time, COLDEX scientists could estimate the age of the ice before they even drill for an ice core.

Figure 11. A scientist testing the ice diver on the Greenland ice sheet. The tip of the ice diver is metal and contains thermal wiring that melts quickly through the ice. [Photo from Dale Winebrenner/University of Washington]

Volcanic ash in ice cores

Volcanic ash, called *tephra*, is also often found in ice cores. Tephra is made up of rock pieces and small shards of glass. The glass is formed when small droplets of magma are erupted and cool quickly. If there is enough ash, tephra can be visually identifiable as unique layers in the ice core (**Figure 12**). Smaller concentrations, invisible to the eye, are detected during analysis.

Figure 12. The volcanic ash is visible as a brown-gray layer in the ice core stored with others at the Ice Core Facility. [Photo by Kelsey Lindsey]

Besides erupting tephra, volcanoes can also release large amounts of gases, such as carbon dioxide, sulfur dioxide (SO_2), and hydrogen sulfide (H_2S). The sulfur-containing gases released in a volcanic eruption combine with water droplets in the atmosphere to form sulfate aerosols that settle onto the ice. If a volcanic eruption is explosive enough to inject ash and gases high enough into the atmosphere, the ash can be deposited as far away as the opposite side of the planet.

Scientists can also identify chemical signatures of eruptions in the ice core, usually an elevated concentration of sulfates. Analyzing the chemistry of the ash can identify which volcano erupted and possibly even which eruption and when it occurred.

Ash, like dust, can date the layers in an ice core, either using radiogenic isotopes or by correlation of chemical compositions with other tephra deposits from sediment cores. This correlation is possible as long as the eruption source is identifiable.

Elaborate | The COLDEX scientific mission

Let's reexamine Figure 2 and the record of CO_2, CH_4, temperature, and dust flux over the past 800,000 years. An A and B were added to the horizontal axis for specific times in Earth's history.

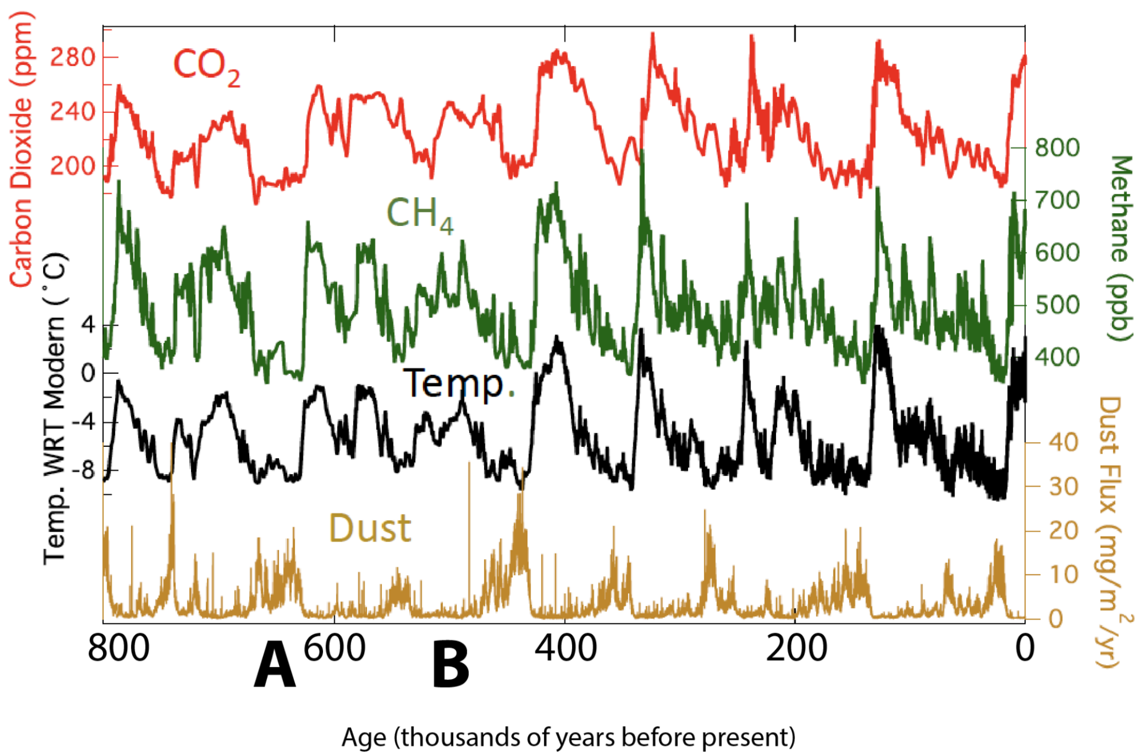

Figure 2. A record of paleoclimate data from ice cores over the past 800,000 years: carbon dioxide concentration (parts per million, ppm), methane concentration (parts per billion, ppb), dust flux (milligrams of dust per square meters per year), and temperature with respect to (WRT) modern temperature. [Adapted from Bereiter et al., 2015; Loulergue et al., 2008; Lambert et al., 2008; Jouzel et al., 2007]

1. Which of the following variables in Figure 2 are negatively correlated over the 800,000 year record?
   a. Carbon dioxide and temperature
   b. Dust and carbon dioxide
   c. Methane and carbon dioxide

2. By comparing the dust concentration to temperature, you can infer that dust flux is low during ______ periods and high during ______ periods.
   a. glacial ... interglacial
   b. interglacial ... glacial

3. Was the time at A likely during a glacial or interglacial cycle?
    a. Glacial
    b. Interglacial
    c. Neither

4. Was the time at B likely during a glacial or interglacial cycle?
    a. Glacial
    b. Interglacial
    c. Neither

5. Which of the data in Figure 2 is NOT directly measured from the ice core?
    a. Carbon dioxide
    b. Methane
    c. Temperature
    d. Dust

Figure 13 shows the ice core record of CO_2 concentration measurements and $\delta^{18}O$ measurements from the shells of foraminifera, benthic (ocean bottom-dwelling) single-celled organisms. This figure makes COLDEX's goal and scientific mission more apparent.

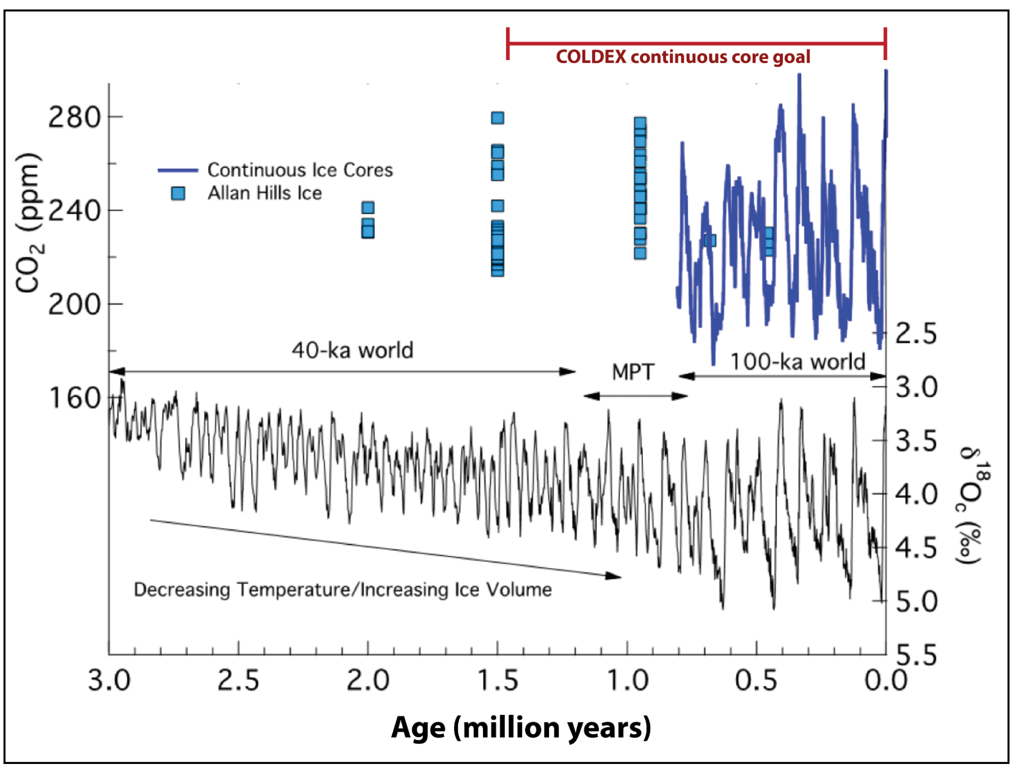

Figure 13. CO_2 concentration from ice core air bubbles in continuous (blue line) and individual samples of ice from the Allan Hills region in Antarctica (blue squares above $\delta^{18}O$ values from benthic foraminifera (bottom). Age is oldest to the left. [Adapted from Bereiter et al., 2015 and Yan et al., 2019]

The Mid-Pleistocene Transition (MPT) occurred around 1.25–0.8 million years ago, when the length between glacial and interglacial cycles changed from every 40,000 years (“40-ka world”) to every 100,000 years (“100-ka world”). Scientists haven’t yet agreed on why this change occurred.

6. One of the main scientific goals for COLDEX is to find a continuous ice core that covers the past 1.5 million years. Which of the following are the likely motivations for collecting this continuous ice core?
   a. This core will provide direct measurements of greenhouse gases in the atmosphere back to 1.5 million years ago
   b. The oldest ice in this core will extend back into a time period of warmer global temperatures than in the 100-ka world
   c. Scientists will be able to make measurements that could help them better understand why the Mid-Pleistocene transition occurred
   d. Both a and b are correct.
   e. All of the above are correct.

7. What are the $\delta^{18}O$ value measurements a proxy for?
   a. Dust concentration
   b. Age of the ice
   c. Temperature

8. There is ______ correlation between $\delta^{18}O$ values and CO_2 measurements in the ice core record.
   a. a negative
   b. no
   c. a positive

A continuous core going back 1.5 million years would provide vital information about past climate, not only CO_2 concentration and temperature, but also how glaciers and ice sheets respond to fluxes in them. This information is essential to model future changes as Earth’s climate warms. **Figure 14** shows historic changes in the Antarctic ice sheet’s volume, and then how it is likely to change in the future on the left axis. The right axis shows the corresponding rise in sea level from ice loss. The blue line and shading represent results from more conservative models, while the red line and shading are the result of more drastic temperature changes.

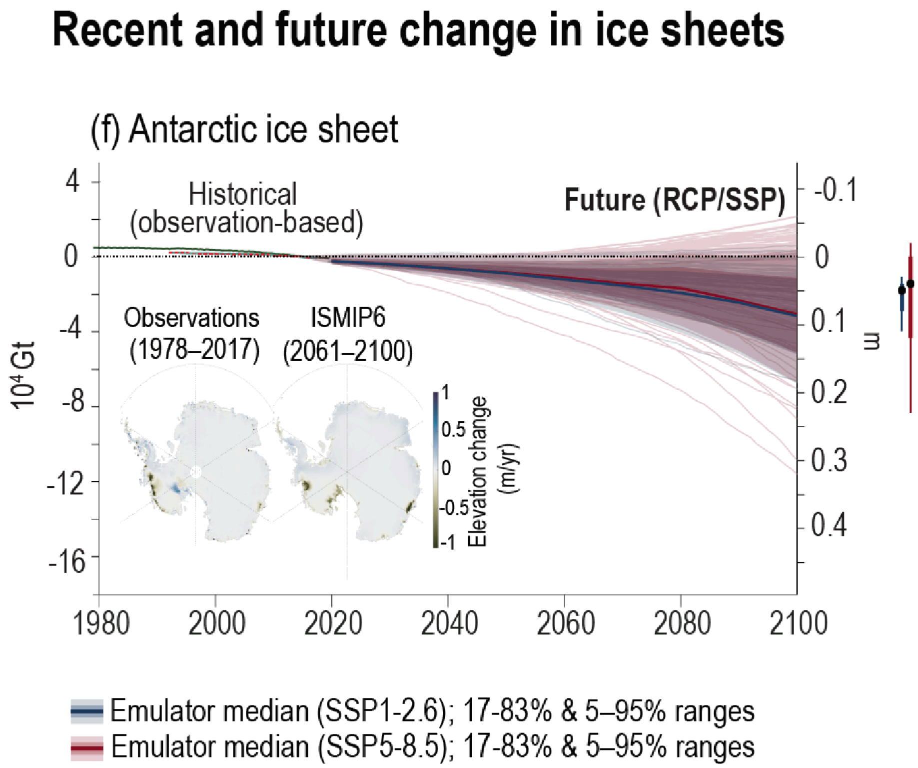

Figure 14. Total ice mass loss (in 10^4 gigatonnes, left axis) and meters of sea level rise (decreases toward the top on the right axis) for both historical (observed) and future levels calculated by climate models for the (f) Antarctic Ice Sheet. Inset maps show historical and future modeled ice sheet surface elevation changes. [Arias, P.A. et al., 2021]

9. Figure 14 shows historical (measured) and modeled data for ice mass loss and resulting sea level rise, which increases downward, due to melting of the Antarctic ice sheet. Which of the following is correct concerning the relationship between the Antarctic ice sheet and sea level?
   a. When ice from the Antarctic ice sheet melts, the meltwater ends up in the ocean and causes sea level to rise
   b. When ice from the Antarctic ice sheet melts, the meltwater ends up in the atmosphere and causes sea level to fall
   c. The meltwater formed when the Antarctic ice sheet melts does not contribute to sea level rise

Unlike before the Mid-Pleistocene Transition, our current climate system is absorbing greenhouse gases at an unprecedented rate in Earth's history. The future modeled sea level rise in Figure 14 has a wide range of possible outcomes because it depends so greatly on how much we change our greenhouse gas emissions in the future.

10. Based on what you've learned from the ice core record, how would increasing greenhouse gas emissions produced by human activities likely impact global temperature?
    a. It would likely decrease global temperature
    b. It would likely increase global temperature
    c. It would likely not affect global temperature

11. Based on the relationship between ice sheet melt and sea level, how would increasing greenhouse gas emissions produced by human activities likely impact sea level?
    a. Sea level will likely decrease
    b. Sea level will likely increase
    c. Sea level will likely remain the same

Evaluate | Understanding the paleoclimate record

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

12. Which of the following isotopes of carbon is not measured to calculate $\delta^{13}C$?
    a. ^{12}C
    b. ^{13}C
    c. ^{14}C

13. When measuring the CO_2 concentration in an ice core bubble, which is older, the gas in the bubble or the ice the bubble is frozen in?
    a. They are both the same age
    b. The ice is older
    c. The gas in the bubble is older

14. In the nearly 800,000 years before 1850, atmospheric CO_2 concentrations stayed below 300 ppm. What is the current concentration?
    a. 325–350 ppm
    b. 375–400 ppm
    c. 425–450 ppm
    d. 475–500 ppm

15. Scientists at COLDEX are measuring oxygen isotopes in ice meltwater. Which of the following variables can be inferred from these isotope measurements?
    a. Age of the ice
    b. Global temperature when the ice was formed
    c. Bubble gas age

16. Ice formed during warm global temperatures will have $\delta^{18}O$ values that are ______ the $\delta^{18}O$ values of ice formed during cold global temperatures.
    a. greater than
    b. less than
    c. the same as

17. During a glacial period, which of the following is seen in the ice core record?
    a. Higher CO_2, CH_4, $\delta^{18}O$ values, and higher dust flux
    b. Higher CO_2, CH_4, $\delta^{18}O$ values, and lower dust flux
    c. Lower CO_2, CH_4, $\delta^{18}O$ values, and higher dust flux
    d. Lower CO_2, CH_4, $\delta^{18}O$ values, and lower dust flux

18. Scientists can identify volcanic ash in an ice core either through visual observation if the layer of ash is large enough or through identifying an increase in which chemical component in the ice?
    a. Methane
    b. Water
    c. Sulfate

19. COLDEX and the University of Washington Applied Physics Laboratory are engineering an ice diver probe to melt through the ice sheet quickly. What is this probe primarily designed to measure?
    a. Ice temperature
    b. Gas concentrations
    c. Dust concentrations
    d. Stable isotope concentrations

20. Which of the following can help scientists correlate the age of an ice core and a sediment core?
    a. Geographical proximity
    b. Presence of volcanic ash from a known eruption
    c. Similar width of the sediment layers and the ice layers

Workshop Extensions | “Ice Core Lab” (at OSU CEOAS)