AMERICAN METEOROLOGICAL SOCIETY:

A COLDEX Center for Oldest Ice Exploration PARTNER

Project Ice

Ice Core Analysis and Paleoclimatology

—

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).

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 Smith 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

Objectives: After completion of this module participants will be able to:

1. Implement scientifically accurate and pedagogically sound instructional resource materials focused on ***ice core analysis and paleoclimatology***;
2. Integrate the scientific method of pursuing questions related to ***ice core analysis and paleoclimatology*** into other educational settings;
3. Construct scientific explanations and demonstrate knowledge of scientific principles for ***ice core analysis and paleoclimatology*** and relate/map these to the Climate Literacy Principles and NGSS.
4. Analyze and interpret scientific observations related to ***ice core analysis and paleoclimatology*** acquired through the chemical and stratigraphic properties of ice
5. Conduct peer training sessions on ***ice core analysis and paleoclimatology*** on a continuing basis, with instructional resource materials, scientific guidance and opportunities to interact with scientists and professionals in the fields of climate science and polar exploration.

STANDARDS:

Ice Core Science - Basic Understandings:

<u>I. Climate Change (1-8)</u>

1. Glaciers, ice sheets, and subglacial environments contain evidence of past atmospheric composition and clues to climate evolution.
2. Earth's climate system involves local, regional, hemispheric, and global phenomena. It is impossible to understand global climate without understanding both individual components of the system and the system as a whole, as evidenced by data from a large number of locations and over a range of time scales.
3. Ice core records show that rapid changes in climate can happen in less than ten years.
4. Ice cores provide direct measurements of Earth's CO_2 levels for the past 800,000 years establishing natural parameters of cycles from about 180 ppm to 280 ppm.
5. Today's CO_2 is higher than at least the last 1 million years of the natural climate cycle.
6. Temperature is determined by proxy measures of hydrogen and oxygen isotopes in the ice cores.
7. Scientists study changes in the chemistry and isotopic composition of the atmosphere over time as evidenced by the bubbles of atmosphere caught in the ice cores.
8. The ice reveals human causes of rising CO_2 since the beginning of the Industrial Revolution and the burning of fossil fuels.

<u>Additional paleoclimate understandings (1,4,10,13-18)</u>

1. Proxy climate data are obtained from indirect methods, such as historical documents, tree rings, lake and ocean sediment cores, and ice cores. Analysis of proxy data discerns trends in atmospheric and geologic variables extending millions of years into the past.
4. The Milankovitch cycle takes into account the precession and tilt of Earth's rotational axis and the eccentricity of its orbit, which determine how it revolves around the Sun and drives climate fluctuations operating over tens of thousands to hundreds of thousands of years.
10. Glacial ice forms as each layer of winter snow accumulates and is then compacted by the newer layers into impermeable ice that retains the original air in bubbles. Carbon dioxide, methane, oxygen, nitrogen, and other greenhouse gases can be discerned from the air bubbles.
13. Physical and chemical analysis of ice cores provides information on temperature, precipitation, atmospheric aerosols (such as dust and volcanic ash), and even levels of solar activity. Ice cores can provide data with a resolution as fine as yearly
14. Analysis of air bubbles trapped in ice cores shows that the concentration of atmospheric CO_2 varies inversely with changes in the volume of glacial ice. During interglacial episodes, rising levels of CO_2 adds to the warming whereas during glacial episodes, falling levels of CO_2 contribute to the cooling.
15. Glass-shards from volcanic eruptions, sea-salt concentrations, and dust can also be found within ice cores.

16. Isotopes are different forms of the same element with equal numbers of protons and different numbers of neutrons.
17. Changes in patterns of incoming sunlight due to changes in Earth's orbit, which correlate to periods of warming or cooling of Earth's temperature, are found by analyzing oxygen isotopes from ice cores to determine when temperatures changed.
18. Paleothermometry is the means of determining the Earth's ambient temperature during the occurrence of a past geological process.

II. Ice Dynamics and Glacial History (1,8,10,11)
1. Understanding glacier dynamics, stability of ice sheets and ice sheet response to climate change are imperative for predicting rapid sea level rise.
8. Ice scientists work to understand and monitor accumulation rate, ice mass loss, and temperature changes on Greenland and Antarctic ice sheets.
10. Ice core records provide high resolution (annual) records of natural variability in ice, ocean, and atmospheric dynamics that place current observations in context.
11. Evidence in ice adds to the records of local volcanic activity, which provides information about climate forcing and geohazard studies.

V. Technology
3. Scientists **begin with a question about a phenomena** and seek to find **theories through inquiry** that can provide explanatory answers with an **outcome of new knowledge.**

Applicable Climate Literacy Principles: 1.A, 1.C, 1.D, 1.E, 2.A, 2.C, 2.D, 2.E, 3.B, 4.A, 4.D, 4.F, 5.B
(from https://cleanet.org/clean/literacy/climate/index.html)

Next Generation Science Standards

Science and Engineering Practices
1. Asking questions (for science) and defining problems (for engineering)
4. Analyzing and interpreting data
6. Constructing explanations (for science) and designing solutions (for engineering)

Crosscutting Concepts
1. Patterns. Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.
2. Cause and effect: Mechanism and explanation. Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.
3. Scale, proportion, and quantity. In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.

4. Systems and system models. Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.
5. Energy and matter: Flows, cycles, and conservation. Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.
7. Stability and change. For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.

Disciplinary Core Ideas in Earth and Space Science

K-2: Water exists as solid ice-2-ESS2-3
Difference between weather and climate—K-ESS2-1
3-5: Glacier processes—4-ESS2-1
6-8: Water movements both on land and underground (subglacial) MS-ESS2-2
Ocean influence on weather and climate—MS-ESS2-6
Human activities and greenhouse gases—MS-ESS3-5
9-12: Cyclical changes in earth's orbit—HS-ESS2-4
Geologic record (relate to ice core record)—HS-ESS2-4
Changes in the atmosphere due to human activity-HS-ESS2-4; HS-ESS2-7
Human impact-HS-ESS3-5

Engage | Why do we focus on climate?

As the American science fiction author Robert Heinlein said, “Climate is what you expect, weather is what you get”. Weather is the day-to-day, localized atmospheric conditions that likely influence your decisions about what to wear everyday. Climate is the long-term, expected weather conditions for a specific region. The climate in your region may tell you to expect snowy and cold conditions in the winter months, however, a warm day in the middle of winter is related to weather conditions rather than climate. Climate change, therefore, is the change in regional or global patterns of weather over long time scales (years to thousands of years). In this module, we are focusing on using ice cores to identify changing conditions in Earth’s past climate, or paleoclimate.

Ice cores allow us to make either direct or proxy measurements of temperature, atmospheric 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. Below is what’s referred to as a “cut plan” for an ice core. Each labeled ice sample will be sent to a scientific laboratory for specific chemical and physical measurements. The scientists at COLDEX make a similar plan for distributing ice. In this way, scientists collaborate by making individual measurements that then contribute to our overall understanding of paleoclimate conditions.

During this module, we will learn about many of the measurements indicated in the cut plan below as well as what these measurements tell us about Earth’s past climate. We will answer questions such as:

- Has the Earth’s climate remained constant over time?
- What was Earth’s climate like before human impacts?
- What are the direct and proxy paleoclimate measurements we can make using ice cores?
- What are the motivations behind COLDEX scientific goals?

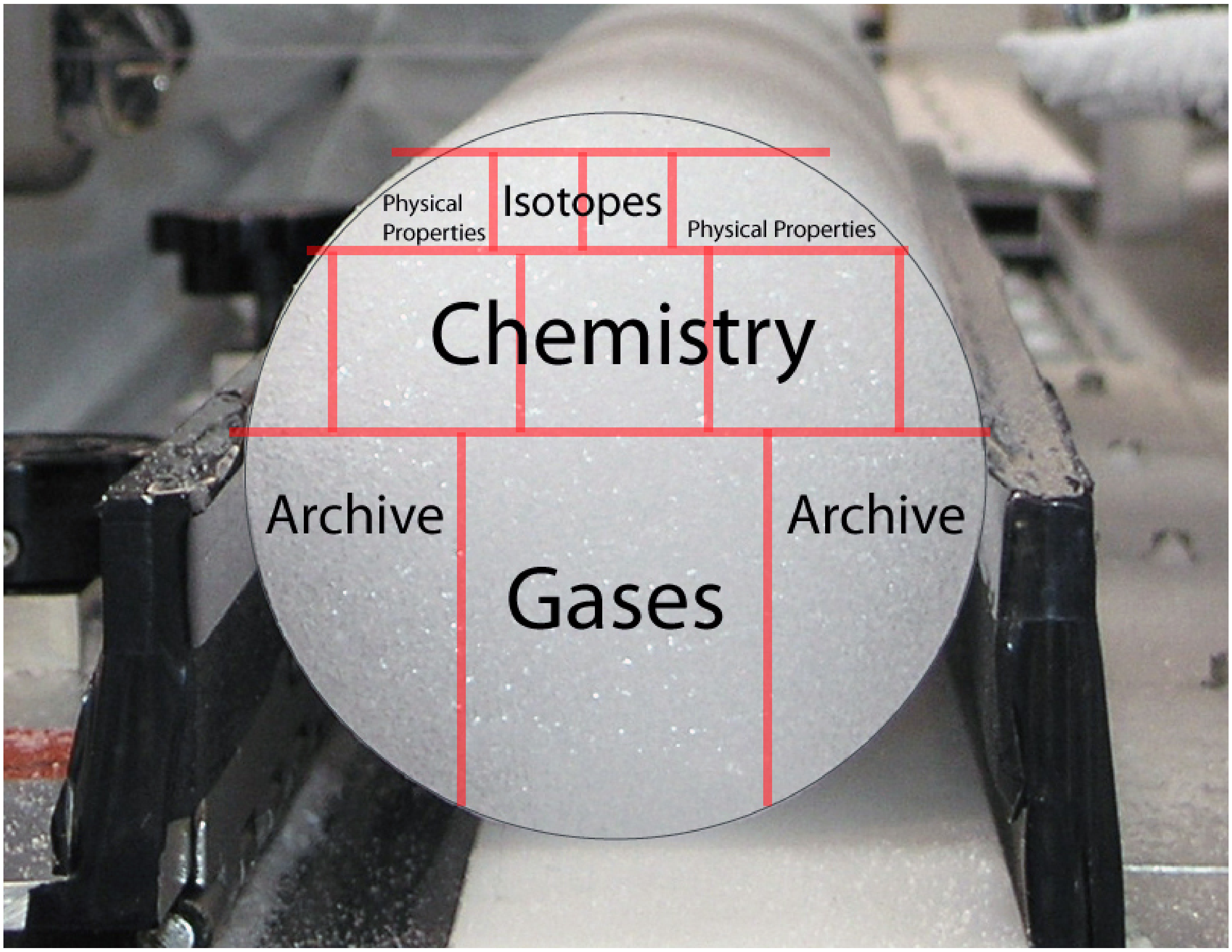

Figure 1. "Cut Plan" of an ice core showing the different samples of ice that will undergo specific chemical and physical measurements. Notice specific "archive" pieces are also set aside to be stored for future measurements. [Photo from the National Ice Core Facility]

Explore | The paleoclimate record from ice cores

Below is a summary of some of the major measurements made using ice cores. Each of these measurements tells us something about the Earth's climate over the past 800,000 years with sample ages getting older as you move left along the X-axis of the graph. Some of these measurements can be made directly from the ice core either in the ice itself or in the air bubbles or dust trapped in the ice. Other parameters, like temperature, are made using proxy measurements. In this case, the proxy measurements use different parameters that can be directly measured from the ice core but are strongly correlated to temperature, allowing us to make conclusions about global and/or regional temperatures on Earth. Notice that the current ice core record shown in Figure 2 only goes back in Earth's history to 800,000 years before present. Scientists at the Center for Oldest Ice Exploration (COLDEX) are working to extend that record back to 1.5

million years before present with a continuous ice core. COLDEX also has the goal to find individual samples of ice that are potentially as old as 5 million years. As you learned in an earlier module, these older ice samples can be folded up into younger ice layers.

The data in Figure 2 requires careful measurements across multiple samples of ice. These ice samples may be from the same ice core or different ice cores. Each measurement requires a specific procedure required to properly prepare the sample for analysis. Following sample preparation, different analytical tools are used. These tools may include scientific instruments that measure specific chemical and/or physical properties. Many times, a specific scientific laboratory will specialize in certain measurements based on the analytical tools they have available. The scientists at COLDEX share the responsibility of analyzing the ice cores brought back from Antarctica across 9 different analytical labs across the United States.

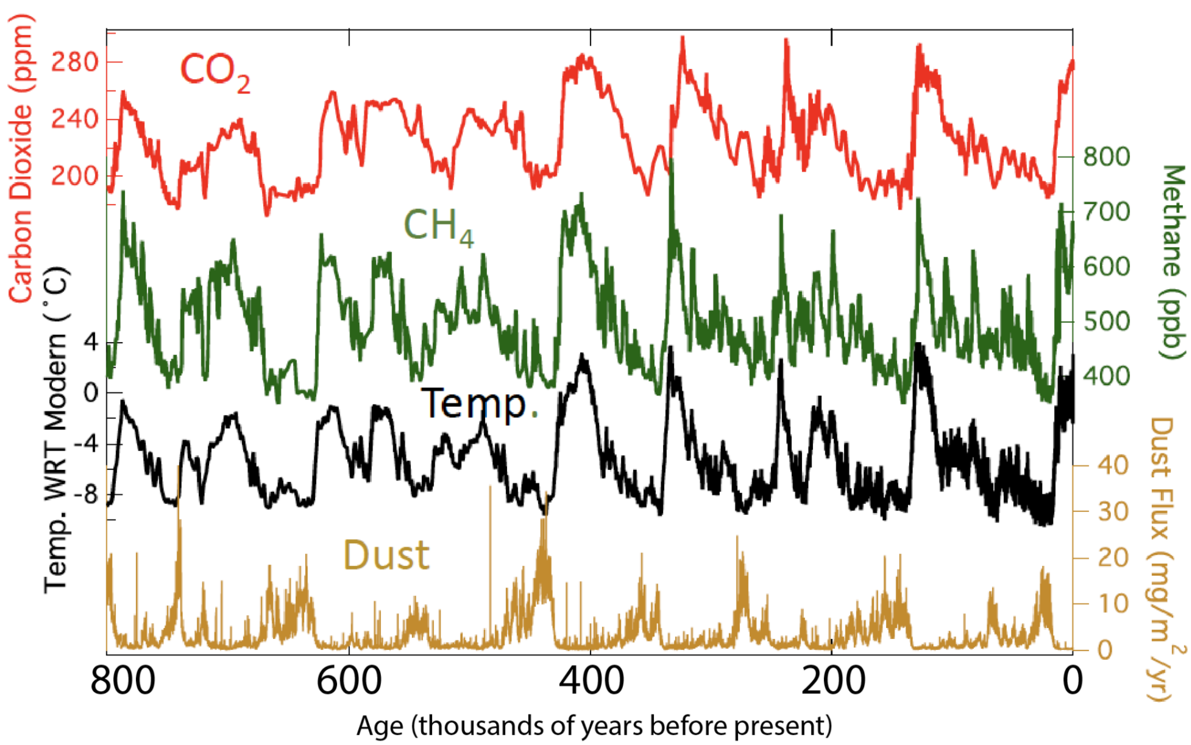

Figure 2. A record of paleoclimate data from ice cores over the past 800,000 years: carbon dioxide concentration (parts per million, ppm), methane concentration (parts per billion, ppb), dust flux (milligrams of dust per square meters per year), and temperature with respect to (WRT) modern temperature.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

Carefully examine the data you see in Figure 2. There are many conclusions you can make even before we delve deeper into the meaning behind these measurements. For example, the data in Figure 2 allows us to draw conclusions about trends for multiple 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 will change in similar directions over time whereas negatively correlated variables will change in opposite directions over time.

Group Review:

1.) How have paleoclimate records from ice cores contributed to our understanding of climate change over thousands of years?

2.) Which variables (if any) are positively correlated with each other over the 800,000-year ice core record?

3.) Which variables (if any) are negatively correlated with each other 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.) Pick one of the variables in Figure 2. Why do you think scientists want to measure this variable in ice cores?

Explain | Ice core analysis and paleoclimate

Group Discussion of Responses from the Explore Section

Figure 2 is a summary of some of the paleoclimate record that we've discerned from measurements made on ice cores. As you examine the data, notice that there are a number of variables that appear to be positively correlated to each other. Positively correlated variables in the paleoclimate record help us make important conclusions about how different aspects of the climate system interact with each other. For example, notice that over the 800,000 year record, the concentration of two "greenhouse gases", carbon dioxide (CO_2) and methane (CH_4), are high when the temperature is high relative to current temperature. Why are these variables positively correlated, which mechanisms in the paleoclimate system result in these trends, and do these effects happen at more or less the same time? The answers to these questions are highly complex, still debated amongst paleoclimate scientists, and exceptionally important for our understanding of how current high, largely anthropogenic-produced greenhouse gas concentrations play a role in our warming climate today. We can also see that dust flux (or change in dust concentration over time) is negatively correlated with temperature. In the following sections, we will learn more about how dust and volcanic ash in ice cores gives us information about the complex nature of the climate system.

Fluctuations in global temperature are normal throughout Earth's history due to changes in Earth's orbit. These changes are called the Milankovitch Cycles and include the following three changes to Earth's orbital movements:

- Eccentricity: The shape of Earth's orbit around the Sun (how elliptical it is).
- Obliquity: The tilt of the Earth's axis
- Procession: The direction of the Earth's tilt as it rotates (whether the Northern Hemisphere or Southern Hemisphere is pointed towards the Sun in January, when the Earth's orbit places it closest to the sun)

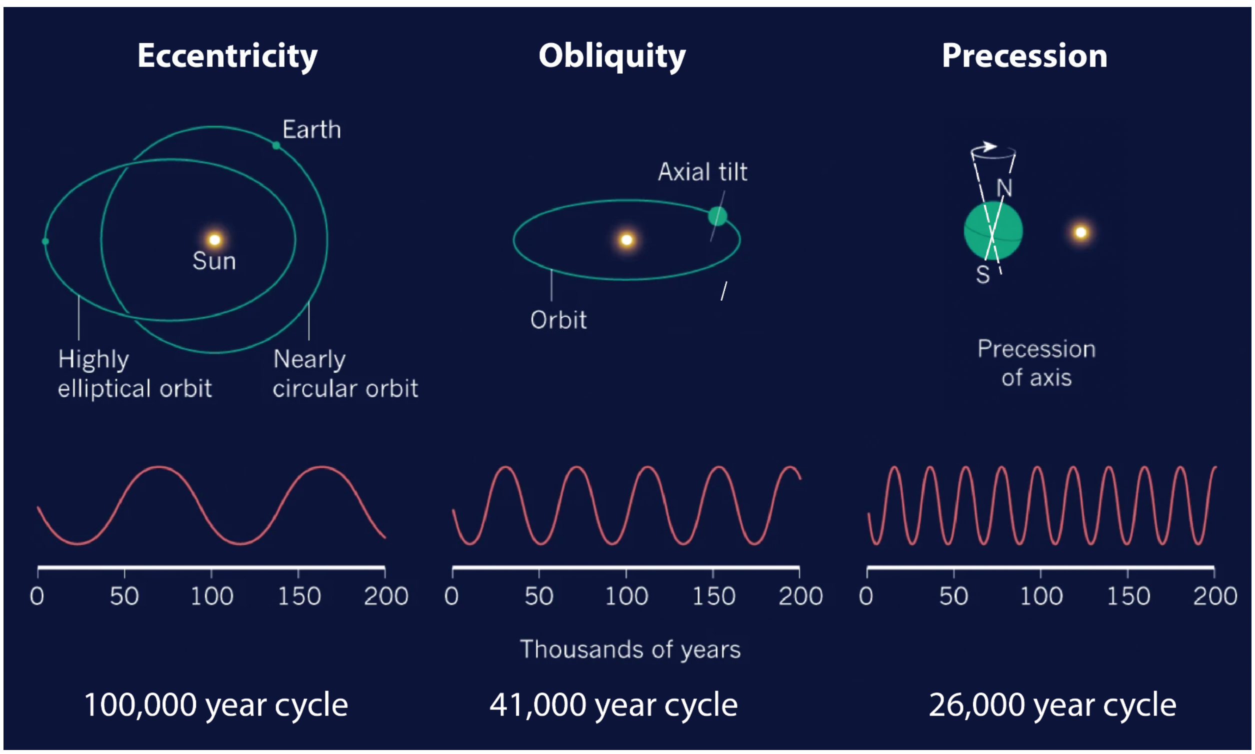

Figure 3. Illustration of the three Milankovitch Cycles and the length of the cycles: Eccentricity, Obliquity, and Precession. [Figure modified from Maslin, M., 2016. Forty years of linking orbits to ice ages. *Nature*, *540*, pp. 208–209. https://doi.org/10.1038/540208a]

The Milankovitch Cycles all occur in highly predictable patterns. Before anthropogenic influences, the Milankovitch Cycles were the drivers of global cooling or warming and contributed to glacial (periods with large ice sheet areas covering Earth's surface) and interglacial cycles due to changes in solar irradiance, or energy from the sun hitting the

Earth's surface. Changes to eccentricity occur every 100,000 years, obliquity cycles are every 41,000 years, and procession cycles are every 26,000 years. The animations at https://climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate/ provide helpful visualizations.

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

Knowledge Check and Discussion - trapping air bubbles in ice cores

When snow gets compressed and forms ice, the air spaces between individual flakes, atmospheric dust, volcanic ash, and other chemicals that were trapped in the snow layers get preserved in the ice. In this section, we will focus specifically on the air bubbles found in ice cores but first we must learn about the process of going from fresh snowfall to firn to ice. **Firn** is older snow that has not melted for at least one year after it first fell. In order for firn to become ice, there has to be enough compressive force of snow layers above to increase the density of the firn. In glaciers with high rates of snow accumulation, such as glaciers on mountains in more temperate climates, firn can take as little as a few years to turn into ice. In Antarctica, the climate is very dry, and firn can take around 100 - 300 years to turn into ice at depths of up to approximately 80 meters below the surface of the ice sheet.

What happens to the air spaces between the original snow flakes? The air bubbles get encapsulated in the ice at the "firn-ice transition". This is an extremely important process as the air at that time is mostly protected from interacting with atmospheric air, resulting in a protected capsule of ancient atmospheric air. The depth at which the air bubbles are closed off is called the "bubble closeoff zone". The bubble closeoff zone can be large - the Vostok ice core has a bubble closeoff zone that is about 8 meters thick, comprising about 300 years of ice within the record. Another complication is that the age of the atmospheric air sample in the bubble is younger in age than the ice it is surrounded by. This is because the age of the gas is actually the time since the bubble was completely closed off in the ice. Ice core scientists must account for this difference in age when reporting the concentration of gases in the air bubbles over time.

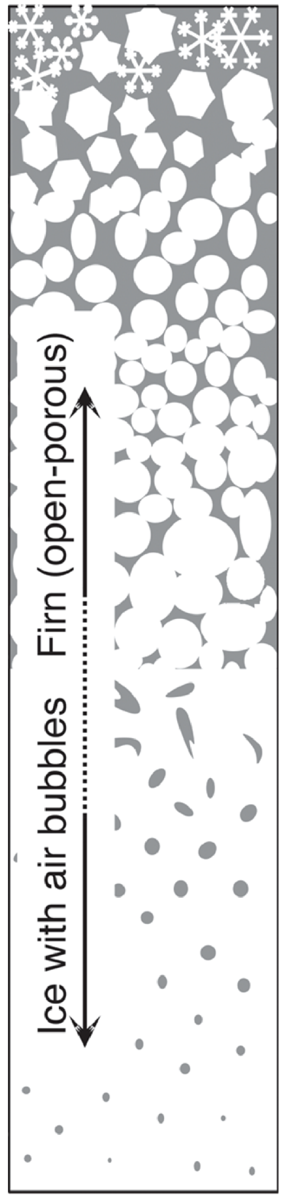

Figure 4. The transition from snow to firn to ice showing the change from open pore spaces in the snow and firn and closed-off air bubbles in the ice. The dashed area in the firn-ice transition zone represents the "bubble closeoff zone". [Figure modified from Schüpbach et al., 2016. Ice core: High-resolution archive of rapid climate changes. Past Global Changes Magazine, 24(1), pp. 12-13. https://doi.org/10.22498/pages.24.1.12]

Knowledge Check and Discussion - Measuring the gases in ice core bubbles

Chemically analyzing the gases in ice core bubbles is one of the primary goals of COLDEX. Bubbles in ice cores provide us direct samples of atmospheric air from the time the bubble was closed off in the ice. Although the bubbles themselves might be small, bubbles comprise about 10% of the volume of the ice core. The gases that are trapped in the bubbles when firn becomes ice include gases that comprise our atmosphere: Oxygen (O_2), Nitrogen (N_2), Argon (Ar), and the gases we've already discussed: carbon dioxide (CO_2) and methane (CH_4). We are going to discuss a few of these gases in this section to discover what they can tell us about Earth's paleoclimate.

There are two types of measurements made on the gases in ice core bubbles: the concentration of the gas and the isotope composition of the gas. 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 that make up the atmosphere), 170 to 300 of them will be 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 are those that absorb infrared (or heat) energy and include CO_2, CH_4, and nitrous oxide (N_2O). Energy from the Sun (solar energy) passes through the atmosphere and heats the surface of the Earth. This heat energy (infrared energy) is then emitted by the Earth's surface. The greenhouse gases in the Earth's atmosphere will absorb some of the heat, keeping the surface of the Earth warm enough to sustain life and maintain liquid water. Higher concentrations of greenhouse gases result in more of that heat energy being absorbed by our ocean and atmosphere, leading to increased global temperatures. In the current climate change crisis, 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, however, what were greenhouse gas concentrations before human activities? The ice core record currently provides us direct measurements with atmospheric samples from the past 800,000 years.

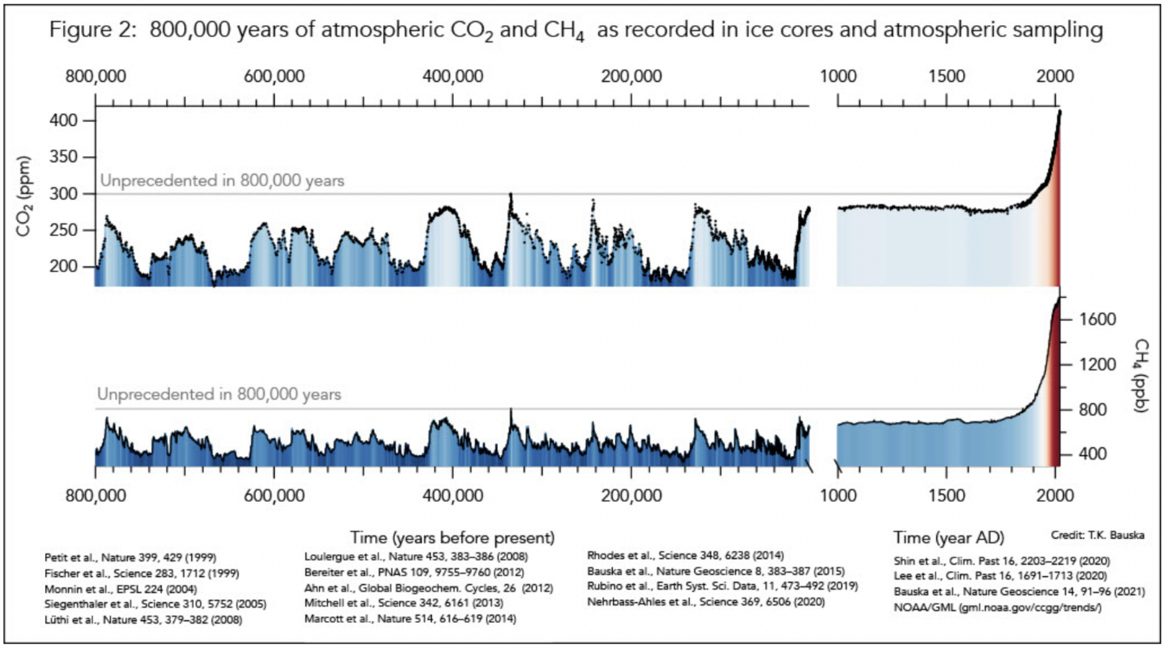

Figure 5. Both CO_2 and CH_4 measured in ice core bubbles shows that cycles of higher and lower concentrations are normal over the past 800,000 years of Earth's history. [Figure from The British Antarctic Survey and T.K. Bauska]

Figure 5 shows the changes in CO_2 and CH_4 concentrations over time based on both 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 equaled the concentrations we see today: 422 parts per million (ppm) of CO_2 as of April 2023 and 1,925 parts per billion (ppb) of CH_4 as of December 2022. This is an important conclusion as it shows us that the CO_2 and CH_4 concentrations of our atmosphere today are outside the range of normal, cyclical values characterizing Earth's atmosphere over the 800,000 years before human impacts. Human activities began more significantly impacting the Earth's climate in the late 19th century during the industrial revolution. However, what caused the changes in CO_2 and CH_4 concentrations hundreds of thousands of years before the industrial revolution? We can use isotopes to help us answer this question.

Using highly sensitive instruments, 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 then can be measured using highly sensitive instruments called mass spectrometers. 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). We notate these as ^{12}C, ^{13}C, and ^{14}C . ^{12}C and ^{13}C are the 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). There are many carbon sources (things that produce more carbon than they absorb) and sinks (things that absorb more carbon than they produce) on Earth. Each of these preferentially absorb or produce a specific ratio of the isotopes of carbon. This allows scientists to use isotopes to help identify the balance of sources and sinks on Earth present when the ice core bubble becomes encapsulated in the ice.

We compare the ratio of $^{13}C/^{12}C$ to a standard value and use the delta notation, "$\delta^{13}C$", to refer to this value. This allows us to calculate ranges of $^{13}C/^{12}C$ values compared to this standard. These values can be used to infer changes in sources and sinks of carbon. The following is the formula for calculating $\delta^{13}C$ compared to a standard. 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 per cent.

$$\delta^{13}\mathrm{C} = \left(\frac{\left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{\text{sample}}}{\left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{\text{standard}}} - 1 \right) \times 1000$$

Using the formula above, if the 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. 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. The standard has a $\delta^{13}C$ value of zero.

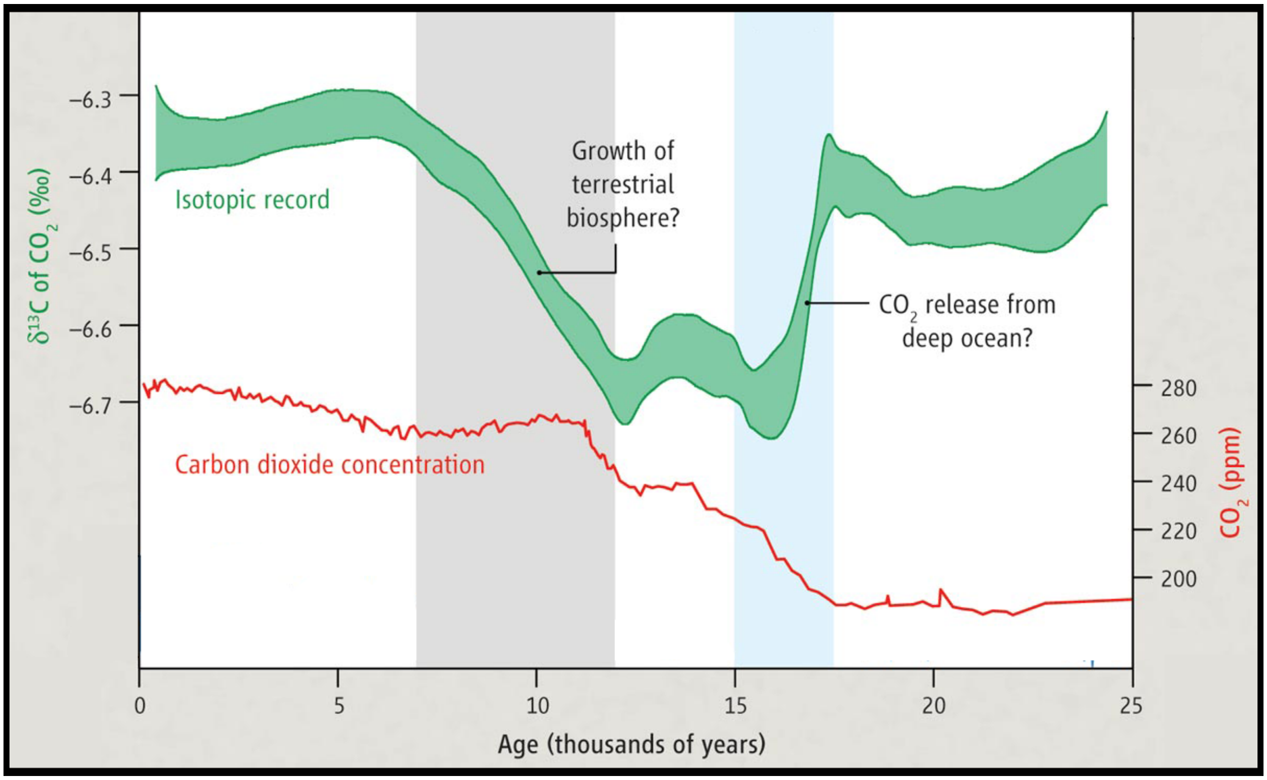

Figure 6. Concentration of carbon dioxide (CO2) in red and carbon isotopic composition of CO_2 (green) in ice core bubbles over the past 25,000 years. Isotope measurements are given as $\delta^{13}C$ values of CO_2. The width of the green line represents the uncertainty around the isotope value measurements. [Figure modified from Brook, E., 2012. The Ice Age Carbon Puzzle. *Science, 336*, pp. 682-683. https://doi.org/10.1126/science.1219710]

How can measuring isotopes be useful in paleoclimate data analysis? Above is an example from the ice core record. Figure 6 shows the concentration and carbon isotope composition of CO_2 in ice core bubbles over the past 25,000 years, with the oldest ice on the right and younger ice as you move left along the X axis. We notice a couple of interesting things: first is that the CO_2 concentration increases from less than 200 ppm to approximately 275 ppm over those 25,000 years, with the increase occurring mostly between around 17,000 to 11,000 years ago. Secondly, we see a decrease in the $\delta^{13}C$ values from around 17,000 to 15,000 years ago (blue shaded region) and then an increase in the $\delta^{13}C$ values from around 12,000 to 7,000 years ago (gray shaded region).

The changes in $\delta^{13}C$ values help us better interpret the possible causes of the change in CO_2 concentrations during these times. It is possible that the release of CO_2 from a reservoir of organic carbon rich in the ^{12}C isotope at the bottom of the deep ocean was a cause of the increase in CO_2 concentration at this time. This caused an increase in the amount of ^{12}C isotopes in the atmosphere, resulting in a decrease in the $\delta^{13}C$ value of

CO_2. From 12,000 to 7,000 years ago, the CO_2 concentration began to stabilize and stopped increasing as rapidly. Why did this occur? The carbon isotope composition of the CO_2 tells us that the amount of ^{12}C isotopes in the atmosphere decreased. The idea is that an increase in land plants at this time caused slowing of the CO_2 concentration increase and an increase in the $\delta^{13}C$ value of that CO_2. Plants take in CO_2 as part of photosynthesis and plants preferentially use the ^{12}C isotope of carbon, removing this specific variety of carbon from the atmosphere.

Knowledge Check and Discussion - Using ice to determine past temperatures

The isotopes of water (H_2O) from melted ice 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”). Similar to carbon isotopes, water isotopes are compared to a standard (called “standard mean ocean water”). This allows us to use delta notation: $\delta^{18}O$ for oxygen and $\delta^{2}H$ (often written as δD for deuterium) for hydrogen. Here is the formula to calculate $\delta^{18}O$, you’ll recognize it has being very similar as the formula for $\delta^{13}C$:

$$\delta^{18}\mathrm{O} = \left(\frac{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{sample}}}{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{standard}}} - 1 \right) \times 1000$$

In general, ice formed during colder temperatures has less of the heavier ^{18}O and ^{2}H isotopes compared to ice formed during warmer temperatures. This is because the heavier isotopes will condense and fall as precipitation first. As the water vapor that forms precipitation moves from lower latitudes towards higher latitudes (towards the poles), more and more ^{18}O and ^{2}H are “rained out” and therefore the water vapor becomes richer in the lighter ^{16}O and ^{1}H isotopes. When global temperatures are colder, the “raining out” of ^{18}O and ^{2}H begins at even lower latitudes, meaning more of the heavier isotopes are lost before the water vapor reaches the poles at colder temperatures than at warmer temperatures.

The values of melted ice water provide a proxy for temperature at the time the snow was formed. Lower $\delta^{18}O$ and δD values in polar ice cores indicate colder global temperatures and higher $\delta^{18}O$ and δD values in polar ice cores indicate warmer global temperatures. This relationship between water isotopes and temperature allows us to use the direct measurements of $\delta^{18}O$ and δD values from the ice as a proxy for past temperature as shown in the figure below. Increasing (less negative) $\delta^{18}O$ values in Figure 7 indicate warming temperatures and decreasing (more negative) $\delta^{18}O$ values inundated cooling temperatures.

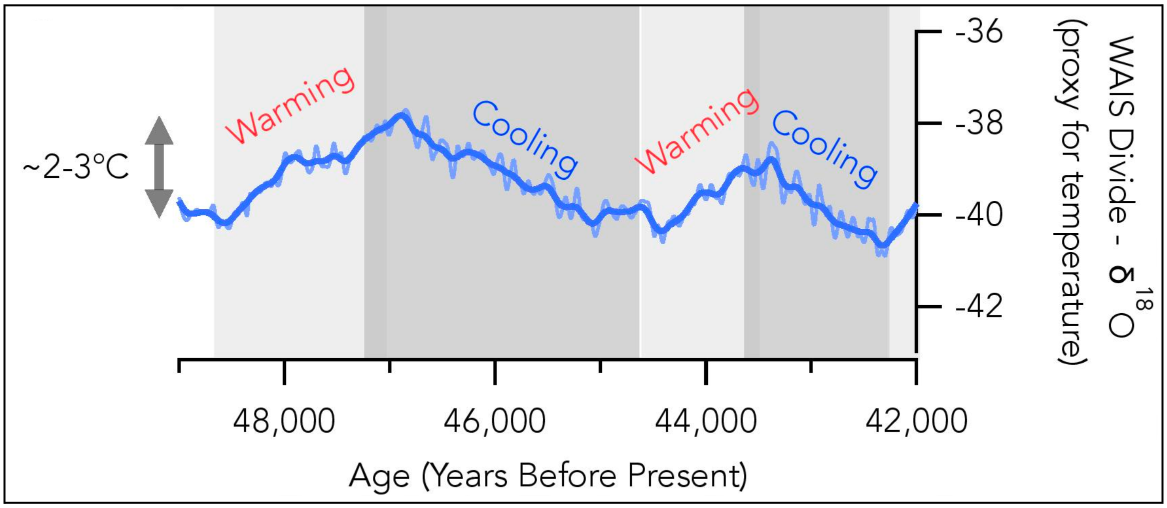

Figure 7. $\delta^{18}O$ values (vs. standard mean ocean water) for ice in the West Antarctic Ice Sheet (WAIS) divide ice core from approximately 49,000 to 42,000 years before present. $\delta^{18}O$ values are used as a proxy for temperature, showing periods of warming (less negative $\delta^{18}O$ values) and cooling (more negative $\delta^{18}O$ values) spanning a range of approximately 2 - 3°C. [Image modified from the British Antarctic Survey]

We also see this effect when moving from coastal to inland precipitation. In large ice sheets like Antarctica, the snow that accumulates along the ice sheet margin will have slightly higher $\delta^{18}O$ and δD values than snow that accumulates in the center of the ice sheet. It is important that scientists consider this effect as well when correlating water isotope values to paleotemperatures. Below (Figure 8) is an illustration of this process on the Antarctic ice sheet.

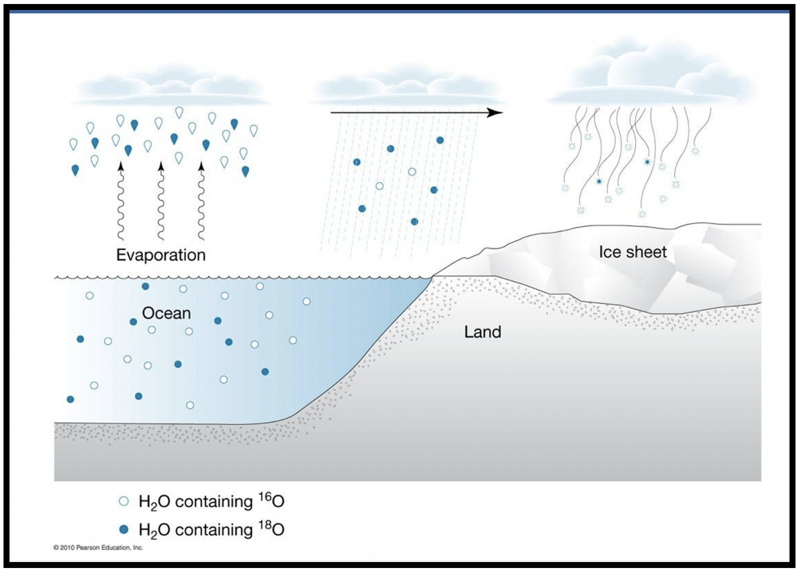

Figure 8. Diagram showing snow formed with more of the heavier ^{18}O isotope along the coastline versus in the middle of the ice sheet.

Knowledge Check and Discussion - Atmospheric dust in the ice core

Atmospheric dust, volcanic ash, and other chemicals like sea salt can also become trapped between snow layers and preserved when the snow becomes ice. We'll start by looking at dust found in the ice. Dust has important global impacts: increased dust in the atmosphere causes more of the incoming solar radiation to be reflected by the atmosphere, decreasing the amount of solar radiation that reaches the Earth's surface. Dust on the surface of glaciers and ice sheets actually does the opposite effect by decreasing the reflectivity of these surfaces and causing more solar radiation to be absorbed. 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.

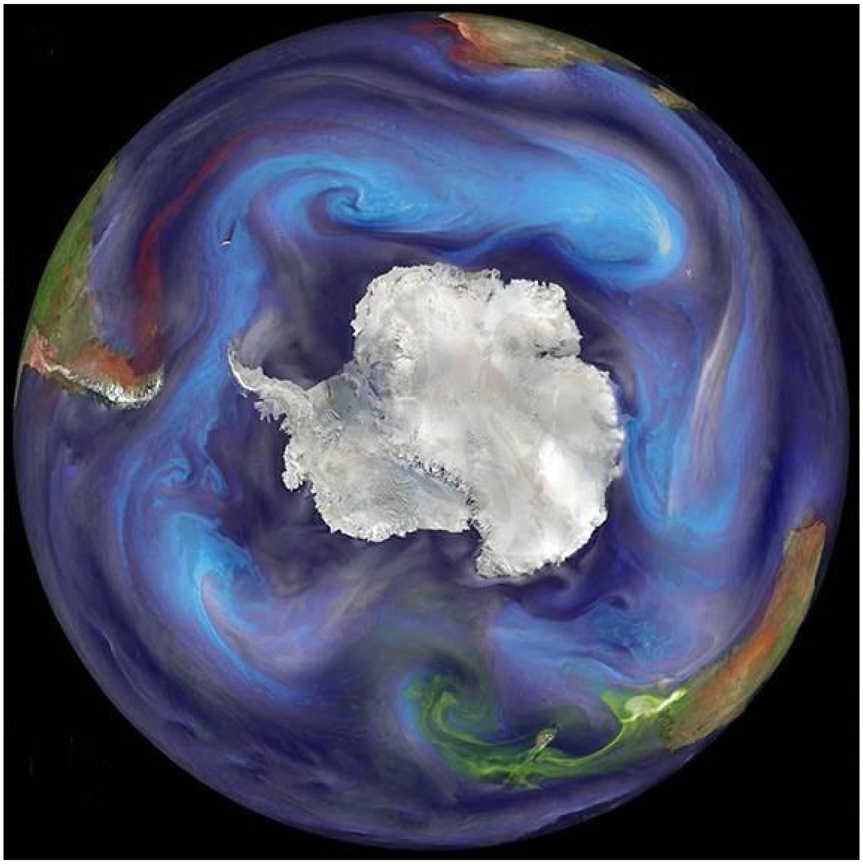

Figure 9. Satellite image from December 2006 of aerosols (solid particles suspended in air) swirling in wind currents around Antarctica. The red-orange colors are dust, blue colors are sea salt, green-yellow colors are organic and black carbon (likely from fossil fuel burning), and white and brown colors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

The concentration of dust particles in the ice core can also provide information about global temperatures and glacial/interglacial cycles. Let's reconsider Figure 2. Dust is generally more prevalent during colder, glacial periods. Recall that we identified the dust flux record over the past 800,000 years as being negatively correlated to the temperature, CO_2, and CH_4 records. When temperature is high, the dust flux is low (suggesting an interglacial period). When temperature is low, the dust flux is high (suggesting a glacial period).

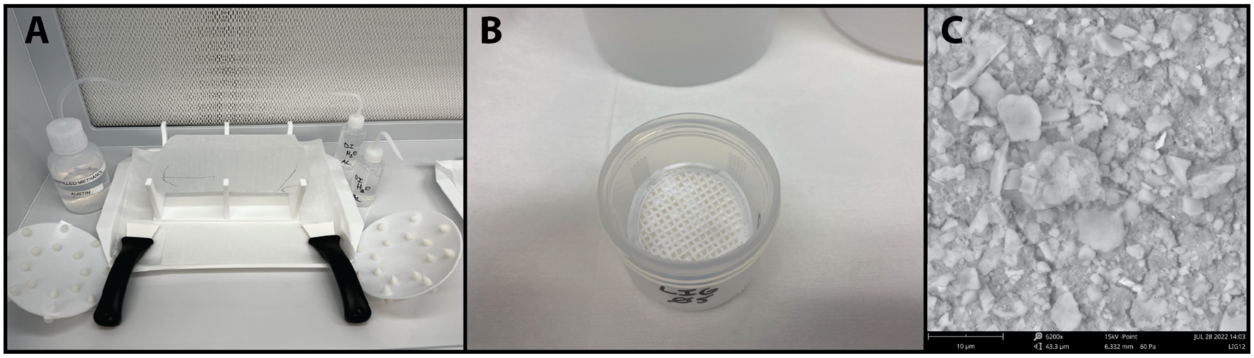

Figure 10. (A) shows a sample of ice ready to be melted to release dust particles. The two chisels are used to scrape off the outer layer of the ice and then the ice is washed with pure water and methanol. The ice then melts into jars and the meltwater is filtered to retrieve the dust particles. (B) If you look closely, you can see the brown dust particles collected in the bottom of this jar. (C) Dust particles can then be examined using a scanning electron microscope. These dust particles are 140,000 years old! [Photos by Austin Carter]

To measure the chemical properties of dust in ice cores, the ice must be melted to release the extremely small particles of dust. Generally, scientists want to analyze the chemistry of the dust to determine the age of the dust and where the dust is from (the source, or "provenance"). Scientists specifically measure radiogenic isotopes in the dust. Radiogenic isotopes are elements that decay over time to produce new elements, called daughter isotopes. If we know the rate of decay for a specific radiogenic isotope in the dust, we can estimate the age of the dust by calculating how many daughter isotopes are present. Analyses of the dust, including measurements of radiogenic isotopes and mineral chemistry, also help scientists identify the origin of the dust. This is helpful in determining changes to land surface and global weather patterns. For instance, most of the dust in Antarctica has a provenance in southern South America but dust can come from other regions as well. Lead-containing dust found in the East Antarctic ice sheet as early as the late 1880's is believed to be from a mine in Southeastern Australia.

COLDEX is partnering with the University of Washington Applied Physics Laboratory to develop a rapidly melting probe (Figure 11) that will include a sensor to measure chemical properties of dust within the ice sheet. This will allow scientists to more easily identify the amount of dust in the ice core, which will provide information about whether the ice was deposited during a glacial or interglacial period. By counting up the number of glacial and interglacial cycles going back in time, COLDEX scientists can 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 the University of Washington Applied Physics Laboratory]

Knowledge Check and Discussion - Volcanic ash in the ice core

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 the layer is large enough, the tephra can be visually identifiable as unique layers in the ice core. Very small layers may not be visible with the naked eye and must be identified using laboratory measurements. Besides erupting tephra, volcanoes can also release large amounts of gases, such as carbon dioxide (CO_2), 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. Scientists can also look for chemical signatures of eruptions, usually identified as spikes in sulfate, in the ice core. Scientists analyze the chemistry of the ash to help identify which volcano and possibly even which eruption the ash came from. Volcanic ash in Antarctic ice cores could have come from one of the Antarctic volcanoes or from a volcano that is not located in Antarctica. If an eruption occurs with enough force to inject the ash high enough into the atmosphere, the ash can be deposited far away from the eruption.

Figure 12. A scientist at the Ice Core Facility shows an ice core with a brown-gray layer of volcanic ash in it. [Photo by Kelsey Lindsey]

When the snow accumulation rate is at least 4 cm per year, this means distinctive, individual layers will be visible. One year is made up of both summer and winter snow layers. Winter snow is denser than summer snow, and therefore looks darker in color. By counting the pairings of winter and summer snow layers, it is possible to calculate the age of the ice at a certain depth. However, processes such as compaction or folding of ice layers often make layer counting an unreliable method for estimating the age of very old ice. Volcanic ash can be one of the ways scientists can date the layers in an ice core. When an eruption occurs, the ash could be deposited in multiple locations. The ash layers in ice cores can sometimes be chemically correlated to the tephra found in marine sediment cores or terrestrial soil cores. If the age of a specific tephra is determined in a marine sediment core then that means identifying that same tephra will tell you the age of the layer in the marine sediment core and the ice core.

Elaborate | The COLDEX scientific mission

Let's re-examine Figure 2: the record of CO_2, CH_4, temperature, and dust flux as measured through the ice core record over the past 800,000 years. Note the added "A" and “B” notations along the X-axis indicating specific times in Earth’s history, these will be discussed in the questions below.

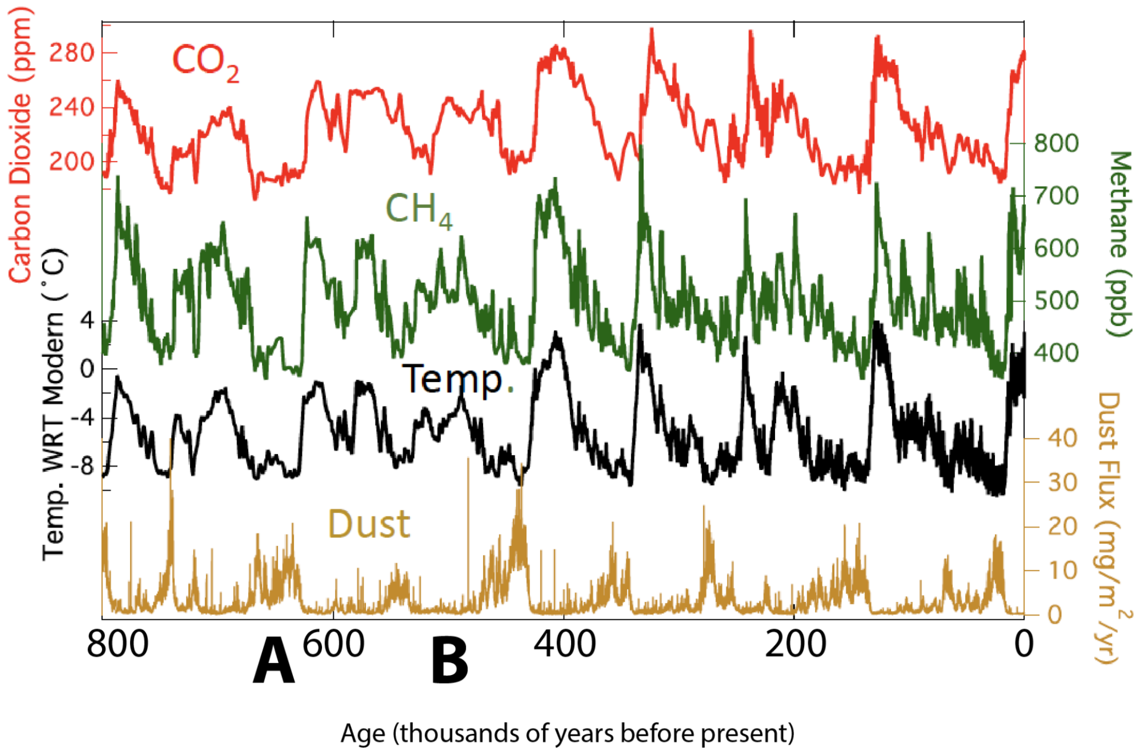

Figure 2. A record of paleoclimate data from ice cores over the past 800,000 years: carbon dioxide concentration (parts per million, ppm), methane concentration (parts per billion, ppb), dust flux (milligrams of dust per square meters per year), and temperature with respect to (WRT) modern temperature. [Figure based on data 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. Based on the data in Figure 2 at the time indicated by the “A”, was this time likely in a glacial or interglacial cycle?
   a. Glacial
   b. Interglacial
   c. Neither

3. Based on the data in Figure 2 at the time indicated by the “B”, was this time likely in a glacial or interglacial cycle?

a. Glacial
b. Interglacial
c. Neither

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

The figure below shows the ice core record of CO_2 concentration measurements as well as $\delta^{18}O$ measurements from the shells of benthic (or ocean bottom-dwelling) single-celled organisms called foraminifera. We'll take a look at this figure and answer questions that will help summarize the COLDEX scientific mission.

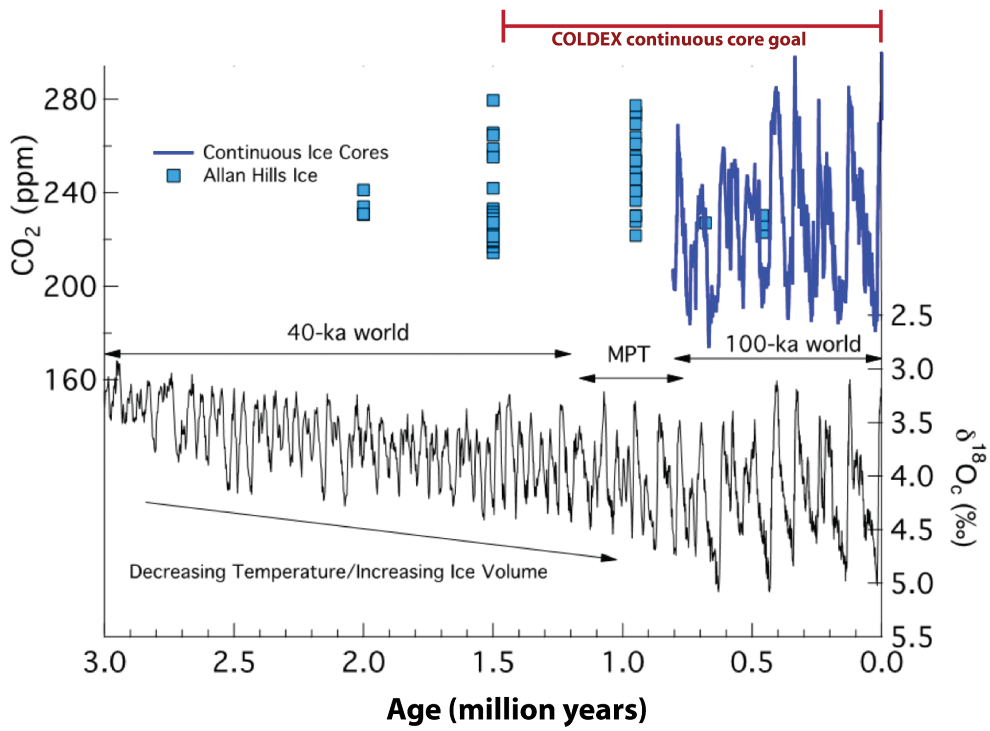

Figure 13. CO_2 concentration from ice core air bubbles (top) in continuous (blue line) and individual samples of ice from the Allan Hills region in Antarctica (blue squares). $\delta^{18}O$ values from benthic foraminifera (bottom). [Continuous carbon dioxide data compiled by Bereiter et al (2015). Allan Hills data from Yan et al. (2019). Oxygen isotope data for benthic foraminifera in ocean sediments (Lisiecki et al., 2005) provide an index of global climate change showing gradual cooling and transition from 40,000 year glacial-interglacial cycles to 100,000 year glacial-interglacial cycles between 1.2 and 0.8 million years ago (MPT="Mid-Pleistocene Transition").]

The Mid-Pleistocene Transition (MPT) is a time from around 1.25 – 0.7 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 occurred.

5. One of the main scientific goals for COLDEX is to find a continuous ice core that extends across the past 1.5 million years. Which of the following is/are the likely motivations behind aiming for this old of a continuous ice core? Select all that apply.

   a. This core will nearly double the current time span of the continuous ice core record
   b. The oldest ice in this core will extend back into a time period of colder global temperatures than in the 100-ka world
   c. The oldest ice in this core will extend back into a time period of warmer global temperatures than in the 100-ka world**
   d. Scientists will be able to make measurements that could help them better understand why the Mid-Pleistocene transition occurred

6. Which of the following variables are the $\delta^{18}O$ value measurements a proxy for?

   a. Bubble density
   b. Ice age
   c. Temperature

7. Based on what you’ve learned about the links between CO_2 and temperature, which of the following would you expect when making CO_2 concentration measurements in ice core bubbles in the continuous COLDEX core?

   a. The CO_2 concentration measurements will be positively correlated with temperature measurements
   b. The CO_2 concentration measurements will be negatively correlated with temperature measurements
   c. The CO_2 concentration measurements will be about the same throughout the 1.5 million years of the continuous COLDEX core

Why is measuring paleoclimate important? The COLDEX scientific mission is to find and analyze ice that was formed before the mid-Pleistocene transition, during a time in Earth’s history when global temperatures were warmer than they are today. One of the benefits of this is that we can measure the Antarctic ice sheet’s response to warmer global temperatures to help scientists model how it will respond to warming temperatures in our future climate outlook. Why do we care about how the Antarctic ice sheet will respond in our future warmer global temperatures?

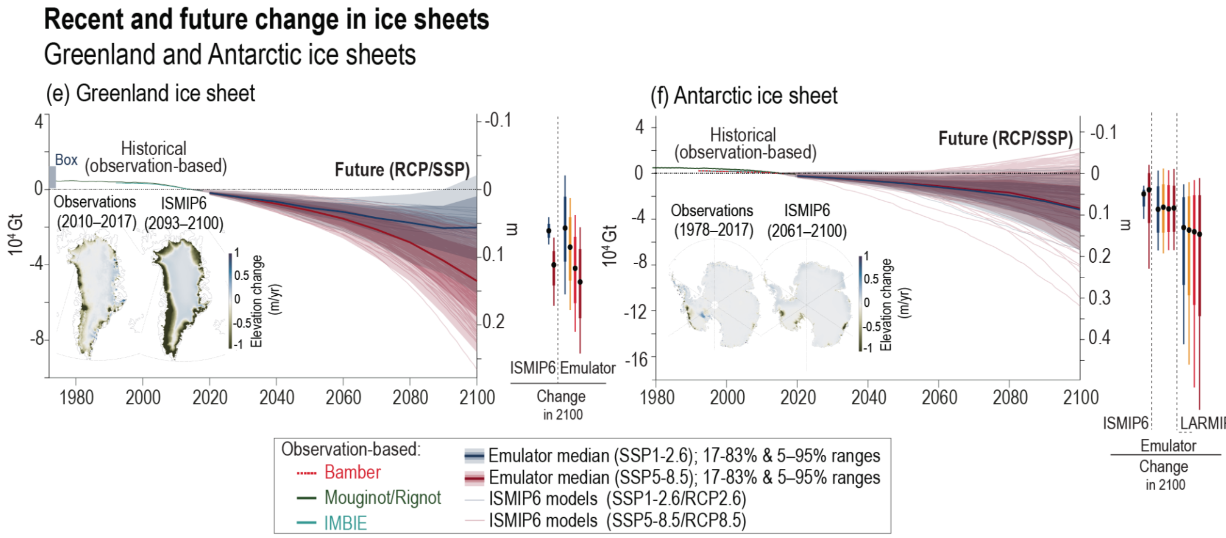

Figure 14. Total ice mass loss (in 10^4 gigatonnes, left axis) and meters of sea level rise (right axis) for both historical (measured or observed data) and future data projected using climate models for the (e) Greenland ice sheet and (f) Antarctic Ice Sheet. Inset maps show recently measured and future modeled ice sheet surface elevation changes. [Figure TS.11, panels e) and f) from Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33−144. doi:10.1017/9781009157896.002.]

8. Figure 14 (right side) shows both historical (measured) and modeled data for ice mass loss and resulting sea level rise 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 eventually ends up in the ocean and causes sea level to rise
b. Scientists can only make inferences about changes to the Antarctic ice sheet and sea level since the mid-1900s due to the unavailability of direct measuring tools before that point
c. The meltwater formed when the Antarctic ice sheet melts does not contribute to sea level rise

One difference between the Earth's climate system before the Mid-Pleistocene Transition and at present is that we are now emitting greenhouse gases into the atmosphere, resulting in atmospheric concentrations never measured before in the ice core record. Notice that the future modeled sea level rise has a wide range of possible values. This is largely based on different greenhouse gas emission scenarios: whether we will decrease or increase our greenhouse gas emissions in the future.

9. Based on what you've learned from the ice core record in this module, 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 cause global temperature to remain the same

10. Based on what you've learned from the ice core record in this module and question 9, how would increasing greenhouse gas emissions produced by human activities likely impact the rate of sea level rise?

a. The rate of sea level rise will likely decrease
b. The rate of sea level rise will likely increase
c. The rate of sea level rise will likely remain the same

Evaluate | Understanding the paleoclimate record

To review what has been presented and investigated during this module, answer the following questions:

11. Which of the following isotopes of carbon is not stable and decays to form another element over time?

a. ^{12}C
b. ^{13}C

c. ^{14}C

12. About how thick is the “bubble closeoff zone” of the Vostok ice core?
    a. 8 meters
    b. 10 meters
    c. 5 meters

13. You measure 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. How long is the Earth’s eccentricity cycle?
    a. 100,000 years
    b. 41,000 years
    c. 26,000 years

15. Scientists at COLDEX are measuring the water isotopes of ice meltwater. Which of the following variables could be determined from these water isotope measurements?
    a. Ice age
    b. Global temperature when the ice was formed
    c. Bubble gas age

16. Higher dust flux in the ice core is generally associated with which of the following:
    a. Glacial periods
    b. Interglacial periods

17. 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

18. COLDEX and the University of Washington Applied Physics Laboratory are collaborating to engineer a probe that can melt through the ice sheet quickly to measure dust concentrations in the ice. What is the name of this probe?
    a. The Ice Diver
    b. The Rapid Access Ice Drill

c. The Blue Ice Drill

19. Which of the following can help scientists correlate the age of an ice core and marine sediment core?

a. If the cores are located near each other
b. If volcanic ash from a known eruption is found in each core
c. If the yearly sediment layers are the same width as the yearly ice layers

20. 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

Workshop Extensions |
"Ice Core Lab" (at OSU CEOAS)