

## **Ice Core Proxy Methods for Tracking Climate Change**

Christopher Readinger

### **Introduction**

Since the Industrial Revolution, the study of climate change has become increasingly important due to the likely influence of human activities. Volumes of evidence clearly depict retreating glaciers, and rising global average temperatures supporting the idea that the anthropogenic effect is happening now. Predicting how climate may change however, is very difficult as the climate system is extremely complex, with many processes, interactions, and oscillations that are either poorly understood or yet undiscovered. Thus, to help expand our frame of reference regarding climate change, scientists must look beyond the limited amount of directly recorded instrumental data to times before historical and instrumental data existed.

Prehistoric climate records can expand our knowledge of climate and the range of variations that occurred before we had reliable instrumental records. These data can provide valuable insights into long-term global oscillations such as ice ages, and the variability of much shorter oscillations such as monsoons, and El Nino. Greater understanding of the potential for climatic variability and the forces that drive climate change will help put today's instrumental data in a much broader perspective and possibly provide the basis for more accurate long-range climatic forecasts. With more accurate forecasts, international groups such as the Intergovernmental Panel on Climate Change (IPCC) should be able to



Drill Site, Alaska - Bona-Churchill (2002)

<http://www-bprc.mps.ohio-state.edu/Icecore/Alaska.html>

Photo by Vladimir Mikhalenko, Byrd Polar Research Center, Ice Core Paleoclimatology Research Group (Scott Hall Room 108, 1090 Carmack Road, The Ohio State University, Columbus, Ohio 43210-1002)

make stronger arguments for government policies restricting greenhouse gas emissions and atmospheric pollution.



U.S. Daily Weather Maps Project  
[http://docs.lib.noaa.gov/rescue/dwm/data\\_rescue\\_daily\\_weather\\_maps.html](http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html)  
 (NOAA Central Library Data Imaging Project, National Oceanic and Atmospheric Administration, 1335 East-West Highway, SSMC1, 8th Floor, Silver Spring, MD 20910)

As our instrumental records extend back no more than ~150 years and are extremely limited in their spatial coverage researchers have found ways to extract climatic data from natural sources in order to reconstruct past climates. Some of these sources include ice cores, ocean and lake sediments, geomorphic surface features, tree rings, coral, stalactites and stalagmites, and others.

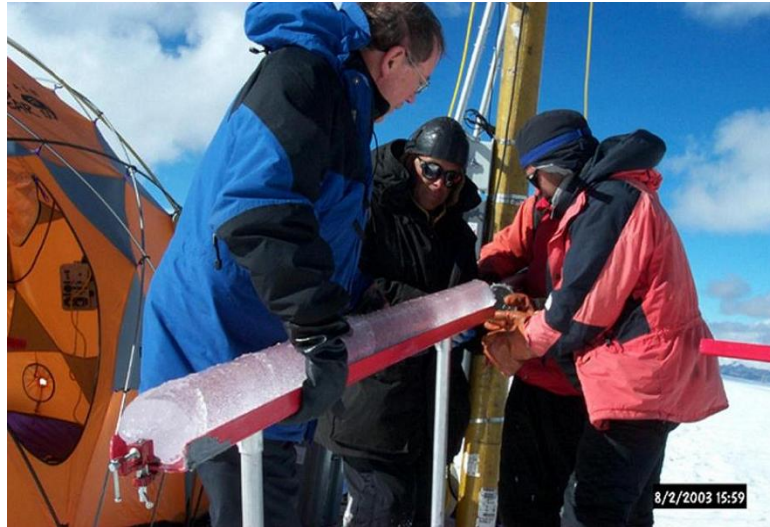
The study and analysis of information contained in proxy data is called paleoclimatology, and the records them-

selves are called paleo-proxies. A paleo-proxy record is in most cases an indirect estimate of more standard meteorological parameters such as air temperature or annual precipitation. Many paleoclimate studies that examine time periods in the Quaternary (from ~2 million years ago until the present) have relied heavily on ice cores and ice cores have proven to contain some of the best paleo-proxy records. While results are not 100% conclusive, numerous datasets support the theory of global warming, showing that the earth's overall surface temperature has increased in an unprecedented way in the last century or so. Ice cores are perhaps the single most powerful means of tracking climate histories that indicates this. In addition to containing many chemical constituents that are deposited in snow, dust, or air bubbles, ice cores can record climatic variations as small as a few years, to much larger variations as long as hundreds of thousands of years.

### Ice cores

As mentioned above, ice cores taken from the world's glaciers and ice sheets have become a critical source of paleo-proxy data. Ice cores can contain extensive time series, some reaching back hundreds of thousands of years, enabling scientists to study climate through glacial cycles and large climatic fluctuations. In addition, some ice cores can be analyzed annually, extending back a few hundred years before the present, allowing for the reconstruction of interannual climatic fluctuations such as El Nino, the North Atlantic Oscillation (NAO), or the Pacific Decadal Oscillation (PDO). Ice fields with the proper characteristics for ice cores are not limited to the polar regions and can be found on 6 of the 7 continents, providing climatic data over a large part of the Earth.

The primary sources of ice cores have been the Antarctic and Greenland ice sheets due to their immense size, extreme thickness, and relatively undisturbed ice. Their thickness makes them ideal for extracting long cores representing time spans that can exceed 100,000 years before the present in Greenland and 400,000 years in Antarctica. More recently, very valuable cores have



Ice Core, Drilling Operation, Peru - Quelccaya (2003)  
<http://www-bprc.mps.ohio-state.edu/Icecore/Quelccaya2003.html>  
 Photo by Doug Hardy, Byrd Polar Research Center, Ice Core Paleoclimatology Research Group (Scott Hall Room 108, 1090 Carmack Road, The Ohio State University, Columbus, Ohio 43210-1002)

been obtained from smaller ice caps from around the world, many in tropical or subtropical latitudes. These ice caps reside at much higher altitudes making their drilling more dangerous and difficult. In fact, many scientists considered the idea of living and working on a glacier 20,000 ft. above sea level for weeks at a time virtually impossible, not to mention the difficult task of bringing all the cores back down the mountain and shipping them frozen and intact to cold storage facilities. That was until the Ice Core Paleoclimatology Group at The Ohio State University's Byrd Polar Research Center decided to try, and have now drilled dozens of multi-century low latitude ice cores. To date, some of the low latitude sites where ice cores have already been drilled include Mt. Kilimanjaro, the Andes of Peru and Bolivia, and the Himalayan plateau. These low latitude records are valuable in that they contain records of very different climatic forces than those in polar ice. Unfortunately, in recent decades temperate and tropical ice fields have been retreating at unprecedented rates, and as this occurs many of the ice cores taken from these ice fields will be the only ones in existence.

When ice cores are drilled they are 4-5 inches in diameter and cut in lengths of about 1 meter to be catalogued and stored for analysis. Some projects allow for the chemical analyses to be done at the drill site; however other projects require the cores to be shipped and stored in cold rooms. For scientists interested in reconstructing climatic histories, the chemical composition of the ice and dust contained in it allows for a wide variety of analytical techniques, as mentioned above. This is a valuable characteristic of ice as it allows scientists to study many proxy parameters, enabling data comparisons from other ice cores and other paleo-proxy sources within the same ice core. This can be extremely useful in helping to determine age/depth relationships of ice cores (ice core dating) and test for data quality. Dating paleo-records is arguably the most important aspect of paleo-

climatic reconstructions, as time series that cannot be placed in time are essentially useless.

### Analytic Techniques

Ice cores can contain several forms of paleo-proxy data that estimate standard meteorological parameters to help reconstruct past climates. Some of the more common meteorological data that can be reflected in ice include air temperature, atmospheric circulation variations, precipitation amount, atmospheric composition, solar activity, and records of volcanic eruptions. These parameters can be represented by corresponding proxy records including stable isotopes, radioisotopes, dust composition, snow accumulation rate, air bubbles, and volcanic ash or sulfate.

All of the modern analytical techniques used to extract these proxy records have been developed and honed over time, and with the assistance of better technology and new ideas more accurate methods of ice core analyses are being developed. Before scientists can begin reconstructing past climates from paleo-proxies derived from ice cores however, the ice must be drilled and analyzed.

Parameter	Proxy Analysis
Paleotemperatures Summer Annual cycles (Days with snowfall)	Melt Layers $\delta D$ , $\delta^{18}O$
Humidity	Deuterium excess
Paleo-accumulation	Seasonal signals, $^{10}Be$
Volcanic activity	Conductivity, $SO_4$
Tropospheric turbidity	ECM, microparticle content, trace elements
Wind speed	Particle size, concentration
Atmospheric composition: Natural Variations and man-made changes	$CO_2$ , $CH_4$ , $N_2O$ content, glaciochemistry
Atmospheric circulation	Glaciochemistry (major ions)
Solar activity	$^{10}Be$
Ice Core Sources of Paleoclimatic Information: Modeled on a figure from Bradley, R. (1999). <i>Paleoclimatology: Reconstructing Climates of the Quaternary</i> . 2 <sup>nd</sup> Ed. San Diego: Academic Press, 126	



There are a variety of ice core drills that can be used, but the specific project goal and the temperature of the ice determines which drill is best. The hand powered auger drill is the most convenient for short cores (30-40m), however for longer cores a power source must be used. For ice that is well below freezing, electro-mechanical drills are preferred for drilling deeper cores. Thermal electric drills are more standard for warmer ice. Fuel is the most common source of power for most drills, however solar power was pioneered by the Ice Core Paleoclimatology Group in the 1980's and has been very effective. Solar panels proved to be portable, reliable, and pollution free.



The Ice Core Drill, Kilimanjar  
<http://www-bprc.mps.ohio-state.edu/Icecore/KilimanjaroDrillSystem.html>  
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Once the ice has been drilled and shipped to laboratories and cold storage facilities the chemical analysis can begin. To be sure of the highest quality of data, laboratories use clean rooms and equipment that is run by experienced laboratory personnel. Some of the instruments used for ice core analyses include mass spectrometers, microparticle counters, spectrophotometers, ion chromatographs, scanning electron microscopes, and gas chromatographers.

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### Stable Isotope Analysis:

One of the most common ice core proxies is the analysis of stable isotopic ratios, primarily deuterium and oxygen 18. Atoms are composed of protons, neutrons, and electrons. The number of protons determines what the element is, while neutrons and electrons can vary. An isotope is an atom with a different number of neutrons from the set number of protons. For example, oxygen, which contains 8 protons, usually has with it 8 neutrons creating oxygen 16. However, in some cases, there may be 9 or even 10 neutrons in the oxygen nucleus creating oxygen 17 and oxygen 18 respectively.



Laboratory Instruments, Analytical Facilities  
<http://www-bprc.mps.ohio-state.edu/Icecore/facilities.html>  
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<http://www.csa.com/discoveryguides/discoveryguides-main.php>

Released February 2006

Water, composed of hydrogen and oxygen, contains naturally occurring isotopes that combine into molecules of differing weights. Oxygen occurs naturally as three different stable isotopes with relative abundance in parenthesis -  $^{16}\text{O}$  (99.76%),  $^{17}\text{O}$  (0.04%), and  $^{18}\text{O}$  (0.2%). Hydrogen can occur with two stable isotopes -  $^1\text{H}$  (99.984%) and  $^2\text{H}$  (0.016%). Together these combine to make up all water molecules, of which only two combinations are important for paleoclimatic research -  $^1\text{H}^2\text{H}^{16}\text{O}$  and  $^1\text{H}_2^{18}\text{O}$ . As these water molecules are evaporated, primarily from the oceans, the lighter molecules, those having fewer neutrons, are preferentially evaporated over the heavier ones, due to a slight difference in vapor pressure caused by the extra neutrons. This causes the vapor to be depleted in heavy molecules but enriched in lighter ones. As the air mass cools and condensation occurs, the heavier molecules preferentially condense due to the same principle. The condensation is then assumed to fall out of the cloud as precipitation. Thus, the oxygen isotopic ratio of rain and snow is strongly related to condensation temperature. If the temperature of the air mass should continue to fall, the condensation will contain decreasing concentrations of the heavy molecules, resulting in a depletion of  $^{18}\text{O}$  relative to precipitation that condensed in a warmer environment. In the current environment this is exemplified by annual layers exhibited in Greenland and Antarctic cores with a much greater depletion of heavier molecules in ice and snow.

In the 1960's this principle was well understood by scientists and engineers; however for researchers around the world to study the relationship between isotopic ratios and air temperature a standard had to be developed to allow for intercomparisons of all samples. Developed in 1961, this is called Standard Mean Ocean Water (SMOW), and all oxygen isotopic deviations from it are denoted as  $\delta^{18}\text{O}$ ; hydrogen isotopic deviations as  $\delta\text{D}$ .

**SMOW equation**

$$\frac{\delta^{18}\text{O} = \left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{sample}} - \left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{SMOW}}}{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{SMOW}}} \times 10^3 \text{ ‰}$$

In the context of ice cores, this technique allows scientists to estimate the actual air temperature of condensation when the snow fell. Expressed as a time series of multiple samples, the technique can show variations in temperature. Depending on the thickness of the ice layers and the frequency of sampling, the variations can be either seasonal, allowing for annual resolution in temperature reconstructions, or of much larger climate fluctuations that may have occurred over thousands of years. As the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  fluctuate with temperature, the ice thickness between successive cold or warm periods allows researchers to estimate the annual snow accumulation rate.

**Dust Analysis**

Another major component of ice cores is dust and other foreign particles. Dust composition and size distribution, along with other chemical analyses, can produce a variety of

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different proxies providing information ranging from atmospheric circulations, volcanic eruptions, wind speed, and tropospheric turbidity.

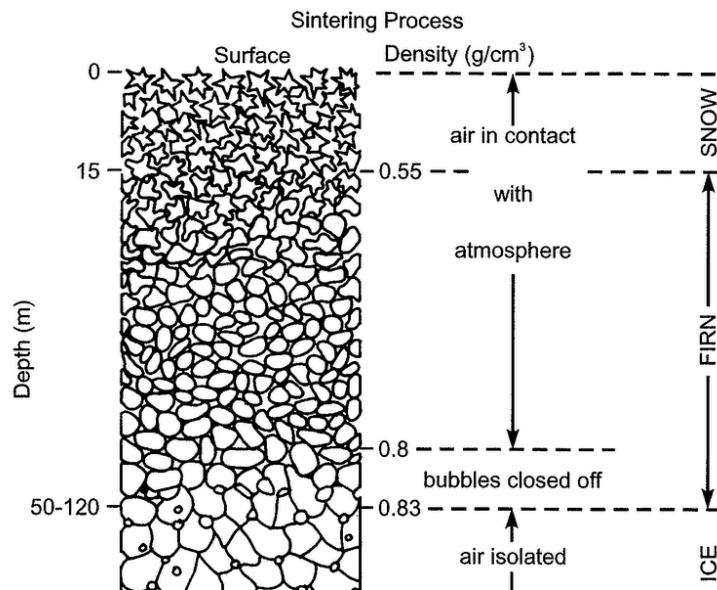
One of the most straightforward analysis techniques is the detection of ash and sulfate layers from explosive volcanic eruptions. When detected in annually dated cores, known eruptions can provide date horizons to constrain the age of ice layers and improve the accuracy of time series. To detect volcanic horizons scientists can look for visible ash layers, test the electrical conductivity of the ice, or chemically sample for sulfate. These techniques are very effective for pre-industrial ice; however, since the industrial revolution and the emission of large amounts of anthropogenic sulfate, some of the volcanic signal is lost in the rising level of background sulfate. This is another good example of the effect humans have on the environment and climate.

Similar to volcanic horizons, another horizon that adds constraints to annual dating occurs in the 1950s and 60s from nuclear bomb test fallout. These provide accurate dates for short annually resolved cores.

Other forms of dust and chemical analyses are used to determine various proxies, and most are governed by where the ice core is located, and what the ice contains. For example, analyses of chlorine and sodium ions in Himalayan ice have been used to estimate the strength of the Indian monsoon. And in South American ice cores, visible dust layers indicate seasonal and climatic variations in wind. The dust layers can be used to help annually date the core for short periods, or estimate atmospheric turbidity and circulations for long periods. These are just a few of the many examples of dust analyses.

### Atmospheric Composition from air bubbles

As new snow falls on the ice sheets it covers older snow and buries it deeper. The weight of the new snow causes older snow to compress and deform, eventually turning it into firn, and then into ice. During the long transition from snow to ice, air bubbles get trapped, providing one of the best methods for determining past atmospheric composition for pre-instrument time periods.



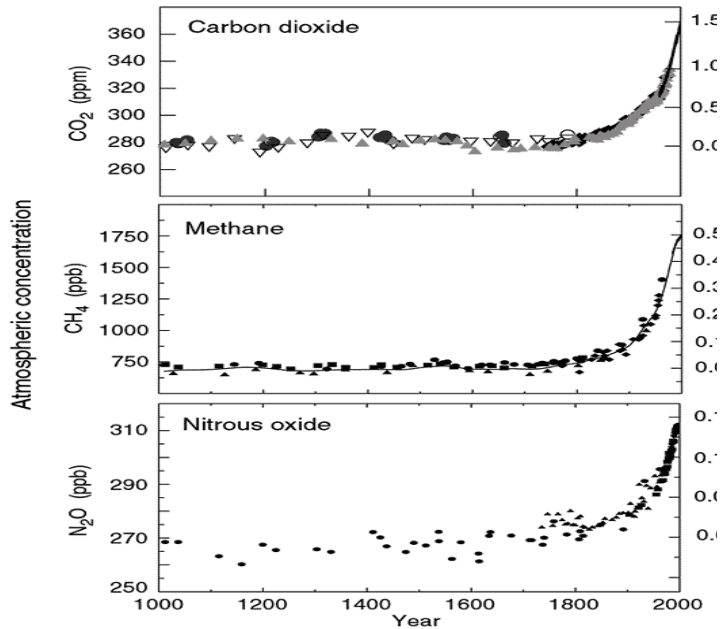
Snow-Ice Transition, Sintering Process  
 Raynaud, D. (1992). The ice record of the atmospheric composition: a summary. In: *Trace Gases and the Biosphere* (B. Moore III, and D. Shimel, eds.). Boulder: UCAR, 165-176. Reprinted in Bradley, R. (1999). *Paleoclimatology: Reconstructing Climates of the Quaternary*. 2<sup>nd</sup> Ed. San Diego: Academic Press, 168.

The transition from snow to ice takes time and is primarily dependant on accumulation rate. More accumulation buries older snow faster, speeding the transition to ice. At high accumulation sites in Greenland for instance, the bubbles are fully closed off after ~100 years. In central Antarctica, where the accumulation rate is very low, bubble close-off can take more than 2000 years. The delay in pore close-off is important because, until the pores fully close, they are still in contact with the outside air and their composition may change with it. Thus, the air bubbles in a specific sample of ice are representative of air that is younger than the ice it is contained in. Still, for atmospheric trace gases with relatively short residence times including greenhouse gases, such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), air bubbles are invaluable for studying past atmospheric composition.

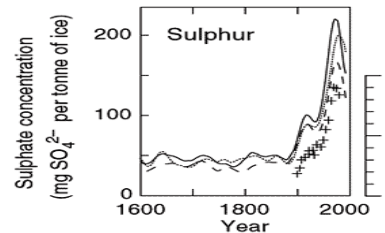
By studying air bubbles trapped in ice, scientists can look at time series spanning a few hundred years to see the effect of anthropogenic pollution on atmospheric composition or look at how greenhouse gases fluctuated during the glacial/interglacial transitions. For example, the Vostok Antarctic ice core has shown large fluctuations in CO<sub>2</sub> and CH<sub>4</sub> over the past 200,000 years. These large variations are believed to be in part due to changes in ocean circulation affecting the amount of dissolved carbon contained in seawater. Furthermore, air bubble analysis has shown that the range of the CO<sub>2</sub> variations, although large, did not reach the magnitude forecast to occur from human activities in coming centuries, and also occurred very slowly (over tens of thousands of years) compared to the rapid increases that have been measured over the past 200 years.

**Indicators of the human influence on the atmosphere during the Industrial Era**

**(a) Global atmospheric concentrations of three well mixed greenhouse gases**



**(b) Sulphate aerosols deposited in Greenland ice**



<http://www.ipcc.ch/present/graphicswithout.htm>  
 Intergovernmental Panel on Climate Change (IPCC Secretariat,  
 c/o World Meteorological Organization, 7bis Avenue de la Paix,  
 C.P. 2300, CH- 1211 Geneva 2, Switzerland)



## Limitations

Using the techniques listed above and more, climatologists can attempt to reconstruct past climates and recreate the climate system. On the whole, ice cores have proven extremely useful for paleoclimatology, and many scientists have worked tirelessly to extract every shred of information from each sample. Unfortunately, ice cores do present some difficulties and have limitations that scientists must overcome.

One major problem that has become more prevalent in recent years is summer melting of the ice fields. Recent surveys of Greenland have shown large areas of summer melt in southern Greenland, and recent visits to Peru's Quelccaya ice cap have shown melt areas where none existed only 25 years ago. The problem that melting presents is that the melted water percolates down through the ice and can destroy the even layering that regular snowfall produces. This makes accurate dating extremely difficult, and contaminates many of the naturally deposited stable isotopes and other chemical constituents in the ice with non-representative concentrations. In the large ice sheets such as Greenland or Antarctica some melt areas can be avoided by drilling in colder or higher regions. Smaller ice caps on the other hand will generally experience the same conditions overall. Some studies, however, have gained significant scientific value by analyzing cores drilled from around the Greenland ice sheet to show how climatic oscillations such as the NAO affect the North Atlantic region in different and unexpected ways. Thus, simply avoiding high melt areas is not always desired and sampling the whole ice sheet can be very important. While summer melt areas are bad, the ice cap on Mount Kilimanjaro has fared even worse. The whole ice cap is forecast to disappear within 20 years, and although the primary cause for Kilimanjaro's disappearing ice cap has not been fully determined, there is plenty of evidence to support the idea that global average temperatures have been rising and glaciers have been retreating over the past several decades.

Another limitation of ice cores is that they only represent data for conditions during snowfall. If little or no snow falls for a few consecutive years, no record will be left in the ice, which could throw off annual dating. If short droughts are a characteristic of a climatic oscillation then they will likely recur, thus accentuating the analytic errors. Antarctica has such low annual snowfall that annual dating is virtually impossible and analyses are only performed for long time periods. A different problem occurs there however, where the ability of wind to transport snow great distances and create drifts must be addressed. That is why, if possible, two cores are often extracted from nearby locations to test the upper layers for data quality and reproducibility.

One other potential limitation of ice cores is that core samples can be altered by ice flow and the effect of basal deformations. For very deep ice cores, the effect of the ice bed is important to consider and some drill sites are chosen over others because of the shape of the bedrock. Irregular flow rates, or flow around basal deformities, can cause melting, folds, and other deformations which can propagate upward into younger layers. These deformations can greatly affect how time series are interpreted and in some cases destroy the paleo-record. Fortunately, the Antarctic ice sheet is so thick that extremely long cli-

mate histories can be extracted without having to drill all the way to bedrock. The Greenland ice sheet is also very thick, and many of the longest cores have been taken from the ice divide where the ice is the thickest and flows in more predictable ways.

## Summary

Because climate change, both natural and anthropogenic, has the potential to alter our way of life in coming decades, paleoclimatology has become critical for atmospheric scientists placing today's climate in the context of past variability. While meteorological instruments have shown important trends over the past century, paleo-proxy data have provided the ultimate basis for climatic variability by extending our records of climate thousands and even millions of years. Although proxy records are not direct measurements, they have been tested and calibrated in the laboratory to create reliable estimates of meteorological parameters.

While paleo-proxy records can be extracted from many sources, ice cores have proven to be flexible and extremely reliable for researching the climates of the Quaternary geologic period and reconstructing climatic variability. They can be resolved annually depicting variations in El Niño, or monsoon, or analyzed for much longer time periods including glacial/interglacial cycles. In addition, the large variety of chemical and physical data contained in ice cores including stable isotopes, atmospheric composition, chemical and dust deposition, and accumulation rate allows scientists to research many different climatic parameters. Analytic variety allows for the creation of the more robust climate reconstructions, including the ability to test for reproducibility, and compare proxy records between multiple sources. Although the drilling and transportation process can be difficult, and there are inherent limitations contained in the ice, scientists have learned to weed out problems, and calibrate proxy records based on tested parameters.

As scientific research in paleoclimatology progresses, the depth of our knowledge of the climate system grows. Ice core records, combined with other paleo-proxy data, are creating a window to the past. Although many important discoveries have already been made, many have yet to be uncovered and may in fact be buried in ice.