Title: *GREENLAND ICE CORES: FROZEN IN TIME* , By: Alley, Richard B., Bender, Michael L., Scientific American, 00368733, Feb98, Vol. 278, Issue 2
Database: *Business Source Premier*

GREENLAND ICE CORES: FROZEN IN TIME

Contents

Ice, frozen in place for tens of thousands of years, provides scientists with clues to past--and future--climate

One of the grand challenges for modem science is to predict climate. Researchers especially wish to learn about large surprises--changes that could help one society flourish or lead another to devastation. Will Europe return to the warmer temperatures of 1,000 years ago, when the Vikings settled Greenland and Britons nurtured vineyards? Or could California suffer extended droughts, lasting centuries, just as the region endured roughly a millennium ago? Recent concerns about global warming and the effects of man-made greenhouse gases have only heightened the need to understand the basic natural processes that cause the climate to change.

To gain this fundamental knowledge, climatologists have turned to the past. Drilling deep below the surface of ice sheets and glaciers in Greenland, Antarctica and elsewhere, scientists have obtained water frozen for tens of thousands of years. Trapped in the ice are trace chemical impurities containing precious information about ancient climate.

Recent work by European and U.S. teams, including us, studying cores of ice from deep drillings in Greenland has shown that large, rapid changes in climate, typically lasting a few hundred to several thousand years, punctuated the longer cycles between glacial (cold) and interglacial (warm) periods. Modern cultures have not experienced such dramatic swings. What caused them? Did they occur simultaneously in the high latitudes of the Northern and Southern hemispheres? How were the tropics affected? The answers to these questions could provide a window to the future. Although current concerns about climate change focus on the influence of human activities, ancient shifts may have been fated by the heavens.

Celestial Effects

During the 1920s and 1930s, Milutin Milankovitch, a Serbian astronomer, studied how the gravitational pull from other planets causes subtle changes in the orbit of the earth. These alterations result in different distributions and intensities of sunlight, which then lead to dramatic variations in climate over tens of thousands to hundreds of thousands of years. Milankovitch investigated three orbital variables: the tilt of the spin axis; the precession of the tilt (a motion similar to the wobbling of a spinning top); and the eccentricity in the orbit around the sun (that is, whether the orbit is almost circular or stretched out into a more elongated ellipse). Changes in these three parameters cause slow but distinct oscillations in climate with periods of about 40,000 years (governed by tilt), 20,000 years (precession) and 100,000 or more years (eccentricity) [see "What Drives Glacial Cycles?" by Wallace S. Broecker and George H. Denton; ***SCIENTIFIC AMERICAN***, January 1990].

Many contemporaries of Milankovitch denounced his astronomical theory of climate change, which remained largely unproved up to his death in 1958. Subsequently, however, scientists studying sediments deposited on the bottom of the ocean made some landmark discoveries.

They found that the past few million years have been characterized by a repeated series of temperature changes during which great glaciers advanced and retreated over vast areas, all the time marching to the beat predicted by Milankovitch. For at least the past half a million years, the basic climate cycle--the period from one glacial or interglacial extreme to the next--has been about 100,000 years, with shorter-term oscillations of roughly 20,000 and 40,000 years.

More recently, researchers have sought to study ancient climate in even finer detail. To that end, investigators have directed some of their attention away from ocean sediments and have examined cores extracted from depths down to three kilometers (about two miles) below the surface of the great ice caps of Greenland and Antarctica, among other areas [see "The Antarctic Ice," by Uwe Radok; ***SCIENTIFIC AMERICAN***, August 1985]. But scientists could not have drilled just anywhere in these frozen wastelands; they had to find "good" glacial deposits, where snow has accumulated over tens of thousands of years. As the snow piles up in such places, it compresses under its own weight and eventually forms ice, preserving in the process a wealth of information about the climate.

Age-Old Question

The crucial prerequisite in the study of ice cores is the accurate determination of the age of the specimens. Without these data, scientists could not build an overall chronology in which to place their other measurements. Fortunately, investigators can often determine the age of the ice by simply counting off the number of years.

In places such as central Greenland, where it snows frequently, the ice forms in annual layers that can be analyzed in much the same way that yearly growth rings can be used to determine the age of a tree. The layering in glacial ice is often noticeable with the naked eye because crystals from summer snow are larger than those of winter snow. Climatologists can also detect the annual layers by measuring the acidity of the ice, which is generally higher for summer snow for reasons that remain somewhat obscure. And researchers can use a laser to determine the concentration of dust particles in an ice specimen. The number of dust particles typically rises in the spring because of the greater strength of the wind in that season.

Using these and other indicators, one of the authors (***Alley***) worked with his colleagues on the U.S. ice-coring project in Greenland, headed by Paul A. Mayewski of the University of New Hampshire, to obtain a chronology that compares well with several independent measures. For example, an analysis of the composition of ash found in certain layers of ice enabled the team to identify the volcanoes involved and the corresponding historical dates of the eruptions. Such corroborative testing indicates that the counting of annual strata introduces virtually no errors for Greenland ice that is several centuries old. For the most recent 11,500 years, the so-called Holocene warm period, layer counting is correct to within 1 percent. Although the accuracy is somewhat poorer in older ice from colder times, it appears to be as good as that of other dating techniques to at least 50,000 years ago. Arguably annual layers remain visible past 100,000 years, but they often appear distorted.

Why are these deep layers so disrupted? Although nominally solid, glaciers and ice sheets spread and thin under the influence of gravity, similar to the motion of pancake batter poured on a griddle. As the movement continues over tens of thousands of years, the bottom layers of ice become extremely drawn out (sometimes disappearing altogether) and crumple easily as the glacier oozes over the ground below.

The resulting deformations make it impossible to count annual layers continuously below a certain depth. For example, the cores the U.S. team obtained in Greenland contained layers that, from top to bottom, went from being horizontal, to having small wiggles, to showing Z-shaped folds, to becoming slanted at angles up to 20 degrees in ice older than about 110,000 years. Cores taken nearby in a parallel effort by European researchers revealed a similarly complex (yet different) pattern in ice older than 110,000 years.

This dissimilarity helped to solve a puzzle. Ice initially believed to be from the previous interglacial period--the Eemian, which ended about 120,000 years ago-indicated severe climate changes with rapid and repeated swings. The result was both surprising and alarming: climatologists had viewed both the present and past warm interglacial times as stable and free of such wild shifts.

Scientists thus began a series of careful examinations that have since shown that flow of the ice disrupted the older layers in both the European and U.S. cores. A clue was that the two sets of climatic records were virtually identical during the most recent 110,000 years but that they could not be positively matched for older times. Apparently, these disturbances occurred farther above the bed than originally had been expected. Paleoclimatologists are now beginning to understand such effects and are developing additional techniques, such as computer simulations, to recognize them.

To obtain a reliable Eemian record, the European team has commenced another deep-drilling project in Greenland, about 340 kilometers northwest of the two earlier drill sites. Layers older than 110,000 years at the new location are thought to be higher above the bedrock than those at the previous bore positions. Thus, distortions from the flow of ice are less likely to be acute.

Ice-Core Secrets

If the Europeans succeed, scientists will gain important insight into how the climate operated, in large part from their estimates of ancient temperatures. The primary thermometer used for this purpose takes advantage of the fact that water comes in "light" and "heavy" flavors, or isotopes. Light isotopes have only ordinary hydrogen and oxygen; heavy ones contain either hydrogen with an added neutron (deuterium) or oxygen with one or two extra neutrons (oxygen 17 or oxygen 18). The cooling of an air mass causes precipitation, which removes more of the heavy water (because of its lower vapor pressure) from the moisture-laden atmosphere. Consequently, snowfall at an inland site during colder times tends to contain "lighter" water, the heavy isotopes having already been squeezed out of the air as it traveled over the ocean and the flanks of the ice sheet before reaching the site.

A second thermometer for ancient climate comes from the current temperature of the ice sheet. Just as a frozen roast placed in a hot oven will tend to maintain the temperature of its former environment by remaining frozen in the center even as its outside begins to warm, the ice sheet is actually colder a kilometer or two (or about a mile) down than at the surface. In essence, the older ice "remembers" the extreme temperatures of the last ice age. Taken together, the two thermometers show that the severest periods of the last ice age were indeed quite frigid-on average Greenland was colder by more than 20 degrees Celsius (36 degrees Fahrenheit) than it is currently.

In addition to records of temperature, ice cores contain a history of precipitation. Scientists have, for example, used the thickness of an annual layer (after correction for any distortions caused by the flow of ice) to gauge the amount of snow that year. This analysis revealed that the coldest periods in central Greenland had four to five times less precipitation than today.

Further clues to ancient climate are supplied by windblown materials trapped in the ice. Coarser dust particles suggest winds of greater strength. Researchers can, in fact, track past patterns of atmospheric circulation by using the composition of the dust to determine its source, just as the analysis of ash enables the identification of the volcanic eruption involved. Other trace materials found in the ice cores include chemicals from marine algae and radioactive isotopes produced in the air by cosmic rays.

A decreased concentration of these substances indicates either a smaller supply or an increased amount of snowfall, which dilutes these materials. Because the annual layering in cores from central Greenland allows scientists to determine the rate at which snow accumulated, they have been able to separate the two effects. After doing so, they uncovered up to 100-fold changes over time for some windblown imports such as calcium, indicating that much stronger winds and perhaps larger deserts existed during cold intervals.

The ice is also an excellent storehouse for samples of ancient air. In freshly fallen snow, gas molecules circulate easily through pores between the ice crystals. The massive weight of snow that piles up on a polar ice sheet, however, presses down on the deeper layers, causing the pores to become smaller and smaller until, between a depth of about 40 and 120 meters, the compression is great enough that air becomes imprisoned as individual bubbles in the ice.

Analyses of these tiny air samples by one of us (Bender) and others studying ice from Greenland and Antarctica reveal how concentrations of atmospheric gases have changed over time. In particular, scientists have determined how various heat-trapping greenhouse gases have varied naturally. From glacial to interglacial periods, for example, the concentrations of carbon dioxide and methane surged by about 50 and 75 percent, respectively. This information has helped put the recent additional increases caused by human activities--30 percent for carbon dioxide and 160 percent for methane--into perspective.

Studies of trapped gas have an ancillary benefit. Because the global atmosphere mixes rapidly, its makeup everywhere is almost the same. Thus, researchers can safely assume that changes in the atmospheric composition occurred simultaneously in Greenland and Antarctica, allowing them to use gas measurements to correlate ice cores taken from opposite sides of the world.

Flickering Climates

Examination of the Greenland ice cores has bolstered the results of previous investigations of Antarctic ice cores and deep-sea sediments. Combined, the different studies provide solid support for Milankovitch's astronomical theory of climate change. For example, the different records show warm temperatures at about 103,000, 82,000, 60,000, 35,000 and 10,000 years ago, which roughly reflect Milankovitch's 20,000-year precession cycle.

But perhaps the most striking features of the Greenland ice-core results are "interstadial events": intervals lasting a few hundred to a few thousand years during which Greenland warmed rapidly, then cooled at first slowly, then quickly. The Greenland ice cores clearly show that between 100,000 and 20,000 years ago, approximately two dozen interstadial events occurred--all unpredicted by Milankovitch theory.

Interestingly, the Greenland ice cores demonstrate that the methane concentration of the atmosphere increased during each interstadial event. Methane is produced by bacteria in environments where oxygen is scarce--for example, in tropical swamps and bogs. The higher methane levels in the ice indicate that the tropical wetlands must have expanded during interstadial times, evidently because of increased rainfall.

An intriguing characteristic of interstadial events is their abruptness. Changes of perhaps five to 10 degrees C (nine to 18 degrees F) or more, twofold in snow accumulation and up to 10-fold in dustiness occurred over mere decades, sometimes even during as little as a few years. This dramatic behavior was most prominent during times of intermediate temperatures over the past 100,000 years; the coldest part of the ice age and the modern period of warmth appear stabler in comparison. Right before and after the large interstadial jumps, the climate at times took smaller hops back and forth between warm and cold--a behavior that scientists have dubbed flickering. So, in addition to the interstadial shifts, the climate apparently bounces repeatedly between a warm and a cold mode all when Milankovitch would have predicted gradual transitions.

Beyond Milankovitch

To explain such seemingly erratic behavior, scientists have begun to investigate other factors in addition to the earth's orbit. Using sophisticated computer models, researchers have sought to understand "teleconnections," by which changes in the climate of one geographic region trigger variations elsewhere. For example, recent investigations indicate that warming in high latitudes could alter the circulation of the ocean or atmosphere in ways that would also heat the tropics. Such warming at low latitudes would enable water to evaporate more quickly there. That increase in the amount of water vapor {a greenhouse gas} would, m turn, trap more heat near the surface of the earth.

Similarly, during glacial times the vast continental ice sheets and the enormous expanses of frozen ocean around them reflected much sunlight back to space. In warm times, melting of the ice sheets allowed more of the sunlight to be absorbed. And the higher concentration of carbon dioxide, as well as other greenhouse gases such as methane and water vapor, led to more heat retention.

Because of such interactions, climatologists reasoned that different regions of the planet would warm or cool together. It came as a surprise, then, when Thomas E Stocker of the University of Bern and Thomas J. Crowley of Texas A&M University independently predicted in 1992 that for rapid climatic events, Greenland and Antarctica would change oppositely.

Studying the effects of ocean currents, Stocker and Crowley noted that today's tepid, salty waters flow in the Gulf Stream from the equator toward the Arctic, where they release heat to the atmosphere, giving northern Europe its relatively equable climate. After cooling, the salty waters become dense and sink to the deep ocean, where they then flow southward as part of a great "conveyor belt." During the harsh, stadial times of the ice ages, the conveyor was off or weakened, and the resulting slower flow of equatorial waters to the Arctic left Greenland and northern Europe particularly frigid. During interstadial periods, the conveyor strengthened.

Stocker and Crowley examined how this oceanic circulation affects the climate of the Southern Hemisphere. Their special insight was to show that the conveyor cools the south at the same time it warms the north, and vice versa, because of two effects. First, the flow of cold, deep waters to the Southern Hemisphere causes a return current of shallower, warmer waters to the north, which brings additional heat there while robbing it from the south. Second, slowing of the conveyor causes more warm waters to reach the surface of the sea around Antarctica, where they release heat that warms the air in the far south.

Support for this theory of out-of-synch climate change came in the mid1990s, when scientists studying fossil foraminifera (microscopic seashells) found that the Antarctic Ocean was warm when the conveyor was not operating. Furthermore, in light of the predictions of Stocker and Crowley, Wallace S. Broecker of Columbia University reexamined the climate records during the last deglaciation, between 20,000 and 10,000 years ago. He showed that warming stalled in Antarctica during times of rapid temperature increases in Greenland, and vice versa.

Bender and several other colleagues have shown that all the major stadial and interstadial events recorded in the Greenland ice cores are also present in Antarctica, although climate changes in the south were not as large or abrupt. Uncertainties in dating the cores precisely have made it difficult to determine whether cooling in Greenland caused warming in Antarctica for all these events. Laboratories in Grenoble, Bern and elsewhere are now in the process of extending exact correlations back to the middle of the last ice age.

This interest in the relative timing of climate change in polar regions is one of the factors spurring new efforts to extract deep ice cores from Antarctica. Teams from the U.S., Japan, Europe and Australia all have deep-drilling projects under way. One goal is to obtain cores containing climate records for the past 110,000 years (or earlier, if possible) that can be precisely correlated with the measurements from Greenland.

These research programs, in addition to the ongoing European effort in Greenland, will help answer fundamental questions about the climate during oscillations between glacial and interglacial periods. Only by obtaining this fuller understanding of the past can scientists begin to predict future climate, including the severity of greenhouse warming in the near term and, further off, the timing of any possible return to an ice age.

The Authors

RICHARD B. ***ALLEY*** and MICHAEL L. BENDER were members of the U.S. team that extracted and analyzed ice cores from central Greenland in the early 1990s. Both men are currently involved in the U.S. project drilling for ice cores in West Antarctica. ***Alley*** is professor of geosciences at Pennsylvania State University and an associate at the Earth System Science Center there. He received his Ph.D. in geology from the University of Wisconsin. His recent research includes studying how glaciers and ice sheets record climate change, how their flow affects sea level, and how they erode and deposit sediments. Bender is professor in the department of geosciences at Princeton University. He did his graduate studies at the LamontDoherty Earth Observatory of Columbia University. He was with the Graduate School of Oceanography at the University of Rhode Island for 25 years. His current research includes analyzing oxygen and its isotopes as a means to learn about ancient climates.

DIAGRAMS: MEASUREMENTS of ancient temperature (a) and atmospheric methane (b) from the Greenland ice cores have corroborated earlier findings about climate at Vostok, Antarctica (c), and for the total volume of ice around the world, as determined from the analyses of deep-sea sediments (d). In particular, the different research shows a warm period approximately every 20,000 years. A more gradual trend of cooling until 20,000 years ago and the rapid warming between 20,000 and 10,000 years ago follow a longer, approximately 100,000-year cycle.

PHOTO (COLOR): GREENLAND ICE CORE

PHOTO (COLOR): VOSTOK ICE CORE

PHOTO (COLOR): CENTRAL GREENLAND, where snow has accumulated for more than 100,000 years, offers researchers the opportunity to probe ancient climate change by drilling into the glacier below.

PHOTO (COLOR): Slicing through Time Scientists make many different kinds of observations in their efforts to decipher the record of climate held in ice cores (such as the cut example at the left). Some key methods of analysis appear below.

PHOTO (COLOR): ANNUAL LAYERS, often visible with the naked eye, are usually horizontal, but slow movement of the glacier sometimes distorts them into Z-shaped folds.

PHOTO (COLOR): AIR BUBBLES become trapped in the snow as it compresses into ice. These samples of the ancient atmosphere reveal how concentrations of greenhouse gases such as carbon dioxide and methane have changed.

PHOTO (COLOR): OXYGEN ATOMS in the ice can vary in composition. The relative abundance of the different types reflects the temperature at the time of precipitation.

PHOTO (COLOR): The drill, essentially a hollow barrel with sharpened cutters at the tip, is lowered into the borehole on a cable from an indoor platform (right). To prevent the hole from collapsing on itself, technicians inject a fluid such as butyl acetate (a pineapple-smelling food additive) to equalize pressure with respect to the surrounding ice.

PHOTO (COLOR): Tools of the trade

PHOTO (COLOR): Detail a shows leaf springs that firmly grip the adjacent ice to keep the upper part of the assembly from twisting or spinning while the lower part is drilling.

PHOTO (COLOR): Detail b shows the electric motor attached to the tube. This motor spins the cutters against the ice, making chips that are pumped up the outside of the barrel. Such drilling leaves a cylinder, or core, of solid ice inside.

PHOTO (COLOR): Detail c shows the sharpened, pivoting metal "core dogs," which are designed to ride lightly down the outside of the core during drilling. When technicians raise the barrel, the dogs, which are slanted slightly upward, dig into the bottom of the core, freeing it from the surrounding ice. The dogs also hold the core inside the barrel while the entire assembly is winched up the hole.

PHOTO (COLOR): EXAMINATION OF ICE CORES by various teams from the U.S., Japan, Europe and Australia is currently taking place in Antarctica and Greenland. One goal of these studies is to determine how the climate in the south and north are related.

Further Reading

ABRUPT INCREASE IN GREENLAND SNOW ACCUMULATION AT THE END OF THE YOUNGER DRYAS EVENT. R. g. ***Alley*** et al. in Nature, Vol. 362, pages 527-529; April 8, 1993.

EVIDENCE FOR GENERAL INSTABILITY OF PAST CLIMATE FROM A 250-1OCR ICE-CORE RECORD. W. Dansgaard et al. in Nature, Vol. 364, pages 218-220; July 15, 1993.

CLIMATE CORRELATIONS BETWEEN GREENLAND AND ANTARCTICA DURING THE PAST 100,000 YEARS. Michael Bender, Todd Sowers, Mary-Lynn Dickson, Joseph Orchardo, Pieter Grootes, Paul A. Mayewski and Debra A. Meese in Nature, Vol. 372, pages 663-666; December 15, 1994.

LARGE ARCTIC TEMPERATURE CHANGE AT THE WISCONSIN-HOLOCENE GLACIAL TRANSITION. Kurt M. Cuffey, Gary D. Clow, Richard B. ***Alley***, Minze Stuiver, Edwin D. Waddington and Richard W. Saltus in Science, Vol. 270, pages 455-458; October 20, 199,5.

~~~~~~~~

by Richard B. ***Alley*** and Michael L. Bender

Copyright of **Scientific American** is the property of Scientific American Inc.. Copyright of PUBLICATION is the property of PUBLISHER. The copyright in an individual article may be maintained by the author in certain cases. Content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.
Source: Scientific American, Feb98, Vol. 278 Issue 2, p80, 6p
Item: 112426
~~~~~~~~