WHAT DRIVES THE GLACIAL CYCLES?


Photo Credit: Gary Comer

WALLY BROECKER

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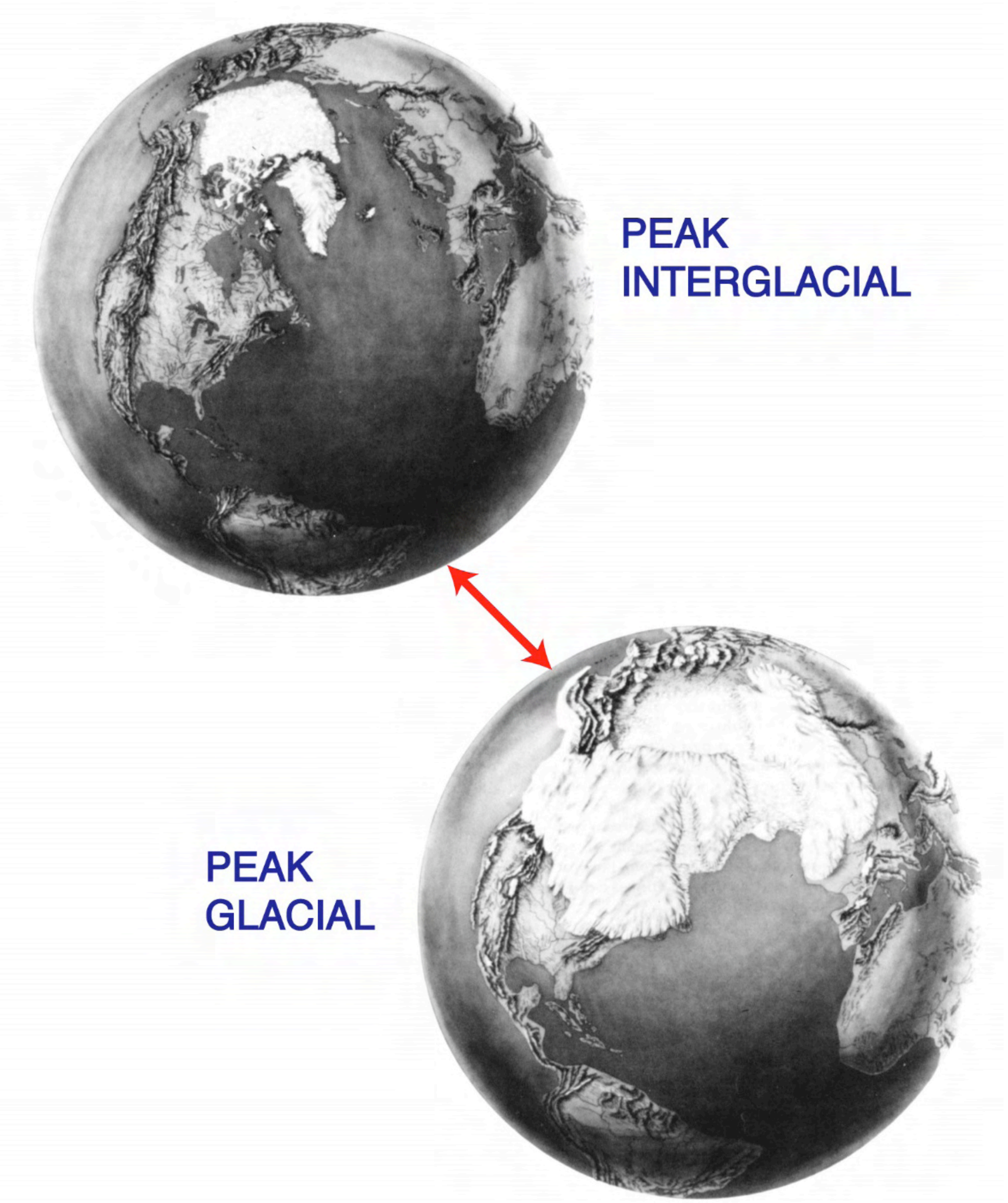

From Imbrie and Imbrie 1979

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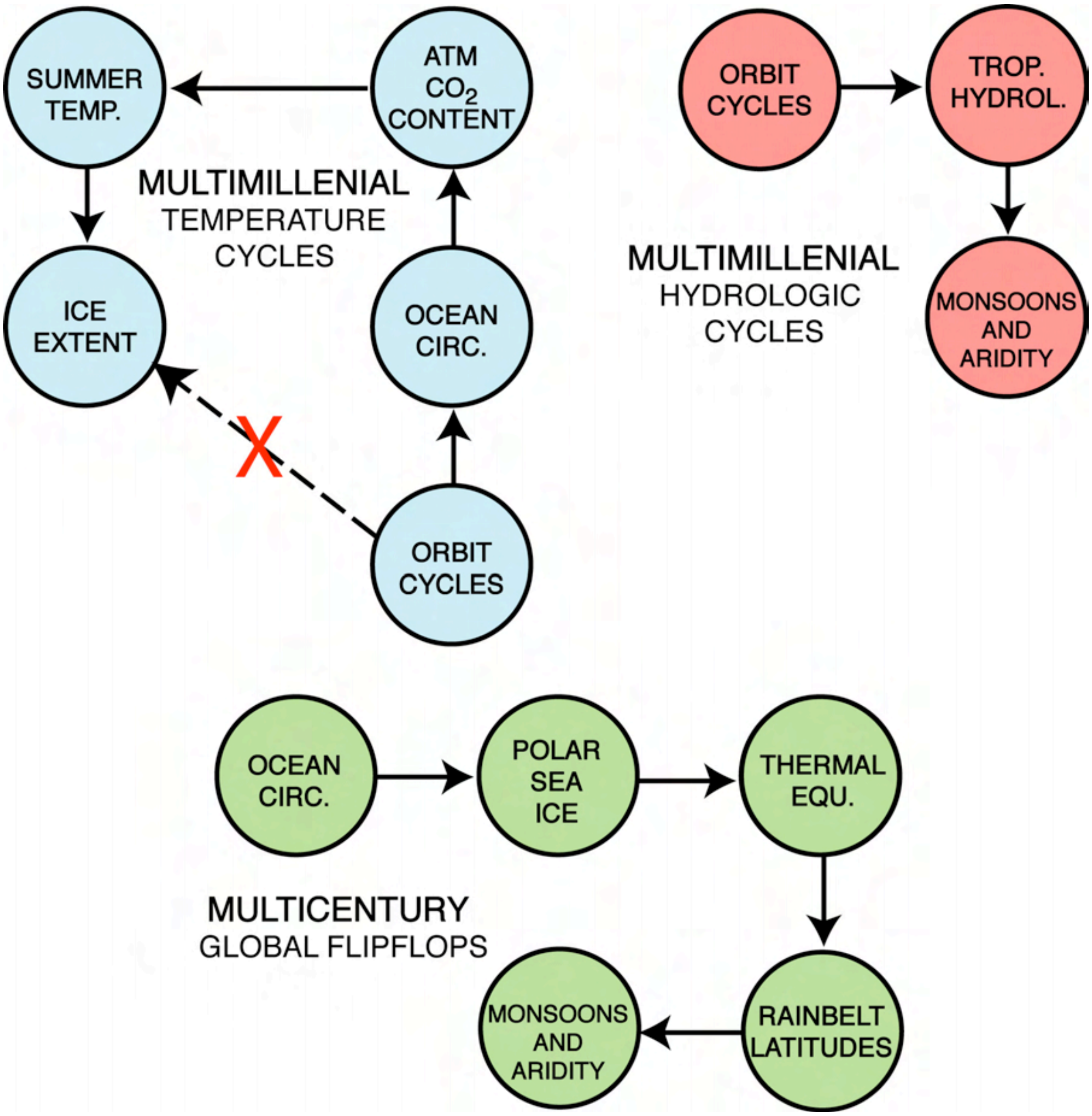
Foreword

This small book outlines an alternate explanation for the tie between orbital cycles and glaciation. Instead of calling on Northern Hemisphere summer insolation to drive the size of the Laurentide and Scandinavian ice sheets, and to somehow cool the rest of the planet, I suggest a less direct connection. It invokes changes in polar seasonality created by orbital cycles as the driver of reorganizations of ocean circulation. These in turn, lead to uptake and release of CO_2. Hence it is atmospheric CO_2 rather than summer insolation that is the primary cause for the advance and retreat of the Earth's glaciers.

The evidence in support of this scenario comes from ^{10}Be dating of northern and southern temperate mountain glaciers carried out by Joerg Schaefer, George Denton and Aaron Putnam. Denton et al. show that the maximum extent of both northern and southern temperate glaciers was achieved during the same time interval (i.e., 24 kyrs to 18 kyrs). The cooling required to achieve these snowline lowerings (i.e., ~6°C) was similar in the south to that in the north.

This amplifies the problem which has dogged the summer insolation - ice extent scenario. Were summer insolation to be the driver, then 21 kyrs ago the south temperate glaciers should have been at a minimum size. Instead they were at their maximum size. The convoluted explanations used to account for the similarity between the Antarctic stable isotope record and the sea level record cannot be extended to explain the mountain glacier record. Rather, CO_2 must be the primary driver.

This being the case one might ask what controls the atmosphere's CO_2 content. About 30 of the 90 ppm peak interglacial to peak glacial change can be explained by a combination of cooling and salinification of the ocean. However, these reductions were likely partly compensated by the CO_2 released as the result of a reduction in terrestrial biomass during glacial time. In any case, the bulk of the CO_2 change is generally attributed to uptake and release of CO_2 by the deep ocean.


SUMMER TEMP.
ATM CO$_2$ CONTENT
MULTIMILLENIAL TEMPERATURE CYCLES
ICE EXTENT
OCEAN CIRC.
X
ORBIT CYCLES
ORBIT CYCLES
TROP. HYDROL.
MULTIMILLENIAL HYDROLOGIC CYCLES
MONSOONS AND ARIDITY
OCEAN CIRC.
POLAR SEA ICE
THERMAL EQU.
MULTICENTURY GLOBAL FLIPFLOPS
MONSOONS AND ARIDITY
RAINBELT LATITUDES

Consistent with the CO_2 scenario is that sea level (the recorder of global ice volume) reached its minimum about 21 kyrs ago. This tells us that the Laurentide and Scandinavian ice sheets reached their maximum size at the same time as CO_2 reached its minimum concentration. Further, during the last deglaciation the rise in Antarctic air temperature and the retreat of south temperate mountain glaciers paralleled the rise in atmospheric CO_2 content. Based on Bob Anderson's record of excess opal deposition, it is thought that both of these changes were related to increased upwelling in the Southern Ocean. The upwelled water not only provided the silica required for diatom production but also the heat necessary to eliminate excess sea ice cover. And it is called upon as the return route for the release of excess CO_2 stored in the glacial ocean.

However, as discussed below, a reduction of the CO_2 input from the planet's interior during glacial time may be equal in importance. As proposed by Peter Huybers and Charlie Langmuir, this reduction is caused by the glacial ice loading of volcanoes.

Chapter 1

Climate's Pacemaker; Cyclic Changes in the Earth's Orbit

The realization that much of the Earth's surface had been modified by glaciers came very late in the game. The reason is that the land forms which should have been attributed to excavation by ice were instead attributed to Noah's flood. To think otherwise was to deny biblical teachings. Only in the 1830s did convincing evidence come to light demonstrating that glaciers in the European Alps were once far more extensive than today's. Jean de Charpentier, a French naturalist, noted that the boulders strewn over the landscape miles down valley from today's ice front were unlike the rocks on which they rested. Rather, they matched bedrock much further up valley. Once the biblical blinders had been removed, geologists were quick to locate evidence for extensive glaciation of Scandinavia and North America.

It wasn't long before it became clear that the glaciers had undergone a series of expansions and contractions. This raised the question: What drove these climate oscillations? Astronomers quickly came up with a suggestion. It had to do with cyclic changes in the Earth's orbit. One such cycle is related to the 26,000-year precession of the Earth's spin axis and another to the 41,000-year cycle in the tilt of its spin axis with respect to the orbital plane (see Figures 1-1 and 1-2). Although this suggestion turned out to be correct, a full century was to pass before it was accepted. One barrier to acceptance was that these cycles changed only the distribution of solar insolation among the seasons and not the total annual insolation. The other was that there was no way to make a comparison of the well-established astronomical time scale with that for glacial cycles. The application of radioisotopes for dating did not come into wide use until after World War II. As we shall see, it was the match between radioisotope-based ages and the astronomical ages that convinced scientists that indeed orbital cycles somehow paced the ice ages. I say 'somehow' because it has proven difficult to come up with a link capable

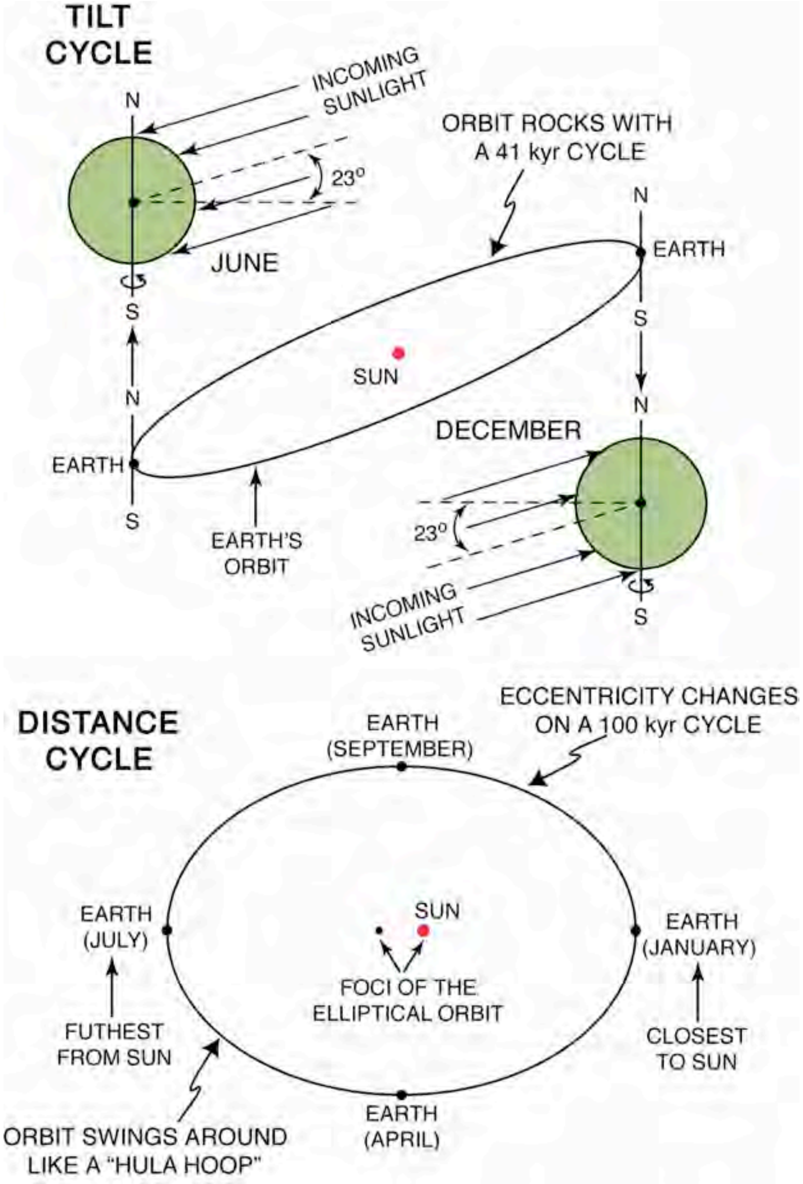


Figure 1-1. As all of us learned in grade school, the Earth's seasons are related to the tilt of its spin axis with respect to its orbit about the Sun. There is however, a second contribution to seasonality, namely, changes in the Earth's distance from the Sun. The reason is that the Earth's orbit is elliptical. Today, during Northern Hemisphere summers, the Earth is furthest from the Sun, and it is closest during winter months. Of course, the opposite is the case for the Southern Hemisphere.

Of interest here are the following: 1) the Earth precesses about its spin axis once each 26 kyrs, 2) the tilt of its spin axis undergoes a cyclic change with a period of 41 kyrs, 3) the eccentricity of the orbit gets larger and smaller on a 100-kyr cycle and 4) the Earth's orbit swings round the Sun like a hula hoop. As these cyclic perturbations are related to the gravitational pull of our fellow planets (and of the moon), Newton's laws allow their time histories to be calculated with a very high degree of accuracy.

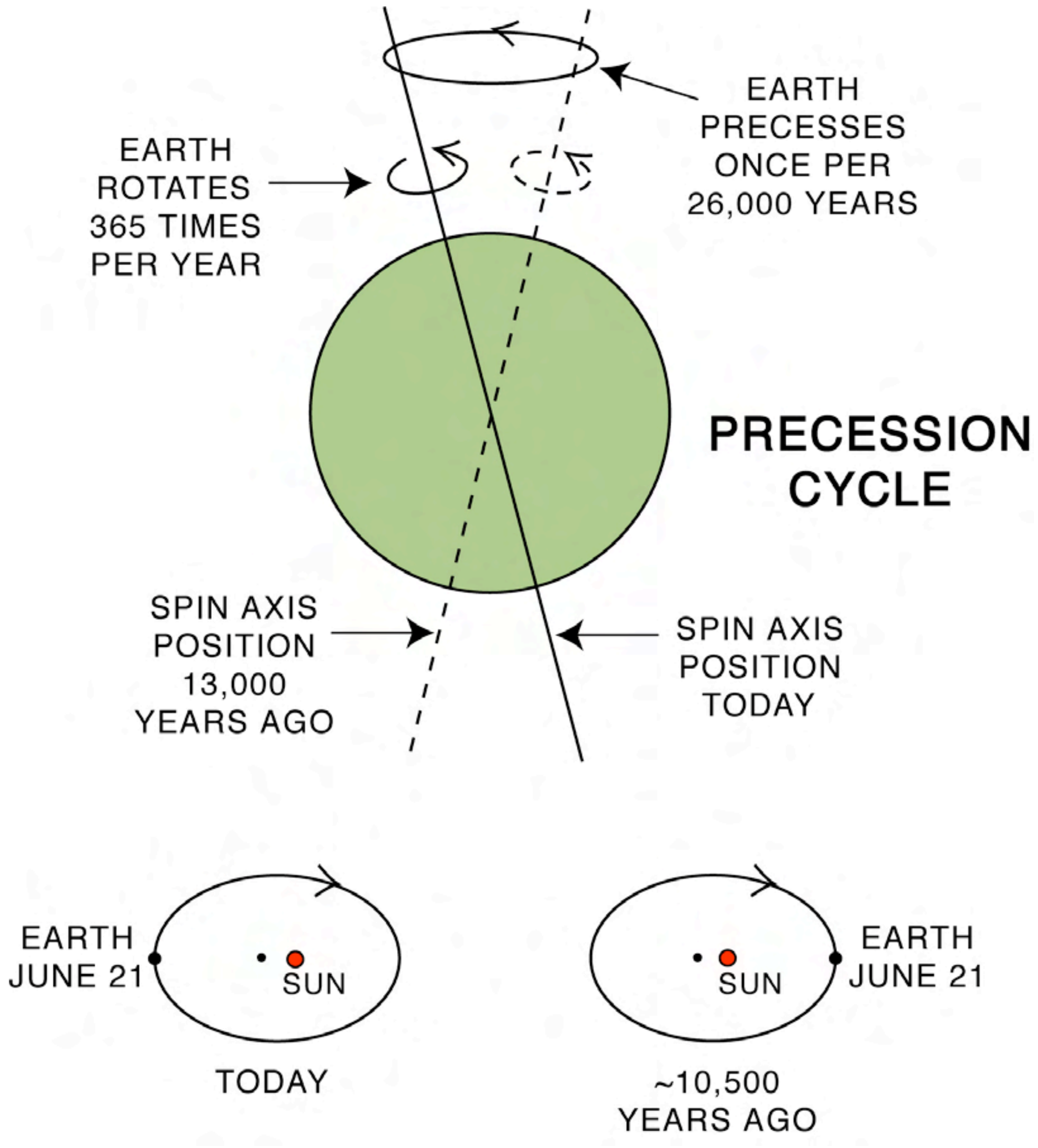


Figure 1-2. The Earth's axis precesses like a top but only very slowly. Although it makes 365 revolutions about its spin axis each year, it makes only one precessional cycle each 26,000 years (i.e., each 26,000 x 365 revolutions). This leads to a 21,000-year cycle in seasonality. Why 21,000 and not 26,000 years? The answer is that the Earth's orbit swings around the Sun, like a hula hoop. This reduces the repeat time in seasonality to 21,000 years. So 10,500 years ago, Northern Hemisphere summers occurred on the short end of the ellipse.

of reproducing many of the well-documented features of the climatic record. The thrust of this book is to propose a quite different scenario than the one which has dominated most thinking.

However, before discussing the creation of a glacial chronology, more must be said about orbital cycles. It is of great importance to this book that when the Northern Hemisphere is experiencing a precession related maximum in seasonal contrast, the Southern is experiencing a minimum and vice versa (see Figure 1-3). Further, the precession cycle (see Figure 1-2) varies widely in amplitude. The reason is that the Earth's orbit undergoes an additional cycle which involves changes in the shape of the orbit. Rather than being circular, it is an ellipse (see Figure 1-1). Its departure from circularity is referred to as the orbit's eccentricity. On a 100,000-year time scale, the Earth's orbit ranges from nearly circular to as much as 5 percent out-of-round. The insolation impacts of the precession cycle are proportional to the eccentricity of the Earth's orbit.

The timing of the precession cycle is modified by yet another orbital cycle. The Earth's orbit is like a hula hoop. Every 105,000 years, it makes one revolution about the Sun. Although a bit harder to comprehend, in combination with the Earth's 26,000-year precession cycle, it produces a 21,000-year cycle in seasonality.

The 41,000-year cycle does not have similar complications. Rather, it is quite regular. However, it must be kept in mind that unlike the precession cycle which is out of phase between the hemispheres, the tilt cycle is in phase.

When all of the cyclic changes are put together, a complex pattern of seasonality in insolation is generated (see Figure 1-4). Even so, the 21-kyr cycle stands out. Although the impact of the 41-kyr tilt cycle is more difficult to see, it makes its mark in the 30- to 50-kyr time interval. During this time interval, the Northern Hemisphere insolation record is rather flat. This is because the tilt maximum at 40 kyrs ago is in direct opposition to the precession minimum.

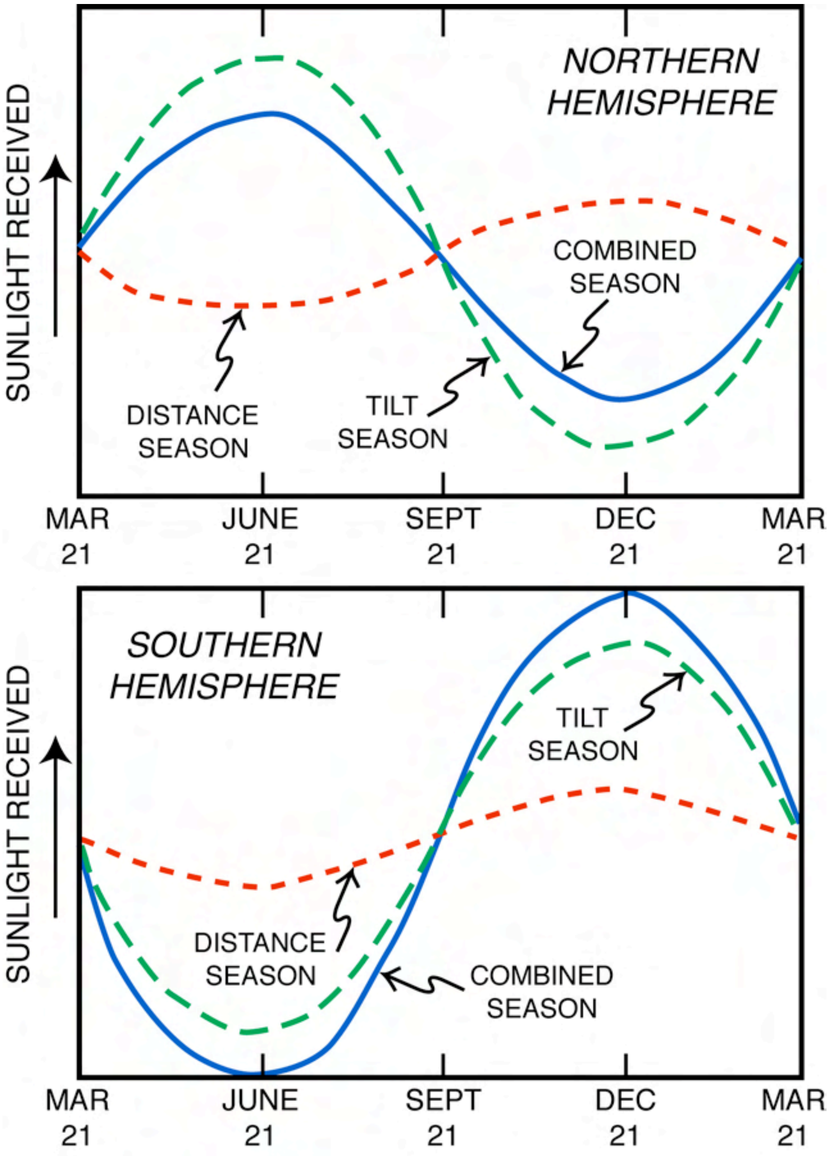
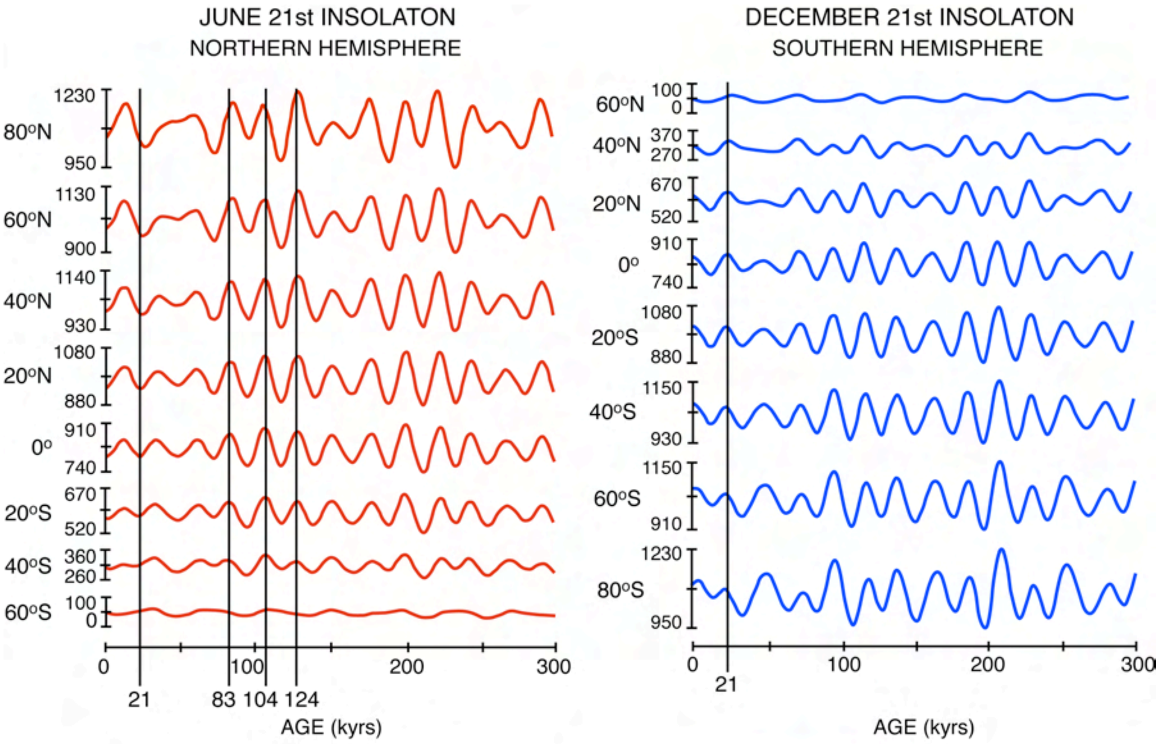


Figure 1-3. North of the equator, summers currently take place at the long end of the elliptical orbit. Consequently, solar insolation is somewhat smaller than it would be if the orbit were circular. By contrast, south of the equator summers take place at the short end of the elliptical orbit, so they experience larger than average solar insolation. It should be kept in mind that, as the eccentricity of the Earth's orbit undergoes cyclic changes, so also does the distance contribution to seasonality.


JUNE 21st INSOLATON
NORTHERN HEMISPHERE

DECEMBER 21st INSOLATON
SOUTHERN HEMISPHERE


MILUTIN MILANKOVITCH


JOHN IMBRIE

Figure 1-4. When added together, these orbital cycles generate a complex pattern of insolation changes. Shown here is the pattern for June 21st and for December 21st. The 21-kyr cycle stands out. Note that there are 14 such peaks during the last 300 kyrs. Also, note that the amplitude of these cycles varies with time in accord with the eccentricity of the Earth's orbit.

The vertical lines show the situation at the time of the last glacial maximum (21 kyrs) and at the times sea level achieved interglacial high stands (83, 104 and 124 kyrs ago).

As shown in Figure 1-4, the summer insolation histories are latitude dependent. The reason is that the insolation impacts of changes in the Earth's tilt are stronger at high latitudes than at low latitudes. As the 21,000-year cycle involves changes in the distance from the Sun to Earth, it is not latitude dependent.

It may surprise the reader that a precise chronology exists for these seasonality changes. Only the 26,000-year precession time scale is determined by observations. This was done by keeping track of the location of the North Star. Since the advent of astronomical observations, it has completed about 10 percent of its circular traverse around the North Pole. Timing of the other cycles are calculated based on Newton's laws and our knowledge of the masses and orbits of our fellow planets, in particular, those of the giants, Jupiter and Saturn. If the capability to do this didn't exist, then there would have been no way for NASA to drop landers on the surface of Mars.

The name most closely associated with orbital forcing of the Earth's seasonality is Milutin Milankovitch, a Yugoslavian mathematician. During the 1930s, he made laborious hand calculations of the time history of summer insolation at a series of latitudes. He expressed the results in terms of equivalent latitude. He postulated that during times of reduced summer insolation, the Northern Hemisphere's ice sheets expanded. In so doing, he created what he envisioned to be the time history of the Northern Hemisphere ice sheets.

Unfortunately, at least in America, Milankovitch's ideas were largely disregarded. One reason was that a dogma of four major glaciations separated by long interglacials appeared to be at odds with Milankovitch's predictions. Yale University's influential Richard Foster Flint instead attributed the cycles to some combination of solar and topographic changes.

The breakthrough came on the heels of discoveries by two Nobel prize-winning University of Chicago professors; Harold Urey demonstrated that the isotopes of the element oxygen could be used as a paleo-thermometer and Willard Libby demonstrated that the ^{14}C to C ratio in wood and in shells could be used to determine their ages. A young Italian paleontologist, Cesare Emiliani employed as a postdoctoral fellow in Urey's lab made $^{18}O/^{16}O$ ratio measurements on the shells of planktonic foraminifera on radiocarbon-dated sediment cores from the deep Atlantic. He found that the coldest surface waters existed about 20,000 years ago. By extrapolation of the radiocarbon-based sediment accumulation rates, the time of the previous interglaciation turned out to be roughly 100 kyrs ago. His paper published in 1954 turned the tide of thinking toward Milankovitch cycles as the pace maker of glaciation. Soon to follow were radiocarbon dates on wood from the outermost moraines left behind when the great northern Atlantic ice sheet began its retreat. They turned out to be close to 20,000 years, again consistent with orbital forcing.

Brown University's Robley Matthews became aware of Bill Sackett's discovery that ^{230}Th, an isotope with a 75,000-year half life could be used to date fossil corals. He became interested in using it to determine the age of corals found on the elevated terraces on the Island of Barbados. When he heard that we had set up a lab for ^{230}Th dating here at Lamont-Doherty, he inquired whether we would be willing to determine the ages of two of these corals. David Thurber and Teh-Lung Ku, graduate students working with me, took up the challenge. The results of 83 kyrs and 104 kyrs caused much excitement, for they matched those of two prominent Northern Hemisphere summer insolation maxima.

But when we reported these ages to Matthews, he informed us that there was a third raised reef with an elevation roughly midway between those of the other two. An age of 104 kyrs was obtained for this sample. As a result, we showed that the level of the sea followed the 21-kyr insolation cycle (see Figure 1-5). As these changes in sea level were the result of waxing and waning of the Earth's Northern Hemisphere ice sheets, they provided a solid confirmation of Emiliani's claim.

Further, proof was provided by Hayes, Imbrie and Shackleton who carried out spectral analyses of a several hundred-thousand-year-duration records of ^{18}O from deep

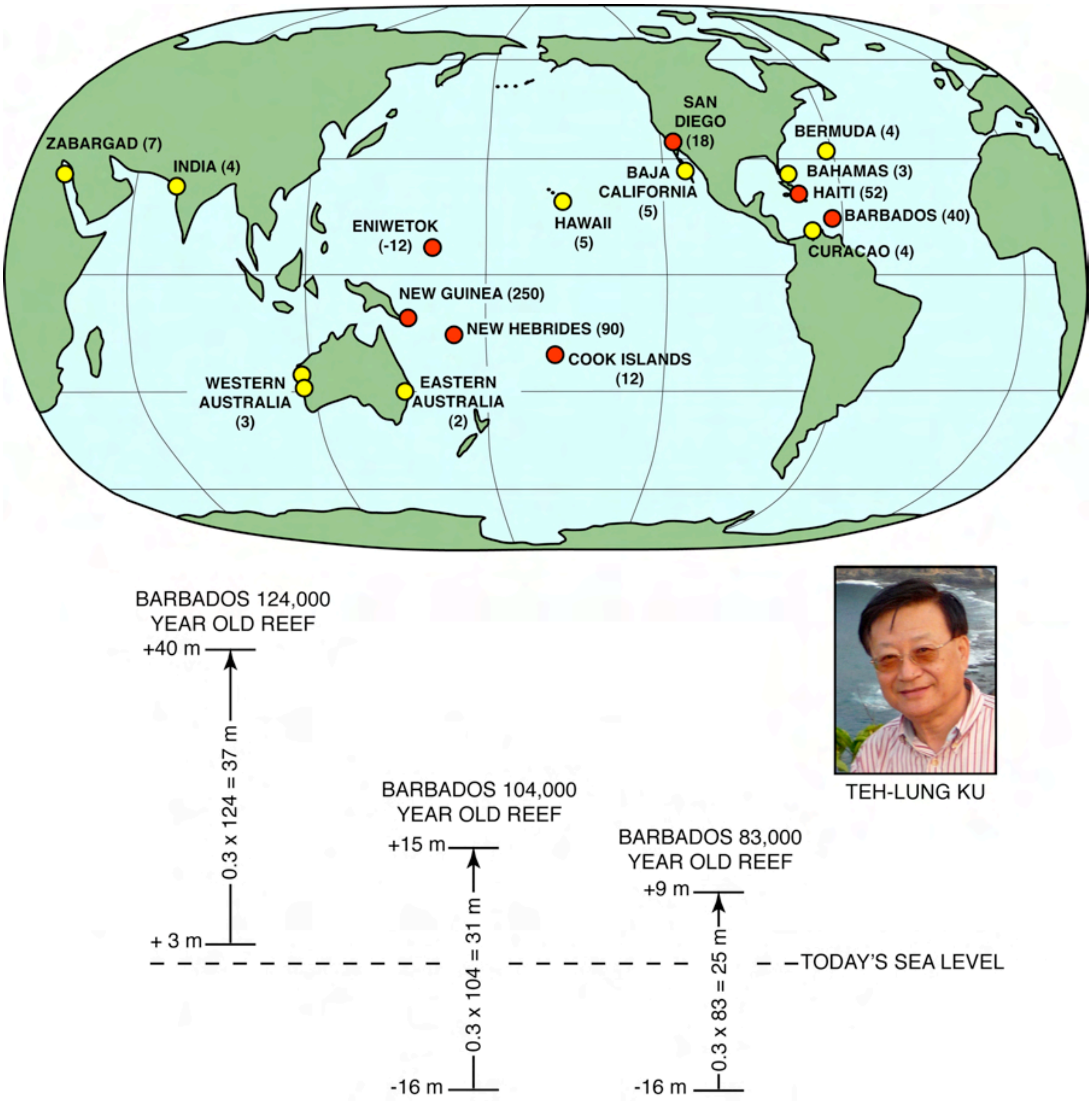


Figure 1-5. The ^{230}Th ages for coral reefs which stand above the current sea level tell us two important things. First, those from tectonically quiet settings shown on the map as yellow circles, tell us that, at the peak of the last glaciation, sea level stood 5 ± 2 meters higher than today's. Second, coral reefs from tectonically (red circles) active areas tell us how much uplift has occurred during the last 124 kyrs (see elevations in meters).

The island of Barbados provides us with two additional pieces of information, namely, the level of the sea 83 kyrs and 104 kyrs ago. As the island is being pushed up by subducting ocean crust, it is reasonable to assume that, at least when averaged over several thousand years, the uplift rate has remained nearly the same, i.e., about 0.3 meters per thousand years. If so, then both the 83 kyr and 104 kyr reefs must have been formed when sea level was about 16 meters below its current level. These reefs record high stands of the sea. As shown in Figure 1-3, these maxima were achieved at times of Northern Hemisphere summer insolation maxima. For reference, it should be kept in mind that during the peak of the last glacial period (about 20 krys ago), sea level stood about 120 meters lower than now.

sea sediment cores. They found statistically significant spectral peaks matching the 21-kyr precession cycle and the 41-kyr tilt cycle. However, the most prominent spectral peak was at 100 kyrs. These 100-kyr cycles are not sinusoidal. Instead they have the shape of asymmetrical triangles. During 90 percent of the cycle, the ocean gradually cooled and then, during the last 10 percent of the cycle it warmed. These sharp warmings are referred to as glacial terminations. The spacing between them is either about 80 kyrs or about 120 kyrs giving rise to the 100-kyr spectral peak. Imbrie and his co-investigators tried very hard to account for this pattern assuming that only Milankovitch cycles were in play. One might say that they viewed the ice ages as a Milankovitch symphony. But explaining the sharp terminations in this way required a big stretch. Ice cores from Greenland demonstrated that the situation is far more complicated.

Most authors have attributed the connection between orbitally-induced seasonality changes and glacial extent to a direct link to summer insolation. Changes in glacial size are dominated by melting. Of course, for glaciers outside the tropics, melting occurs mainly during summer months. Changes in snowfall account for no more than 15 percent of the fluctuations in size of these glaciers. Although summer temperatures change with orbital cycles, they also change with the CO_2 content of the atmosphere. In the next chapter, I make the case that it is CO_2 changes, rather than insolation changes, that have driven glacial size. Hence I propose that the link between orbital cycles and glacial extent is via reorganizations of ocean circulation which lead to uptake and release of CO_2 by the ocean. If so, reorganizations of ocean circulation are important drivers of glacial extent.

Absolute dating of deep sea sediments, corals, mountain glaciers, stalagmites, ice cores… is essential to our reading of the climate record (see Figure 1-6). Without accurate chronology we cannot correlate events which occurred at diverse places on our planet. The work horses are annual layer counting in polar ice and in trees, radiocarbon dating (see Figures 1-7, 1-8 and 1-9), uranium series dating (see Figure 1-9) and radio-beryllium dating (see Figure 1-10). Although perfecting these four methods has taken

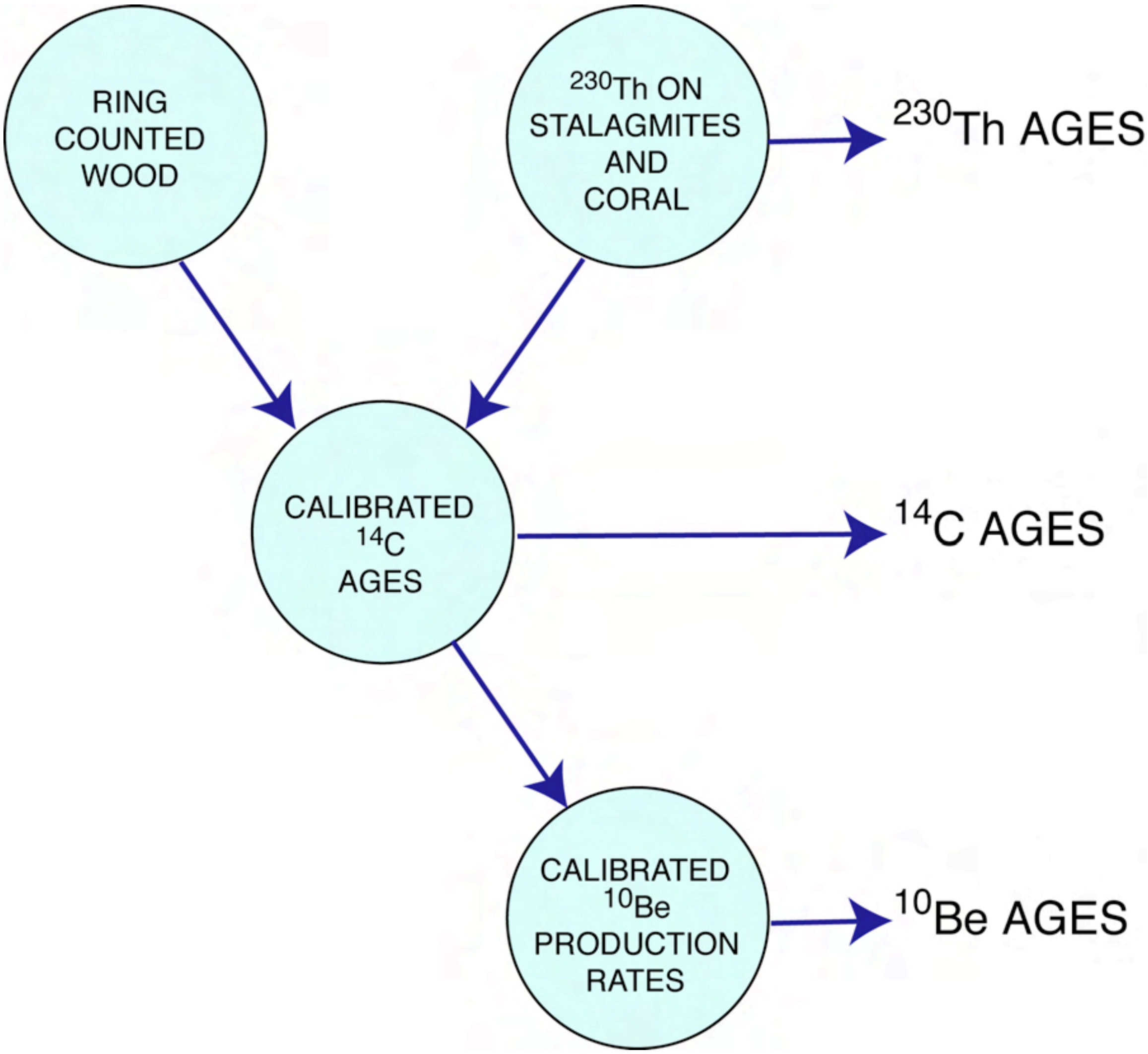
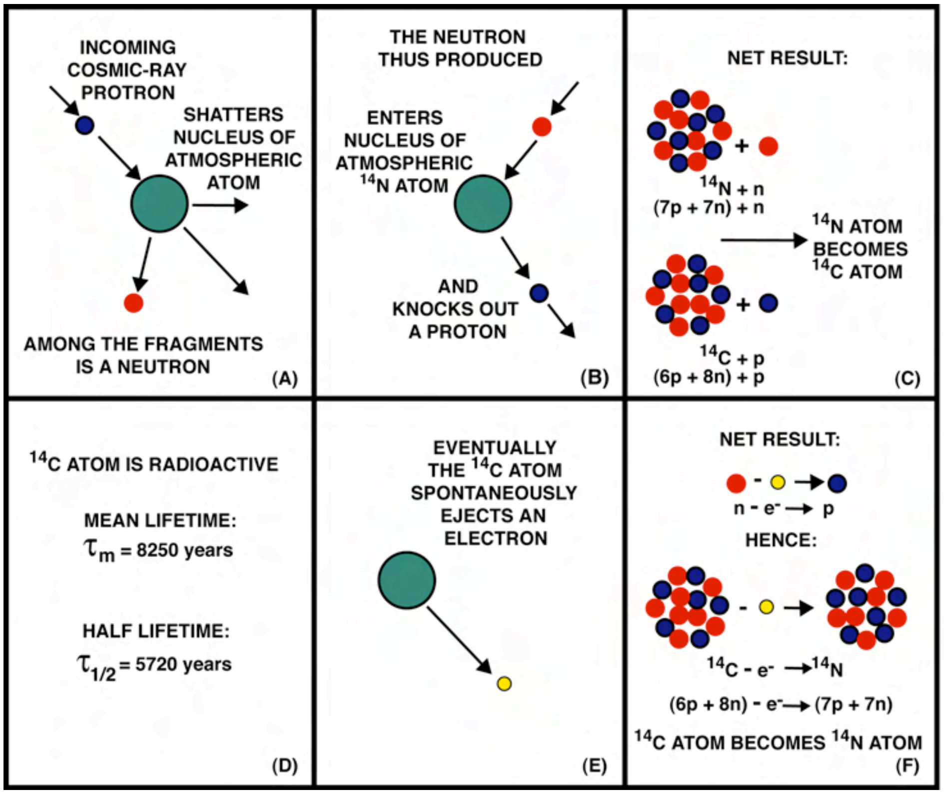


Figure 1-6. The chronologies for the records to be discussed in this book are based on ages obtained by the ^{230}Th, ^{14}C and ^{10}Be methods. Of these, only ^{230}Th gives absolute ages. The temporal variations in the atmosphere's ^{14}C to C ratio have been reconstructed by ^{14}C measurements on ring-dated wood and ^{230}Th-dated corals and stalagmites. The production rate of ^{10}Be in quartz is determined by measurements of rocks associated with organic matter which has been radiocarbon dated (i.e., woody material in landslide deposits).

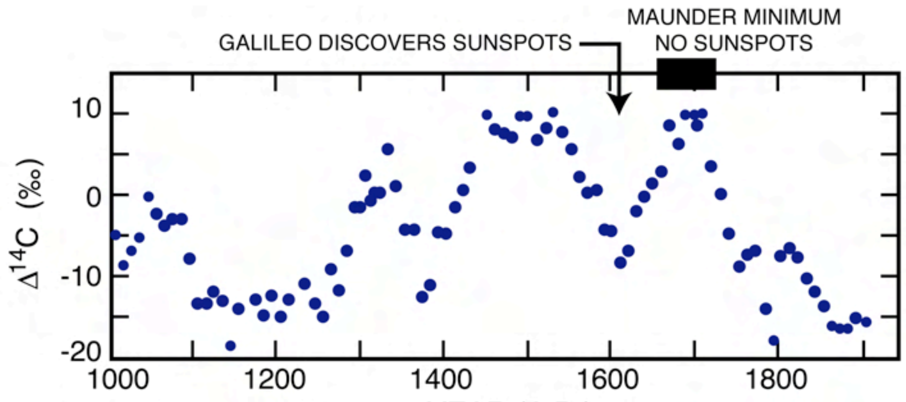


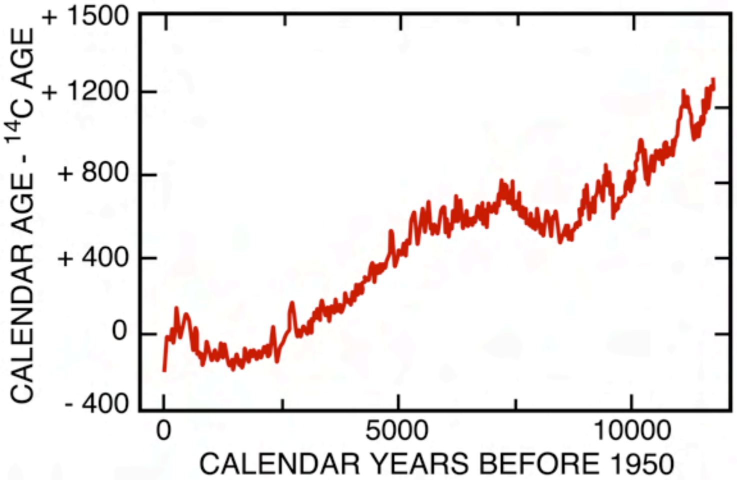
WILLARD LIBBY

Figure 1-7. Radiocarbon dating: ^{14}C is a radioactive isotope produced in our atmosphere when cosmic-ray neutrons encounter nuclei of ^{14}N atoms. The neutron knocks out a proton transforming ^{14}N into ^{14}C. The half life of radiocarbon atoms is 5720 years. During their lifetime, ^{14}C atoms are distributed throughout the atmosphere as carbon dioxide, through the ocean as bicarbonate and carbonate ions and in the organic matter and $CaCO_3$ shells made by the Earth's biota.

Dating is done by measuring the ratio of radioactive ^{14}C atoms to stable C atoms. Originally this was done by measuring the electrons shot out of the ^{14}C nucleus when it converts itself back to ^{14}N. The ejection of an electron converts a neutron into a proton. Starting in about 1985, measurements were made by counting ^{14}C atoms themselves using a high energy mass spectrometer. The major advantage of this switch was that electron counting requires a gram of carbon while the atom counting requires only a milligram of carbon.

Willard Libby, who invented this method, assumed that all the materials he dated began with the same ^{14}C to C ratio as their present-day equivalents. But, it turns out that this assumption was not valid. By measuring the ^{14}C to C ratio in ring-counted tree wood and in ^{230}Th-dated corals and stalagmites, it was shown that substantial offsets exist between Libby's radiocarbon ages and calendar ages. This makes it clear that changes in the ^{14}C to C ratio of atmospheric CO_2 have undergone surprisingly large changes. Of importance to this book is that during the last glacial maximum, the offset was about 3300 years. Hence, a ^{14}C age of 18,000 years for a stump overrun by a glacier at the time of the last glacial maximum becomes 21,300 when corrected for this offset.






MINZE STUIVER


BERND KRONER

Figure 1-8. Tree-ring dating. As everyone knows, tree trunks have rings. The reason is that spring wood and summer wood have different size cells. By counting the rings in a pencil-sized boring made in a tree, its age can be determined. Giant sequoia trees live to be more than 1000 years in age. Counts made on stumps left behind when one of these trees is cut down provide known-age material which can be used to convert radiocarbon ages to calendar ages.

Despite the fact that reliably-dated living trees extend back only a couple of thousand years, the tree-ring-based calibration now reaches back to about 13,000 years. The secret is using the signature of year-to-year variations in ring thickness to match the record in fossil trees with that in living trees and to go even further back in time by matching fossil trees with fossil trees.

Fortunately, not all fallen tree trunks rot as do those we see in our forests. Rather, trees buried in sands and silts deposited in rivers and swamps are beautifully preserved. The reason is that as rapidly as atmospheric oxygen diffuses into the water-filled sediment pores, it is consumed by bacteria. The low oxygen environment created in this way excludes beetles and worms from boring into the wood. The largest archive of such wood yet to be studied comes from the beds of German rivers. Construction companies mine aggregate for cement manufacture from these deposits. When a tree trunk is encountered, tree-ring experts are alerted to come by and cut off a slab. In this way, a collection of thousands of fossil wood sections have been archived providing precisely dated material for radiocarbon calibration.

Two names stand out among those who have conducted such studies. University of Washington's Minze Stuiver used radiocarbon measurements on ring-dated wood to demonstrate that sunspot activity was causing the rain of cosmic rays onto the Earth to change. Shown here are his results. The key finding is that when sunspots were absent, the ^{14}C to C ratio reached a maximum. Bernd Kromer extended Stuiver's record back to 12,000 years. As can be seen, the offset between calendar ages and ^{14}C ages, steadily increase back in time reaching a whopping 1200 years 11,500 years ago. The centennial and longer changes are thought to be the result of changes in the strength of the Earth's magnetic field.

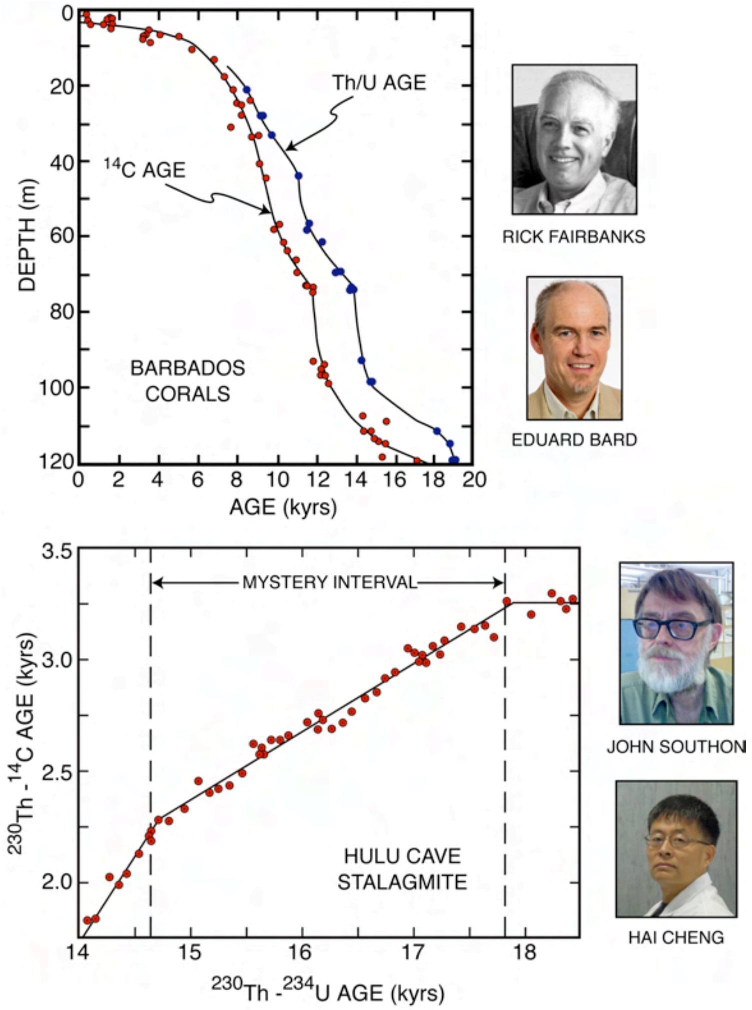


Figure 1-9. Uranium series dating. The dominant isotope of the element uranium (i.e., ^{238}U) slowly decays to an isotope of lead (i. e., ^{206}Pb). Its half life is nearly the same as the age of the Earth (i.e., 4.5 billion years). To reach ^{206}Pb requires the emission of 8 alpha particles and 6 electrons. Two members of this decay chain are of particular interest for age determination, ^{234}U with a half life of about 250,000 years and ^{230}Th with a half life of about 75,000 years. They can be used for dating because uranium and thorium are efficiently separated when dissolved in water. Uranium is quite soluble and thorium highly insoluble. Hence, corals and stalagmites build in ^{238}U and ^{234}U into their $CaCO_3$. But, as there is very little ^{230}Th in the water, very little is incorporated in the coral.

As is the case for ^{14}C measurements, the uranium series isotopes were initially measured by counting alpha particles shot out by the radiodecays. Then, in the mid-1980s, Larry Edwards showed that the measurement error could be greatly reduced by counting atoms using a conventional mass spectrometer. Since then, the method has been refined so that the best quality interglacial-age samples can be measured with an accuracy of ± 60 years (compared with alpha counting errors of ± 2000 years).

Shown here are ^{230}Th – ^{14}C age comparisons made by Lamont-Doherty's Richard Fairbanks on pristine corals recovered by drilling along the margin of the island of Barbados. Also shown are ^{230}Th – ^{14}C age difference obtained by University of California, Irvine's John Southon (^{14}C) and University of Minnesota's Hai Cheng (^{230}Th) from measurements made on a stalagmite from China's Hulu Cave.

ROSEANNE SCHWARTZ

Figure 1-10. ^{10}Be measurement on quartz contained in the outer portion of boulder tops yield exposure ages (i.e. the time elapsed since the boulder was emplaced in its present position). Shown here on the left is a huge boulder left behind as the toe of one of New Zealand's glaciers melted back. On the right is the debris from a major New Zealand landslide. It spread across a small woodland, uprooting the trees it encountered. Their calibrated radiocarbon age is 9.7 kyrs. Measurements of ^{10}Be on boulders exposed in the hummocky topography permit the production rate of this radioisotope to be established.

Below is shown the entire group responsible for collecting, processing and ^{10}Be analysis on samples from New Zealand. In addition to Schaefer, Putnam and Denton, on the far right is Lawrence Livermore's Bob Finkel who is responsible for the accelerator mass spectrometer used to make the ^{10}Be measurements. Also shown are four scientists in involved in the fieldwork. From left to right New Zealand's Trevor Chinn and David Barrell, Lamont Doherty's Mike Kaplan and Norway's Bjorn Anderson. Roseanne Schwartz makes the ^{10}Be preparation lab hum**.**

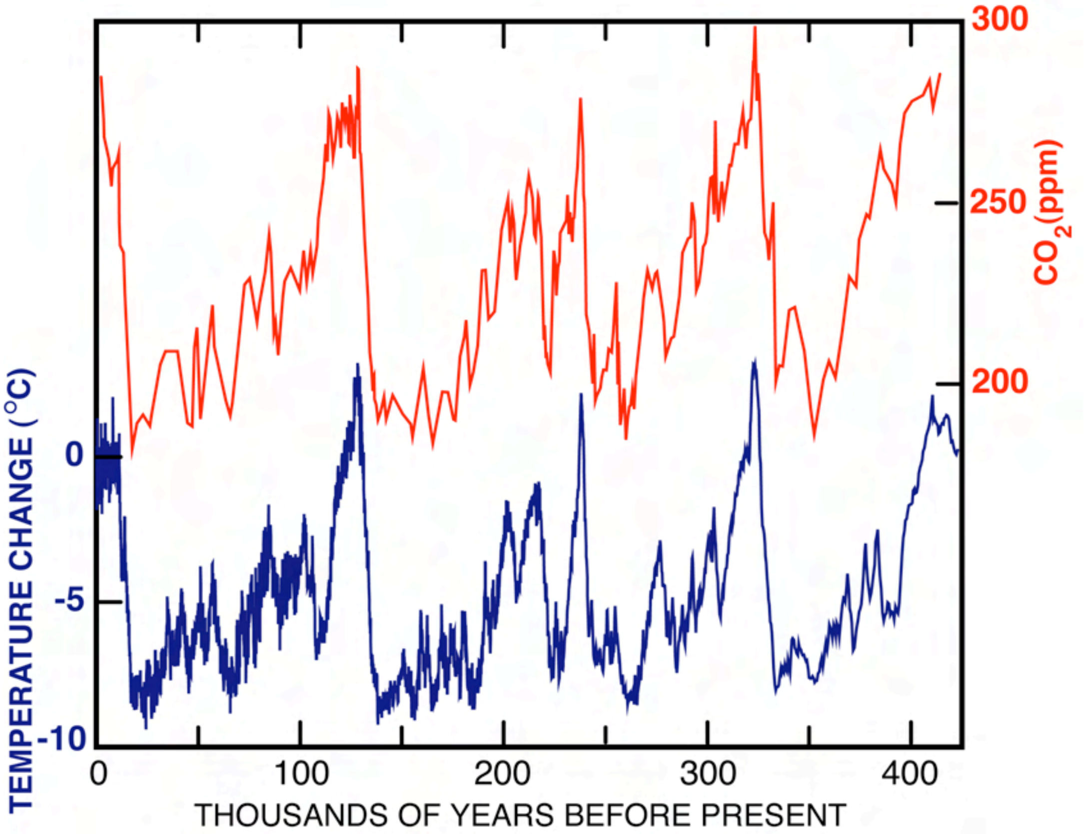
many decades, the results of this long effort are spectacular. Not only do we have a highly accurate age scale, but we can correlate records from diverse environments to a gnat's eyebrow! Of these, only ^{230}Th and annual layer counting yield absolute ages. As the ^{14}C to C ratio in atmospheric CO_2 has undergone large changes, in order to convert so-called Libby ages to calendar ages has required that extensive ^{14}C measurements be made on ring-counted wood and on ^{230}Th-dated corals and stalagmites. For high accuracy ^{10}Be dating, measurements had to be made on samples whose age is constrained by precise radiocarbon measurements. While a complex web, it has been beautifully deciphered.

Chapter 2

Atmospheric CO_2: The Link between Ocean Circulation and Ice Extent

Bubbles of air trapped in Antarctic ice constitute a pristine archive for the greenhouse gas CO_2 (see Figure 2-1). This has been demonstrated by the consistency among the CO_2 reconstructions obtained from ice cores from several Antarctic locales. The most prominent feature of the CO_2 record is how closely it mimics that for the stable isotope composition of the ice itself. Stable isotope variations (i.e., either ^{18}O to ^{16}O or ^{2}H to ^{1}H) are stand-ins for air temperature. Both the stable isotope and the CO_2 records are dominated by the asymmetrical 100-kyr cycle. Long intervals of declining CO_2 are matched by long intervals of cooling. These declines terminate with an abrupt return to interglacial conditions. Hence atmospheric CO_2 content and Antarctic air temperatures must be closely linked. For the last 420 kyrs, CO_2 ranged from close to 280 ppm during peak interglacials to close to 190 ppm during peak glacials. Prior to 450-kyrs ago, while the glacial concentration remains about the same, the peak interglacial concentrations rose to only about 250 ppm.

A puzzling feature of this record is that the duration of the peaks in interglacial temperature exceed those for CO_2. This is telling us either that, at the onset of interglacials, the temperature warming leads the CO_2 rise or that, at the close of interglacials, the CO_2 decline lags temperature cooling. Except for the present interglacial, it is impossible to say for sure which is the case, or whether it is some combination of both. The reason is that only ice cores from the Antarctic plateau penetrate previous interglacials. As little moisture accompanies the air masses which reach the frigid plateau, the accumulation rate of ice is only a few centimeters per year. At these low snow accumulation sites, the offset between the bubble age and ice age (see Figure 2-2) turns out to be two to three thousand years. Thus, the uncertainty in the exact magnitude of this offset foils our ability to reliably answer the question posed above.



JEROME CHAPPELLAZ

JEAN JOUZEL

Figure 2-1. Records of CO_2 and air temperature for the last 400,000 years from an ice core drilled by Russian scientists at the Vostok Camp site on the Antarctica polar plateau. The CO_2 record generated by Jerome Chappellaz is based on measurements on air trapped in bubbles in the ice. The temperature record is derived from deuterium to hydrogen ratios measured by Jean Jouzel in the ice itself. Both are geochemists working in France. As the air bubbles closed off at a depth of about 80 meters and the ice accumulates at only a few centimeters per year, a time offset of several thousand years separates these two records. In order to compare the timing of the two records, an adjustment must be made for the duration of this offset. As the magnitude of this adjustment is uncertain, careful consideration must be given to the phasing of the interglacial peaks (see text).

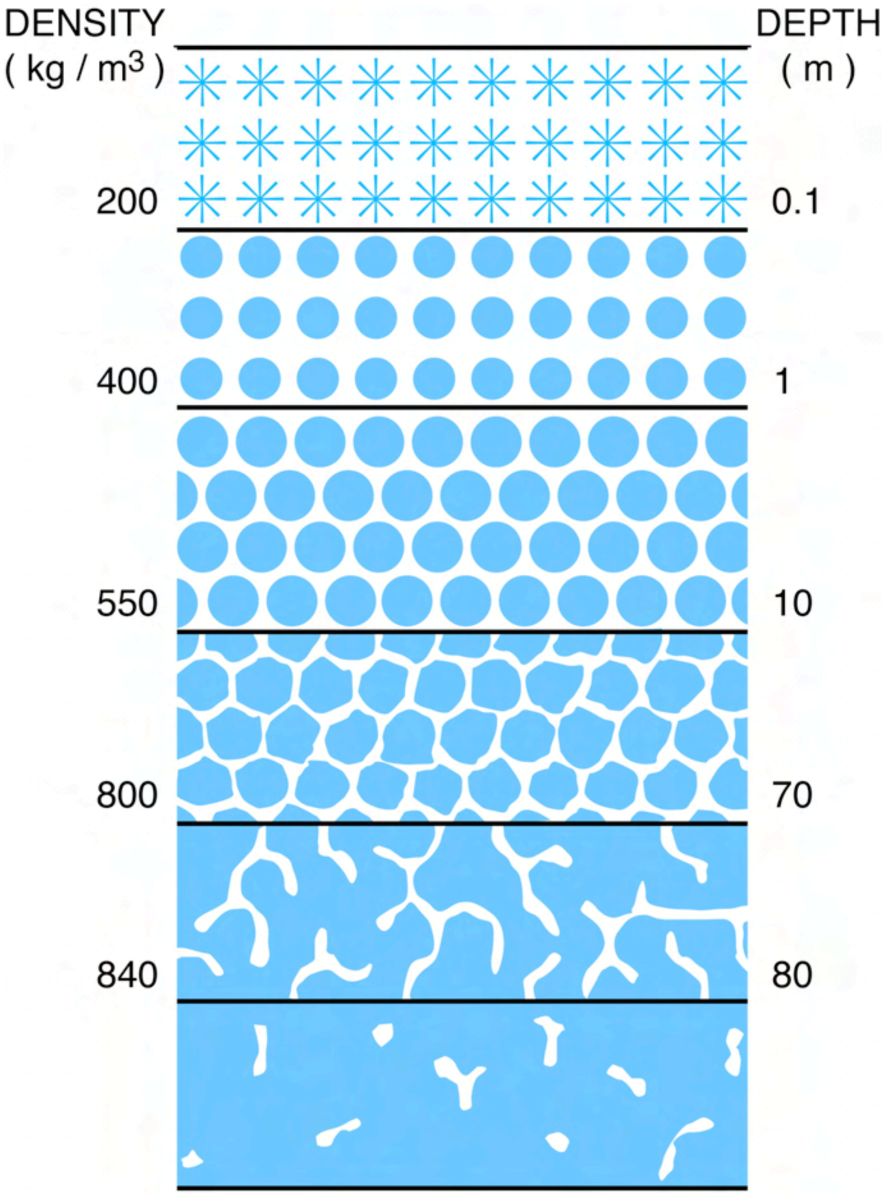


Figure 2-2. The snow which accumulates on the Greenland and Antarctic ice caps gradually lithifies into ice. As this process proceeds, the pore space diminishes. When complete, closed air-filled 'bubbles' remain. As the weight of overlying ice dominates the closure, the age offset is inversely proportional to the ice accumulation rate. On the frigid Antarctic plateau, ice accumulates at a rate of a few centimeters per year. In this case, the ice-air age offset is several thousand years. In Greenland and at sites around the fringe of Antarctica, the ice accumulation rates are a few tens of centimeters per year and the age offset several hundred years. Correcting for these offsets is necessary if the leads and lags between properties of the ice and the concentrations and isotope compositions of trapped gases are to be determined.

This being the case, we have to turn to the last deglaciation. It is recorded in high deposition-rate Antarctic ice cores where the age offset between the bubbles and the ice is only a couple of hundred years. In this case, the uncertainty in the offset correction is no more than 100 years. Hence it can be shown that the Antarctic warming which occurred between 18 and 11 kyrs matches the rise in CO_2. Assuming that the last termination typifies previous ones, then the difference between the duration of the CO_2 interglacial and temperature interglacial must reflect a lag of the decline in CO_2 at the end of interglacials. As discussed in Chapter 5, this is one of the flies in the ointment for my scenario which calls on ocean circulation rather than insolation seasonality as the link between orbital cycles and glacial extent. So, the evidence from Antarctic ice is ambiguous. During the 'cold' half of glacial cycles, CO_2 appears to drive Antarctic warming. But, during the warm half, CO_2 lags Antarctic cooling.

Rather than basing our estimates of the temperature history of the Southern Hemisphere on the Antarctic ice core record, I choose to base it on the mountain glacial record at temperate latitudes. What does it tell us? The definitive test comes from comparing the records for temperate latitude glaciers in the Southern Hemisphere with that for those in the Northern Hemisphere. As shown in Figure 2-3, if orbitally-induced changes in seasonality were to directly impact ice extent, then one would expect there to be a distinct difference between the mountain glacier records in the two hemispheres. But, if CO_2 were the driver, then they should be similar. Indeed, careful field work and precise dating conducted by George Denton, Joerg Schaefer and Aaron Putnam convincingly demonstrates that the maximum extent of mountain glaciers at temperate latitudes in the Southern Hemisphere was achieved during the same time period, (i.e., between 25 and 18 kyrs) as that in the Northern Hemisphere (see Figure 2-3). They did this by carefully mapping the sets of terminal moraines looped around three of the lakes filling the fjord-like valleys carved out by the glaciers. In New Zealand they documented the age of these moraines by ^{10}Be dating a dozen or so large boulders perched on each

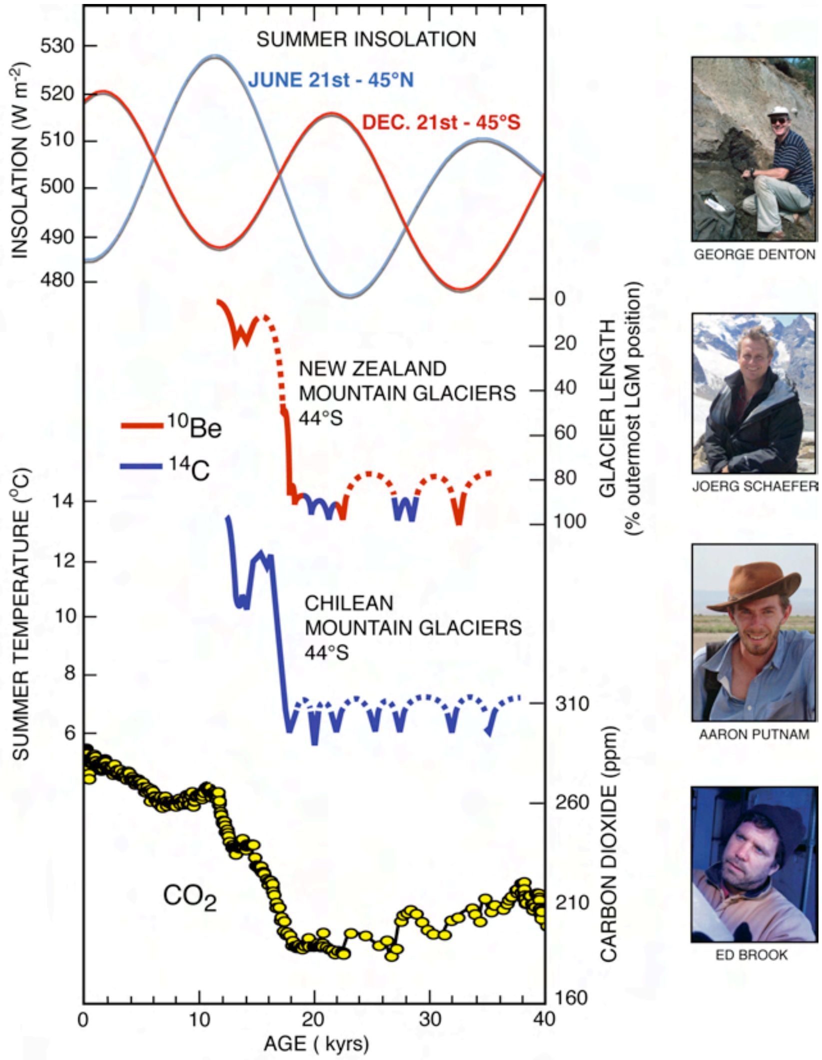


Figure 2-3. The timing of the Last Glacial Maximum in the Southern Hemisphere is key to distinguishing between insolation and CO_2 forcing. Working together, three scientists have nailed this chronology. George Denton of the University of Maine, carried out detailed mapping and sample collection in both the Southern Andes and New Zealand's Alps. Joerg Schaefer of Columbia's Lamont-Doherty Earth Observatory has taken ^{10}Be dating to a new level of precision and accuracy. Aaron Putnam, first as Denton's student and then as Schaefer's post-doctoral fellow, contributed to both the field and lab programs. These are the heroes of this book, for it is based on their research.

Working on the wet (Chilean) side of the Andes, Denton developed a radiocarbon chronology for deposits formed during the last glacial maximum. He then joined forces with Schaefer to develop a ^{10}Be chronology for New Zealand Alps. The latter is based on ages for the moraines themselves. The former is based on ^{14}C dates, on organic-matter bracketing the glacial deposits.

The important finding is that these records beautifully match the atmospheric CO_2 record. Of particular interest is that at both locales the glaciers stood very close to their maximum extent until 18 krys ago and then underwent very rapid and extensive retreats. This retreat matches the rise in atmospheric CO_2 content. The CO_2 curve is a composite generated by Oregon State University's Ed Brook for use in this book.

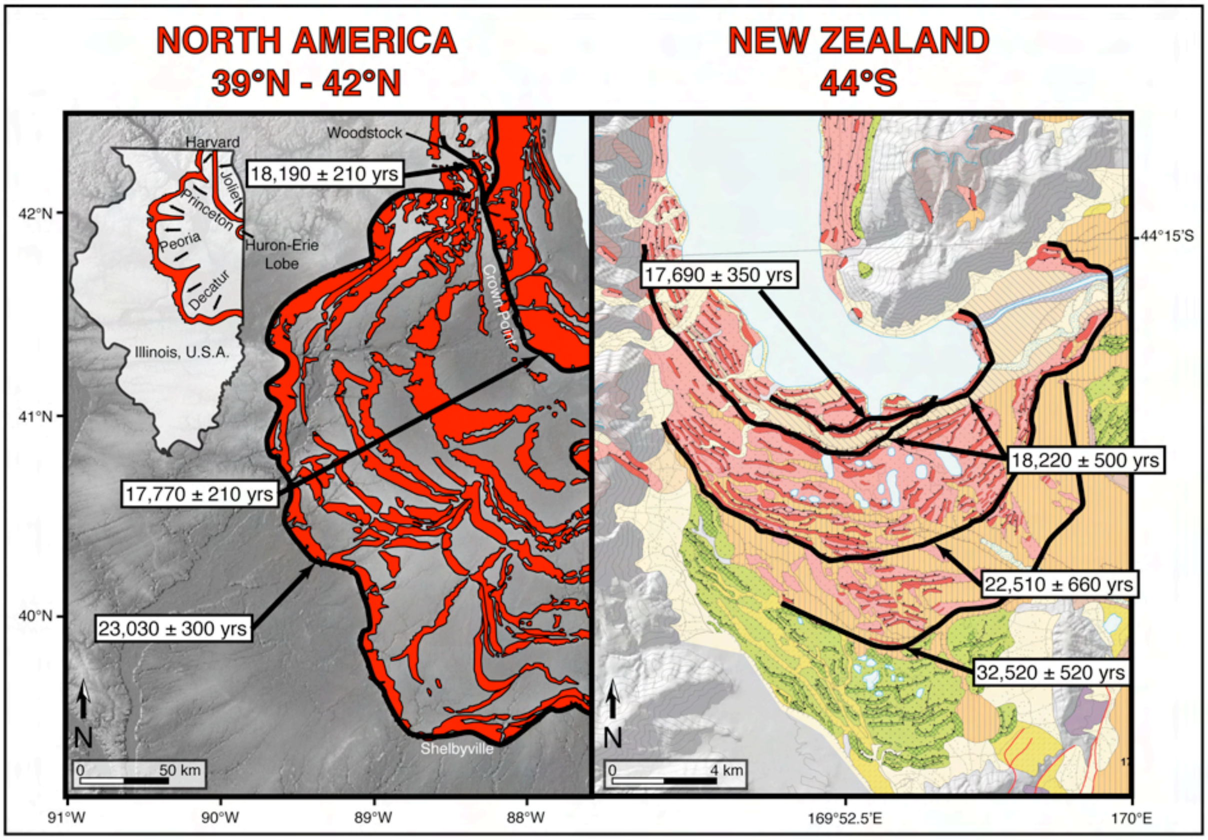
moraine. Except for a few outliers, the ages obtained for a given moraine agree within the measurement error. The closer the moraine is to the lake, the younger its age (see Figure 2-4). The youngest of these moraines has an age close to 18 kyrs. The next in this sequence of is located far up the valley. Its age is 13 kyrs, indicating that the glacier underwent a major shrinkage between 18 and 13 kyrs. Modeling suggests that during this time interval summer temperatures warmed by about 4°C.

In an earlier study of glaciated terrain in the Chilean lake district, George Denton put together a similar chronology. Instead of ^{10}Be, this chronology is based on ^{14}C dates of organic material overlying and underlying each glacial till. As shown in Figure 2-3, once again the glaciers stood near their outer limit for more than 10 kyrs and then underwent a very rapid retreat. Once again, modeling suggests that between 18 and 13 kyrs, the summer temperatures warmed by about 4°C.

The glacial record for both mountain glaciers and the Laurentian ice sheet for the Northern Hemisphere is similar to that in the Southern Hemisphere (see Figure 2-4). The maximum size was achieved about 22,000 years ago. This has been documented by radiocarbon dating of wood from the southern margin of that great American ice sheet in Ohio and Indiana. It has also been documented by ^{10}Be dating carried out by Greg Balco on numerous boulders from the eastern margin of the American ice sheet. Finally, as yet unpublished ^{10}Be dates by Aaron Putnam document that mountain glaciers in Wyoming's Wind River Range and in California's Sierra Nevada Range reached their maximum at the same time.

Meredith Kelly of Dartmouth College conducted field work on mountain glaciers located on the equator in Uganda, Africa. She was able to obtain quartz-bearing rocks from the outermost moraine. They yielded ^{10}Be age of close to 22,000 years.

However, two important differences must be mentioned. One is that both the ^{18}O record kept by benthic foraminifera and the sea level record kept by corals and deconvolved from the Red Sea planktic ^{18}O record suggest that the Northern Hemisphere



TOM LOWELL

AARON PUTNAM

JOERG SCHAEFER

GEORGE DENTON

Figure 2-4. Comparison of the moraine chronologies for the Last Glacial Maximum in Illinois with that for the South Island of New Zealand. That for Illinois was obtained by Tom Lowell of the University of Cincinnati. That for New Zealand was obtained by Putnam, Schaefer, and Denton.

ice sheets underwent a significant expansion between 30 and 25 kyrs. Further, as shown by Denton as part of his PhD thesis, glaciers in Alaska's White Mountain did the same. By contrast, mountain glaciers in the Southern hemisphere stood close to their maximum extent at about 40, 32 and 28 kyrs. As illustrated in Figure 2-5, this difference may reflect a contribution of summer insolation. During the 40- to 28-time period, southern summers received less insolation than average and northern received more than average insolation.

Another difference is that, while the Southern Hemisphere glaciers began a rapid retreat at the same time as CO_2 started to rise (i.e., 18 kyrs ago), as shown by Putnam, the rapid retreat of Northern Hemisphere mountain glaciers was delayed by about 1700 years. This delay may be the product of shifts in the latitude of the thermal equator (see Figure 2-5).

The near synchrony of mountain glaciers in the two hemispheres does not come as a surprise. Four decades ago, John Mercer obtained radiocarbon ages on Chilean mountain glaciers showing this to be the case. Nor should the similarity in snowline lowering. Reconstruction of the maximum snowline lowering in the American Cordillera have long suggested that the LGM cooling in this south was similar to that in the north (see Figure 2-6).

It has long been assumed that during the Younger Dryas cold snap glaciers in the Northern Hemisphere advanced. But, if CO_2 is the primary driver, then, as it was rising during the course of the Younger Dryas, glaciers should instead have retreated. So what is the truth in this matter? I well remember that when I was a young professor I carried out very precise ^{14}C dating of lignin and cellulose from several pieces of wood from the then famous Two Creeks Wisconsin site. As the trees at this site had been overrun by a glacier, the thought was that they might be Younger Dryas in age. However, the un-calibrated ^{14}C age of 11.8 kyrs I obtained, placed the time of this glacial re-advance prior to the Y.D. Since then we have learned that when calibrated, the age turns out to be close to 13 kyrs. Many years later in a *Science* paper, George Denton showed that Waiko Loop

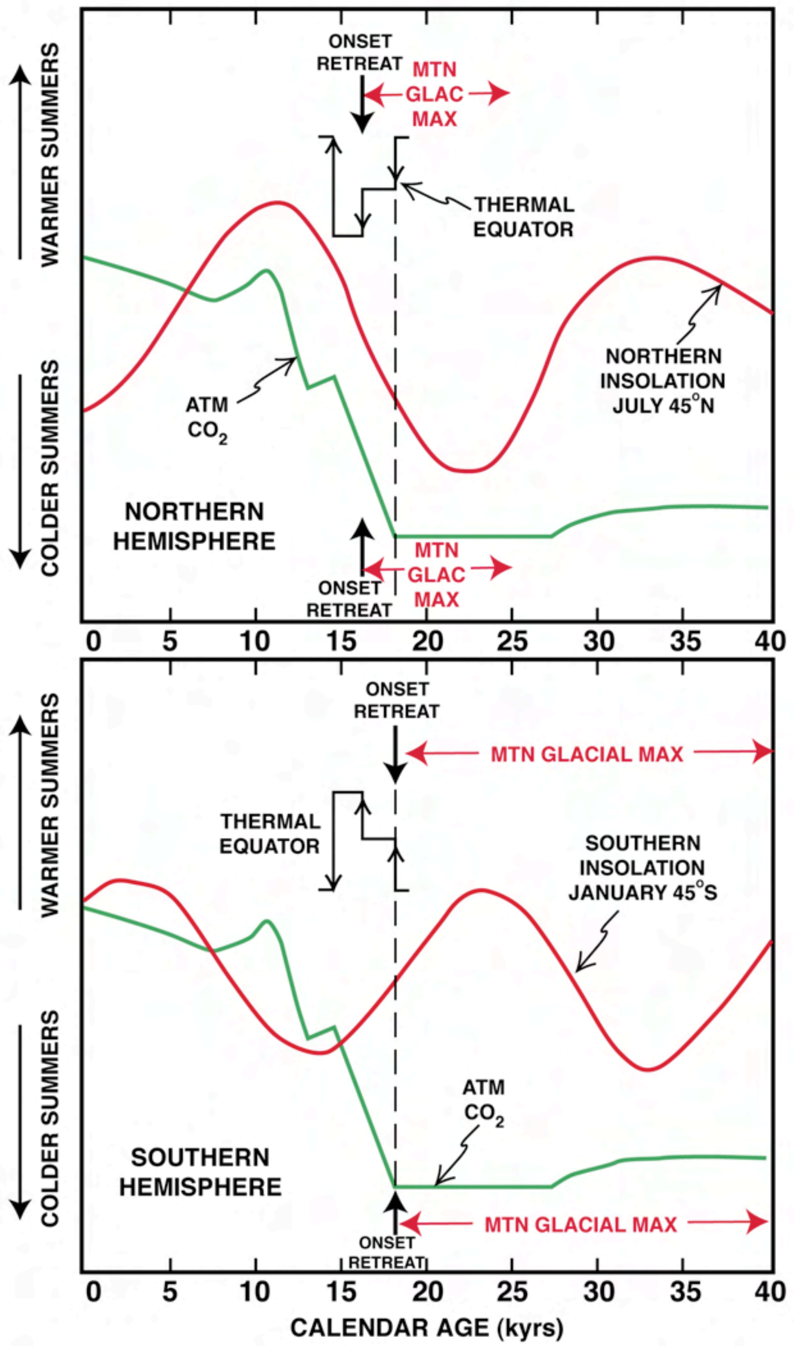


Figure 2-5. The advances and retreats of mid-latitude glaciers is orchestrated by some combination of forcing by CO_2, by summer insolation and by shifts in the thermal equator. As one of these is the same in both hemispheres and the other two are hemispherically antiphased, reconstruction of the temporal histories of glacial extents offers a means of evaluating their individual contributions.

In order to explain the observed chronologies, all three appear to have played a role. However, CO_2 must be the dominant forcing.

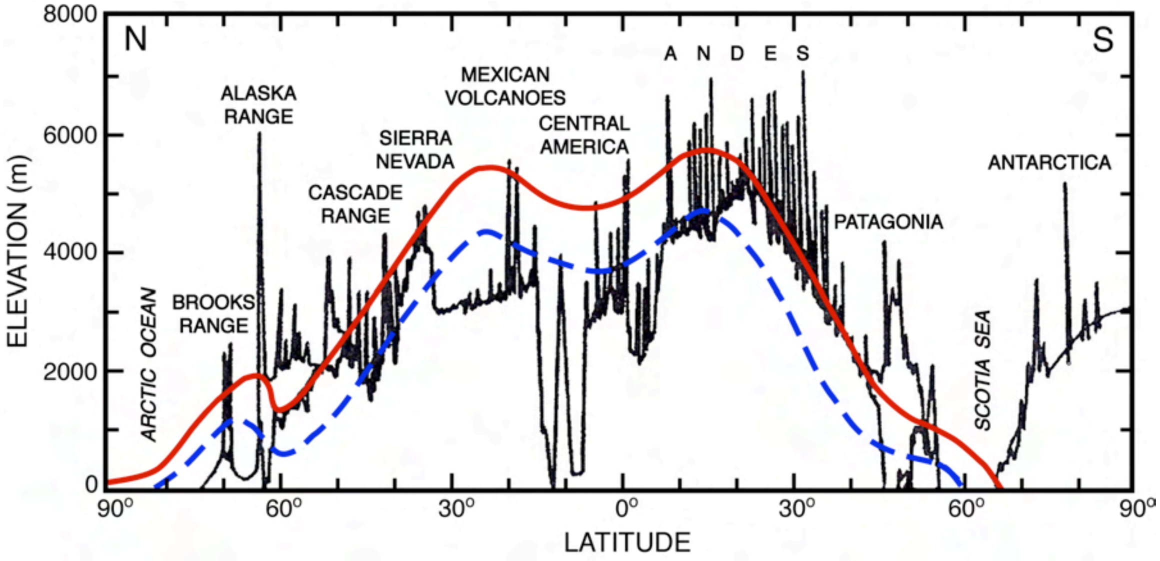


Figure 2-6. Comparison of the elevation of today's equilibrium snowlines (solid red) with those for the last glacial maximum (dashed blue) along the American Cordillera. Taken together with the well-dated temperate latitude mountain glaciers now in hand, this reconstruction strengthens the argument that there was no significant inter-hemispheric difference in the extent of glacial cooling.

moraine in the South island of New Zealand also had an age of about 13 kyrs. Although both these ages place these advances close to the beginning of the Younger Dryas, they also place them close to the end of the Antarctic Cold Reversal.

By contrast, early ^{10}Be measurements on boulders from what were thought to be Younger Dryas moraines in both the Swiss Alps and New Zealand Alps gave ages falling within the Younger Dryas age bounds. But when it was found that the production rate used to calculate these ages was too high, these ages had to be increased by about 1000 years placing them close to the boundary near the end of the Antarctic Cold Reversal. In the last couple of years, the deglacial re-advance has now been dated in a number of places. They include: Scotland, Norway, and also several locales in both the New Zealand Alps and the South American Andes. All suggest that they were formed during the latter part of the Antarctic Cold Reversal (i.e., the pause in the CO_2 rise). This greatly strengthens the case that CO_2 is the primary driver of glaciers. It should be mentioned that the glacial retreat during the Younger Dryas occurred in the Northern Hemisphere despite fearfully cold winters.

Unfortunately, the mountain glacier record does not extend back into the interglacial portion of the last climate cycle. All we have for this time interval is the reconstruction of sea level. However, as it is dominated by the waxing and waning of the North American and Scandinavian ice sheets, it tells us nothing about glaciation in the Southern Hemisphere. But if CO_2 drives glacial extent, then the record of sea level should have the same shape similar to for CO_2. As shown in Figure 2-7, for the last 25 kyrs this is the case. However, the large drop in sea level 30 and 25 krys has only a small equivalent in the CO_2 record but the minimum in sea level does match the time when the southern lobe of the Laurentide ice sheet reached its maximum (see Figure 2-4). Another mismatch exists for the first half of the cycle. The CO_2 record contains only two of the three prominent interglacial sea level maxima (see Figure 2-7).

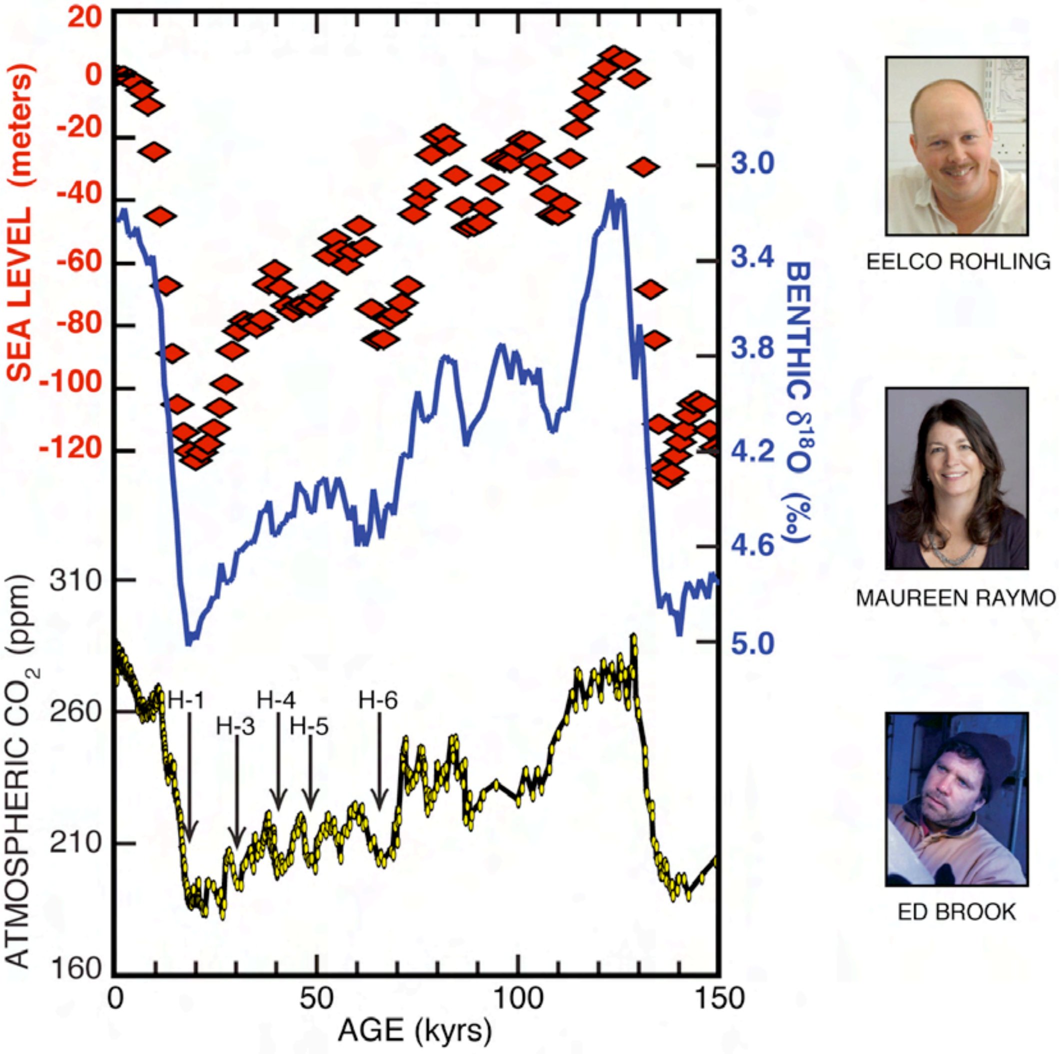


Figure 2-7. Comparison between the records for sea level (red diamonds) and atmospheric CO_2 (yellow curve) for the last 150,000 years. Although the ups and downs of sea level track CO_2 reasonably well, there are certainly significant mismatches. Also shown is the well documented ^{18}O record for benthic foraminifera (blue curve). It records some combination of ice volume and deep ocean temperature. Eelco Rohling is largely responsible for the sea level record, Maureen Raymo for the ^{18}O record and Ed Brook for the CO_2 record.

Another comparison is worth mentioning. It is that between the CO_2 record and the ^{18}O record for benthic foraminifera. As it has been reproduced in sediment cores from dozens of locales in the deep ocean, its details are more believable than those in the less reliable sea level record. However, it has the major drawback that only about half its amplitude is the result of change in the volume of the ^{18}O-deficient ice caps. The other half is the result of changes in deep ocean temperature. Isolating the ice volume component from the temperature component remains uncertain. However, if the dips in the ^{18}O record between the 124, 104 and 84 kyr ^{18}O maxima are attributed entirely to changes in ice volume, then there is an obvious mismatch with CO_2.

Putting aside for the moment these seeming flaws in my scenario, a reasonably strong case can be made that CO_2 is the primary driver of mountain glacier extent. If so, the question arises as to what drives atmospheric CO_2 content changes? A majority of climate scientists believe that it is uptake and release of CO_2 by the ocean. As the ocean contains 60 times more dissolved inorganic carbon (i.e., CO_2, HCO_3^- and $CO_3^=$) than the atmosphere, it is easy to see that it might accommodate the CO_2 missing from the atmosphere during glacial time. However, despite 30 years of research, there is still no consensus on the details of what drove the uptake and release. Nor is it clear where in the ocean this excess CO_2 resided. In Chapter 4, I present thoughts as to how this might have occurred.

It must be mentioned that the lack of a consensus among oceanographers regarding a scenario to explain the uptake and release of CO_2 by the ocean has led to a non-oceanic explanation. Harvard's Peter Huybers and Charles Langmuir propose instead that it was, at least in part, the result of a pulsing of the CO_2 release from volcanoes. Their idea is that the weight of excess glacial ice squelched volcanic eruptions and hence reduced the resupply of CO_2 to the ocean-atmosphere reservoir. As the result, accumulation of $CaCO_3$ and organic matter in marine sediments would exceed the carbon supply and the CO_2 content of the atmosphere would be drawn down. During deglaciation when the weight of this excess ice was removed, the volcanic input would be restored adding back the missing CO_2. One might conclude that this hypothesis were to be proven the correct one, then ice extent drove CO_2 rather than, as proposed here, CO_2 drove glacial extent. However, as will be discussed below, it is likely that both ocean uptake and volcano stoppage contributed. If so, the volcanic contribution could be considered to be the result of ocean drawdown.

Before moving on to the millennial-duration climate changes and to CO_2 uptake by the ocean, it must be pointed out that, unlike glaciers, tropical hydrology appears to be directly impacted by seasonality cycles. It lacks the downward ramp so prominently displayed by the sea level, benthic ^{18}O and CO_2 records. The best evidence comes from the ^{18}O record kept in Chinese stalagmites. The oxygen isotopic composition of cave calcite reflects that for the rain falling above the cave. The isotopic composition of monsoon rainfall is influenced by what is referred to as the amount effect. If a cloud dumps most of its vapor in a single thunderstorm, the rain will be deficient in ^{18}O. If instead, it loses a small fraction of its vapor to a sprinkle, the rain will be, by comparison, ^{18}O rich. As shown in Figure 2-8, although the oxygen isotope record in Chinese stalagmite correlates very nicely with Northern Hemisphere summer insolation, it has almost no similarity to the CO_2 record. It lacks the 100-kyr downward ramp.

During times of strong summer insolation, the ^{18}O content of the stalagmites is lower than during times of weak summer insolation. Larry Edwards, Hai Cheng and Xianfeng Wang, who produced these records, interpret them as direct indicators of the strength of monsoon rainfall. David Battisti, a modeler, takes issue with this interpretation and claims, instead, that it is related to the path taken by the air masses which deliver the precipitation. Regardless of which interpretation proves to be the correct one, both would agree that the strong 21-kyr cycle in the Chinese stalagmite record reflects changes in the magnitude of summer heating of Southeast Asia. Curiously then, both ice extent in the cold parts of the globe and monsoon rainfall in the warm parts

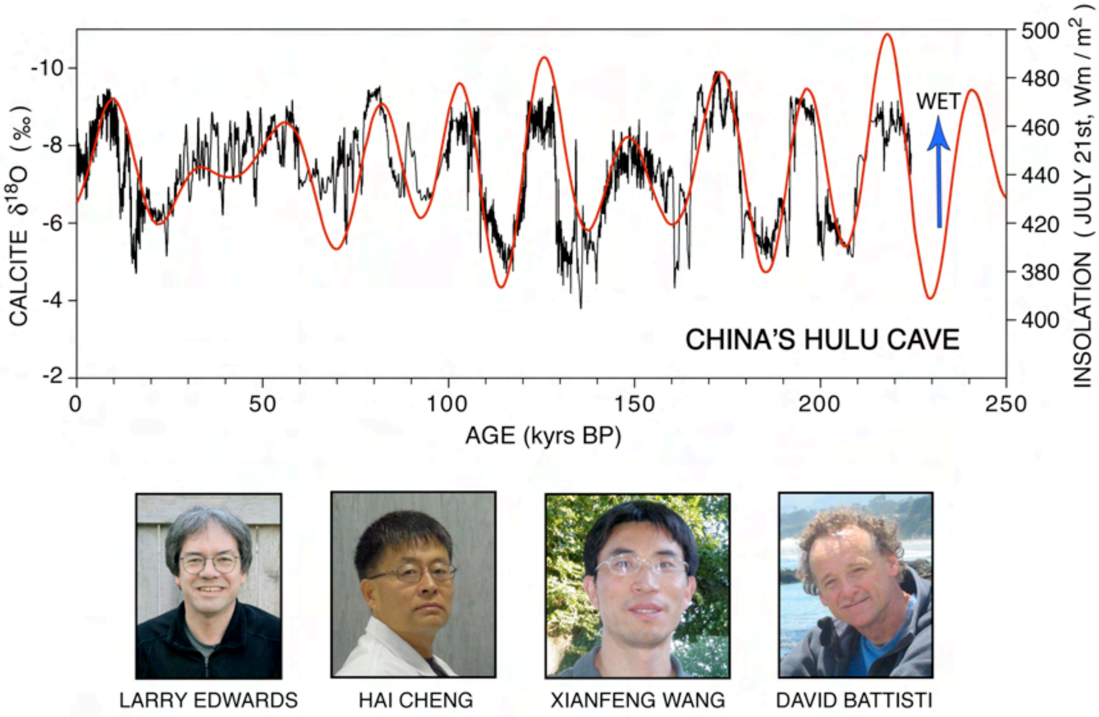


Figure 2-8. Working together at the University of Minnesota, Larry Edwards, Hai Cheng and Xianfeng Wang generated numerous precisely dated ^{18}O records for stalagmites from caves in China and elsewhere in Southern Asia. All look like the one for China's Hulu Cave reproduced here. Instead of following atmospheric CO_2, as do the mountain snowlines, they track Northern Hemisphere summer insolation. If the Edwards et al. explanation for these variations is correct, then the more negative the δ^{18}O value, the stronger the monsoons. This is consistent with the observation that the peaks in the δ^{18}O minima match summer insolation (red curve). However, based on simulations carried out in ocean-atmosphere models, the University of Washington's David Battisti concludes that instead, they are caused by reorganizations of atmospheric circulation.

sense summer heating. Yet, in one case, it is heating by summer insolation, and in the other, it's heating by CO_2. Just as puzzling is that while temperature in the cold world was dominated by the 100-kyr cycle, the rainfall in the warm world is dominated by the 20-kyr cycle.

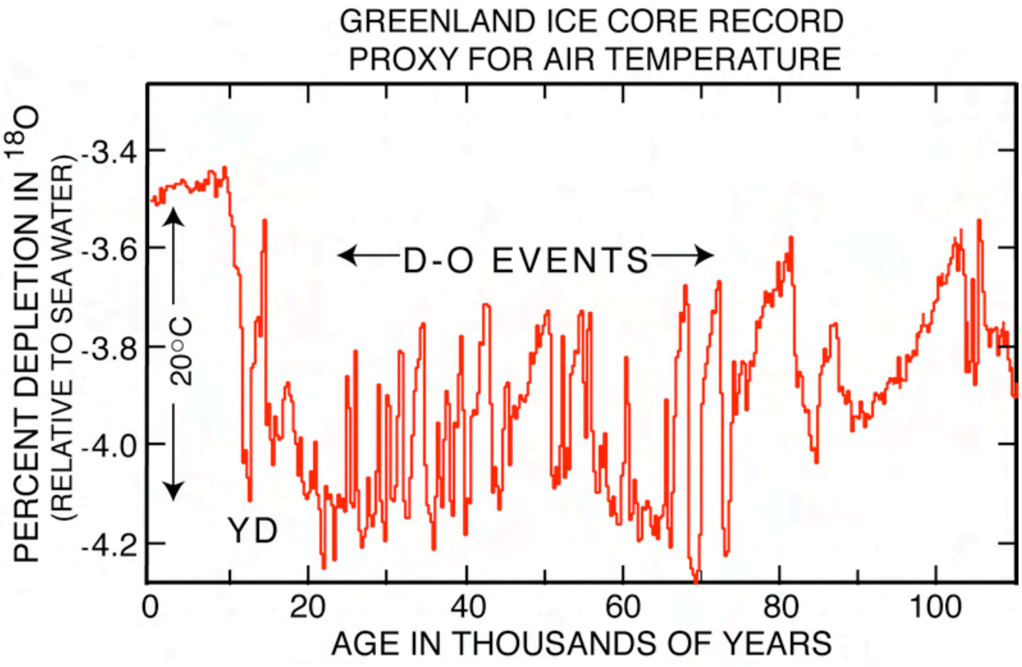
Chapter 3

Climate's Punctuator: Millennial Reoganizations of Ocean Circulation

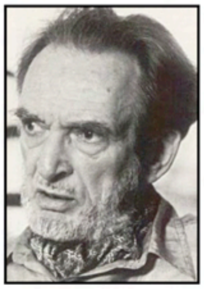
Complicating the situation are millennial-duration rectangular-shaped climate changes which modulate the longer term orbital cycles in records from everywhere on the planet. It is widely accepted that these changes involve reorganizations of the ocean's large-scale circulation. But they produce only small changes in atmospheric CO_2 content. Hence, the question is, do they rule out the hypothesis that longer term orbitally-driven circulation changes govern the uptake and release of CO_2 by the ocean? Before attempting to answer this question, a discussion of the discovery and geographical reach of the abrupt changes is in order.

In 1971, the oxygen isotope record from the first core drilled through the Greenland ice cap was presented at a meeting held at Yale University. Willi Dansgaard, who pioneered the application of Urey's oxygen-isotope method to ice cores, stunned us all by showing results from a core to bedrock recovered at the Camp Century locale in northwestern Greenland. Rather than displaying the expected smooth Milankovitch rhythms, it was dominated by a series of millennial-duration steep-sided rectangles (see Figure 3-1). If, as Dansgaard postulated, these abrupt back and forth shifts in oxygen isotope ratio reflected large changes in air temperature, then the Greenland's climate must be responding to some forcing other than orbital cycles. The shock was so great that most of us passed off the Camp Century record as some curiosity associated with Greenland ice. How wrong we were!

A decade passed before the results from a second Greenland ice core became available. At a meeting held at Switzerland's University of Bern, Hans Oeschger presented Dansgaard's ^{18}O record for an ice core from the Dye 3 site in south Greenland. It looked very much like the earlier Camp Century record confirming that these rectangular changes were Greenland wide. In addition, Oeschger showed a companion



HANS OESCHGER



WILLI DANSGAARD

Figure 3-1. Seven ice cores penetrating to bedrock have been obtained in Greenland. They form a traverse extending from Camp Century in the north to Dye 3 in the south. All of them bottom out at about 110,000 years (i.e., part way through the last interglacial). The ^{18}O to ^{16}O ratio records for ice reveal an identical set of features. Switches from frigid stadials to moderate interstadials punctuate the middle portion of the record. In honor of the two scientists, Denmark's Willi Dansgaard and Switzerland's Hans Oeschger who pioneered studies of Greenland ice, they are referred to as Dansgaard-Oeschger (D-O) events. Note that these events are absent during the time of peak glaciation 18 to 24 kyrs ago. A D-O-like event called the Younger Dryas (YD) punctuates the deglacial time interval.

record of the CO_2 content of air trapped in bubbles in the ice. Once again I was stunned. For a sequence of four successive rectangular oxygen isotope excursions, he found matching CO_2 excursions (See Figure 3-2). Warmer times corresponded to elevated CO_2 and cooler times to reduced CO_2. No longer could we ignore these strange records. Clearly Greenland was telling us something very important.

As I had spent much of the 1970s attempting to determine how much of the CO_2 produced by the burning of fossil fuels was being taken up by the ocean, I was puzzled as to how these abrupt 50 ppm changes in the atmosphere's CO_2 content could have been generated. This led me to consider deep water production in the northern Atlantic for it was the major conduit by which water was transferred from the surface to the deep sea. I was aware that the Gulf Stream carried an enormous amount of heat to the region around Iceland. During the winter, frigid winds flowing off North America extracted this heat cooling the water to the point where it was dense enough to sink to the abyss. I pondered what would happen if this deep water production were to be turned off.

Although I had hit upon a suitable explanation for the back and forth oxygen isotope excursions, I could think of no way in which stopping and restarting of deep water production could generate the observed abrupt 50 or so ppm changes in the atmosphere's CO_2 content (see Figure 3-2). Fortunately, this problem soon disappeared. Detailed measurements on one of the transitions demonstrated the lack of any offset in depth between the CO_2 shifts and the oxygen isotope shifts in Dye 3. But as the closure of the bubbles which trap the air occurs tens of meters below the snow surface, there should have been an offset. Additional evidence that these CO_2 shifts were false was soon provided when these CO_2 excursions were shown to be absent in an ice core from Antarctica. Instead, the elevated CO_2 in Greenland's interstadials appears to have been generated within the ice by reaction between $CaCO_3$ dust and acid aerosols. Despite being misled, were it not for my search for a way to explain the Oeschger's CO_2 results, I

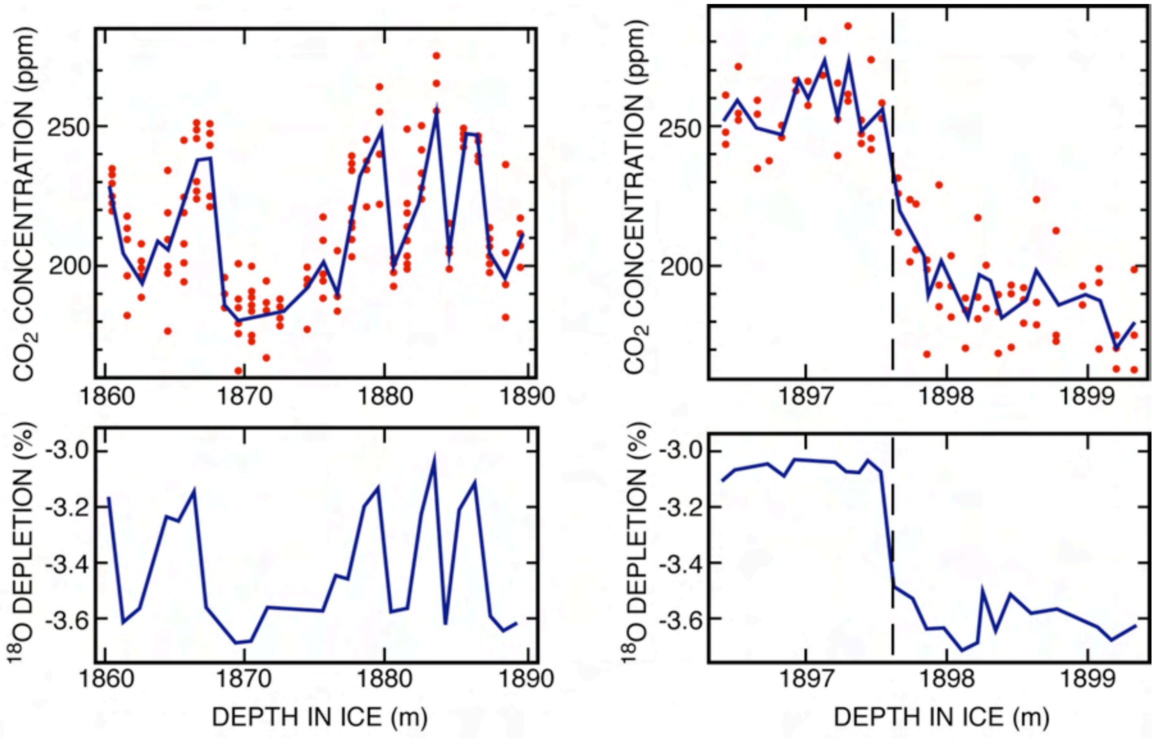


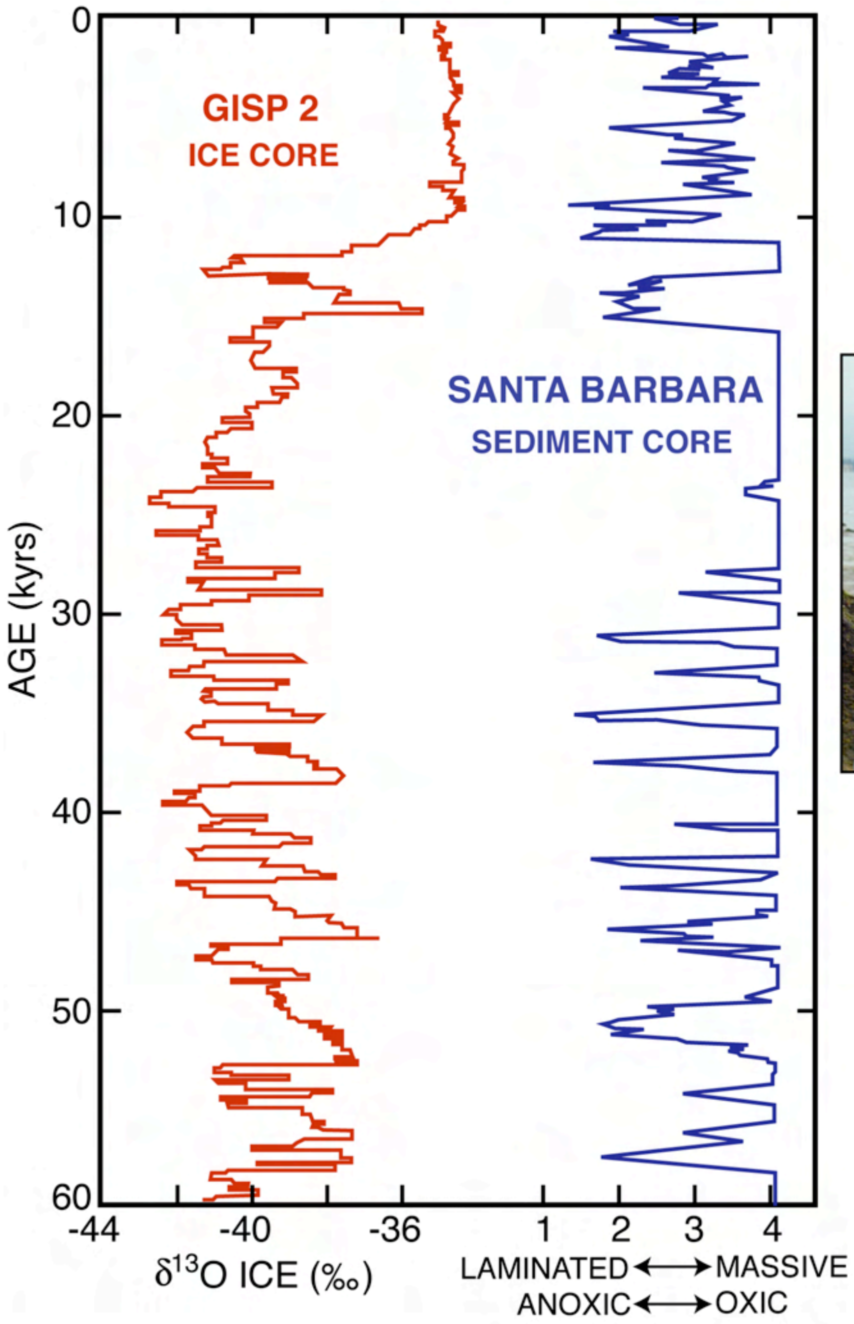
Figure 3-2. Comparisons of the ^{18}O and CO_2 records for five Dansgaard-Oeschger events in Greenland's Dye 3 ice core. It was the elevated CO_2 concentrations in the interstadials that led me to propose turn-ons and –offs of deep water formation in the northern Atlantic as the cause for the Younger Dryas and Dansgaard Oeschger events recorded in Greenland ice. It turns out that the CO_2 peaks did not record changes in the atmosphere. Rather they were the result of the reaction within the ice between $CaCO_3$ dust and acidic aerosols. But they did lead me to an important discovery.

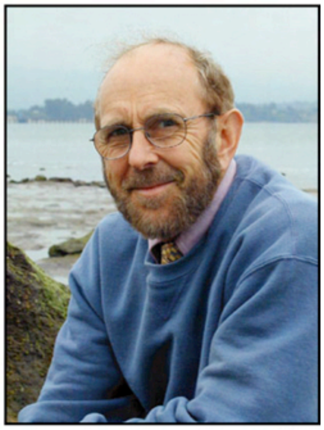
would probably not have been the one to discover the cause of the abrupt shifts in Greenland temperature.

One might ask, why aren't similar anomalies present in the Antarctic record? The answer is 'no'. The rain of $CaCO_3$ dust and acid aerosols onto Antarctica is 20 or so times smaller than onto Greenland. The reason is the absence of high-latitude dust and acid-generating land masses in the Southern Hemisphere.

Early on, I thought that the shutdown of deep water formation would have impacted mainly the climate of northern Europe. Instead of being warmed by the release of ocean heat, the winter westerly winds reaching Europe would have been considerably colder. Indeed, evidence for such a cooling was made clear from records of the pollen assemblages and of oxygen isotopes in $CaCO_3$ deposited in European lakes during the Younger Dryas.

But soon my colleague, Dorothy Peteet, found clear evidence for a Younger Dryas cold snap in the pollen record from the sediments deposited in a small bog in Alpine, New Jersey located only a half mile from my office at Columbia University's Lamont-Doherty campus and, a few years later, a record appeared indicating that the Younger Dryas impacts were present in faraway California. It was provided by a long sediment core from the Santa Barbara Basin (see Figure 3-3). As this sediment accumulated at a rate of a meter per thousand years, it preserved a detailed record which covered the last 60 millennia. Not only the Younger Dryas, but also all of the Dansgaard-Oeschger events present in the Greenland ice cores. Several years before an oxygen isotope record was generated, this sequence of events was established by visual examination of the core. In some sections of the sediment annual laminations were preserved and in others these laminations were either broken up or obliterated. The University of California's Jim Kennett, who led this study, quickly realized that during periods when the annual laminations were preserved, little or no oxygen was present in the basin's deep water. In the absence of oxygen, there could be no worms to burrow into





JIM KENNET

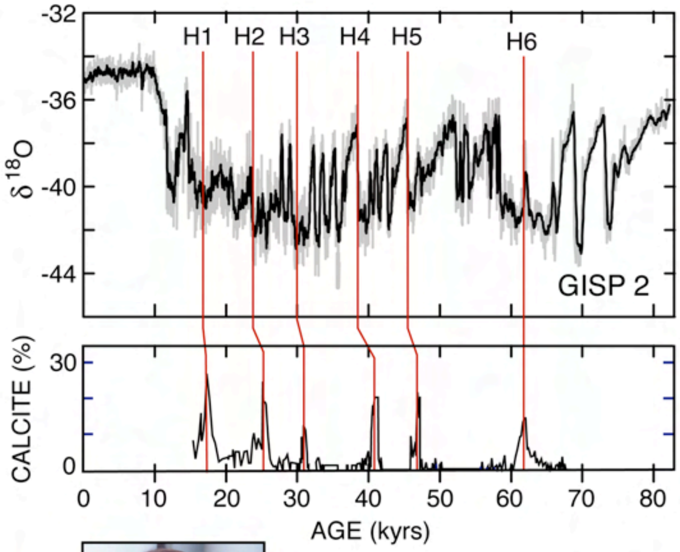
Figure 3-3. Comparison between an ice core record from Greenland and a sediment core record from the Santa Barbara Basin. During the cold phases of Dansgaard Oeschger events (and the Younger Dryas), the annual laminations are totally obliterated by burrowing worms. At all other times, the oxygen content was too low to support a worm population. Note that during the course of the Last Glacial Maximum adequate O_2 was present. This suggests that at that time the Santa Barbara Basin was ventilated by O_2-rich intermediate water produced in the northern Pacific rather than by O_2-poor water transported northward from the northern fringe of the Southern Ocean.

and churn the sediment. Hence, the annual laminations remained intact. By contrast, when oxygen was present, worms mixed the sediment, damaging or destroying the laminations. When matched with the Greenland record, the sections of Santa Barbara lacking laminations corresponded to the Last Glacial Maximum (LGM) and cold portions of the Dangaard-Oeschger (D-O) cycles (see Figure 3-3).

The Santa Barbara Basin record points to changes in Pacific Ocean circulation. During the warm portions of this record (including the Holocene), the bottom waters in this isolated basin were renewed by the inflow of intermediate depth water generated along the northern fringe of the far away Southern Ocean. During their long trip up the Pacific, these waters lose most of their oxygen to respiration. Hence, the presence of oxygen during the cold portions of D-O events suggests that the basin was ventilated by intermediate depth waters formed in the nearby northern Pacific. If so, when deep water production was turned off in the northern Atlantic, it appears that intermediate water production was turned on in the northern Pacific.

Complicating this situation are six Heinrich events recorded in northern Atlantic sediments by layers dominated by in ice-rafted debris (see Figure 3-4). They range in age from about 60 kyrs to about 18 kyrs. They are thought to have their origin in the melting of armadas of debris-rich icebergs abruptly launched from Hudson Straits into the northern Atlantic as the result of the collapse of the Laurentide ice sheet’s Hudson Bay lobe. The fresh water released by the melting of these bergs created a low salinity cap which squelched deep water production in the northern Atlantic. Once created, the low salinity cap appears to have remained in place for 700 or so years.

A puzzle exists with regard to the relationship between Heinrich events and Dansgaard-Oeschger events and between the Younger Dryas and the others. It involves the difference in the geographic pattern of their impacts. As listed in Table 3-1, although most records document the Younger Dryas, some record Heinrich events, but not



HARTMUT HEINRICH

SIDNEY HEMMING

GERARD BOND

JERRY McMANUS

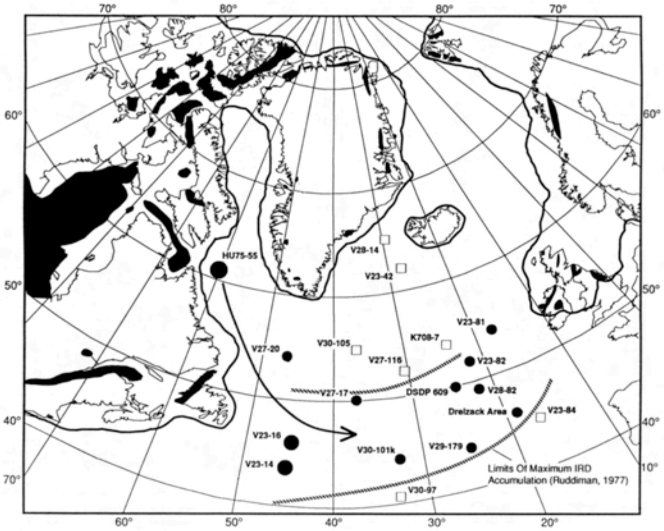


Figure 3-4. While a graduate student at the University of Kiel, Harmut Heinrich made an amazing discovery. In a deep sea core raised from the Dreizack area, he found that the ambient foraminifera-rich sediment was interrupted by 6 pulses of ice-rafted material. He postulated, correctly, that these lithic grains were delivered by huge armadas of icebergs produced by the collapse of the Hudson Bay lobe of the Laurentide Ice Sheet. The rain of lithic grains overwhelmed that of foraminifera shells. Despite the fact that these events produced global impacts, they do not show up in any prominent way in the Greenland ice core ^{18}O record. Gerard Bond picked up on Heinrich's discovery by mapping the locations where the debris from these armadas is present (closed circles) and absent (open squares). He also made the correlation with the Greenland record. Jerry McManus documented the presence of Heinrich debris at each of the Terminations which occurred during the last half million years. Sidney Hemming published a comprehensive review paper summarizing what is known about these ice armadas.

Table 3-1. Presence or absence of impacts of the Younger Dryas, Dansgaard-Oeschger and Heinrich events.

	Younger Dryas	Dansgaard-Oeschger	Heinrich
Greenland ^{18}O	Yes	Yes	No
Santa Barbara Basin	Yes	Yes	No
Florida Pollen	Yes	No	Yes
Brazil River Runoff	Yes	No	Yes
Upwelling off Pakistan	Yes	Yes	Yes
Chinese Stalagmites	Yes	Yes	Yes
Venezuelan Runoff	Yes	Yes	Yes

Dansgaard-Oeschger events, and others, Dansgaard-Oeschger events, but not Heinrich events. And some record all three.

Records for ice cores from Antarctica differ significantly from those from Greenland. Orbital cycles are prominent. Dansgaard-Oeschger cycles and Heinrich events are muted. Of particular interest is the placement of the Younger Dryas time interval in this record. At first, many of us thought that it corresponded to a plateau in the CO_2 rise which occurred during the transition from the Last Glacial Maximum to the Holocene (see Figure 3-5). However, in a lecture presented at Lamont-Doherty, Grenoble's Jerome Chappallaz showed that this was not the case. Rather, he demonstrated convincingly that the Younger Dryas corresponded to the period of CO_2 rise following the plateau. He did this by comparing the methane record preserved in bubbles in Antarctic ice with that preserved in Greenland ice. During the Younger Dryas, a large drop in atmospheric methane is recorded in Greenland. As methane is globally well mixed, the corresponding methane low found by Chappallaz in Antarctic ice allowed the two records to be correctly correlated. The plateau in the CO_2 rise recorded in Antarctic ice (known as the Antarctic Cold Reversal) corresponds to the Bølling Allerød false interglacial recorded in the Greenland record (see Figure 3-5).

Right there in the Lamont-Doherty seminar room, it dawned on me what this was telling us. There must be a bipolar ocean seesaw. The turning on and off of deep water production in the northern Atlantic must have created some sort of opposing change in the Southern Ocean. It took a number of years before an acceptable scenario appeared. It involved antiphased expansions and contractions of sea ice cover in the two polar oceans.

Early on, I failed to recognize the most important consequence of the shutdown of deep water formation in the northern Atlantic (see Figures 3-6 and 3-7). If this shutdown were a result of dilution of salt by the input of fresh water, then, under the cold conditions of glacial time, the very next winter sea ice would have formed. Once formed, no longer would heat from the underlying water column be able to penetrate to the surface, and in

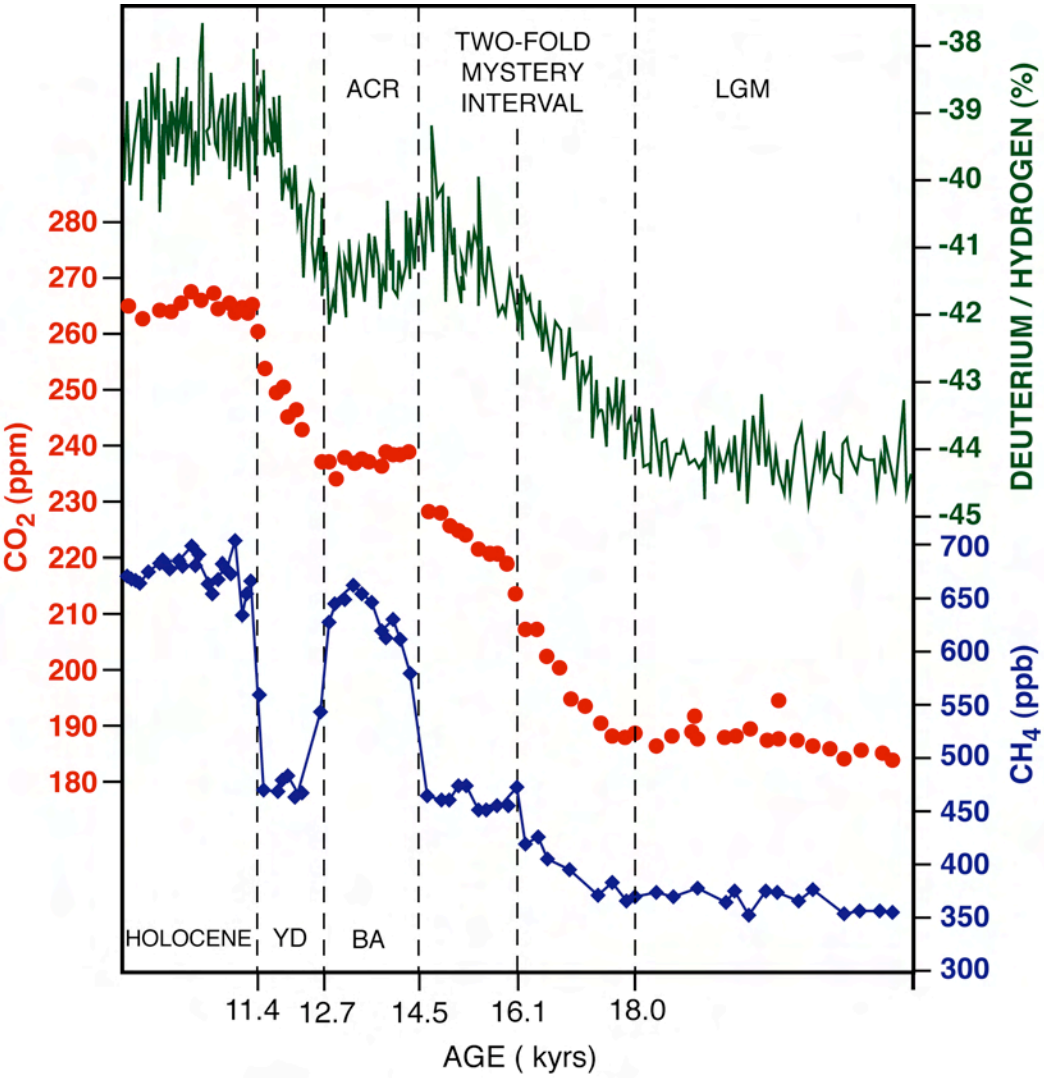


Figure 3-5. Comparison of records in Antarctic ice for methane (blue) and carbon dioxide (red) of trapped air with that of the D to H ratio on the ice itself (a stand-in for air temperature). As can be seen, the methane record differs from that of the other two properties. Instead it looks very much like the Greenland oxygen isotope record, reaching a concentration close to that for the early Holocene during the Antarctic Cold Reversal, and then plummeting during the time of the Younger Dryas. As methane is uniformly distributed throughout the atmosphere, its variations allow the Greenland and Antarctic records to be precisely correlated. Methane follows Greenland air temperature because much of it is produced in Northern Hemisphere swamps. It was this record that triggered me to propose the bipolar seesaw.

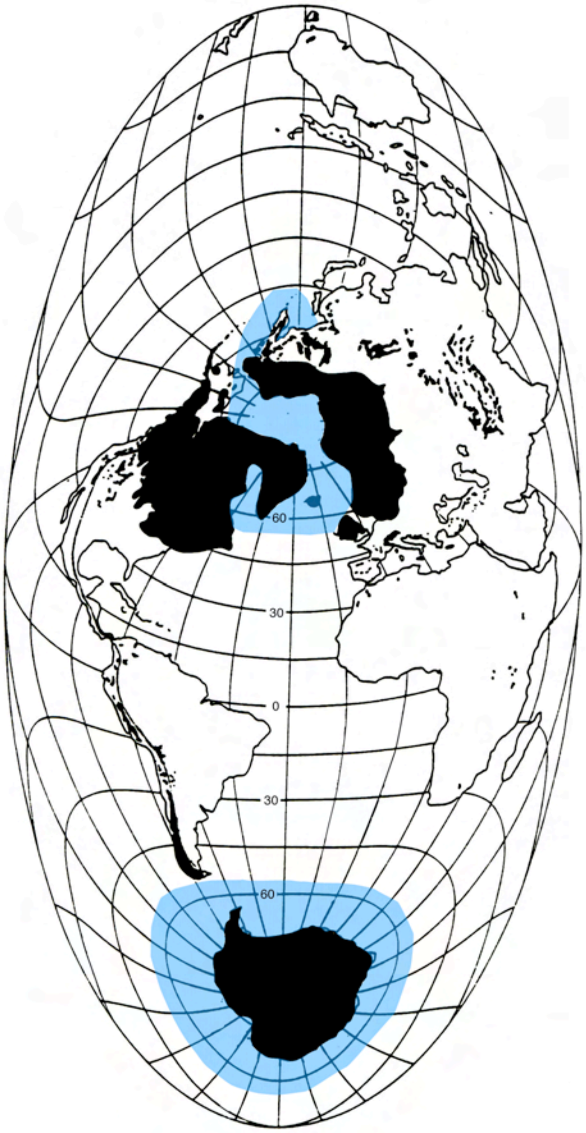
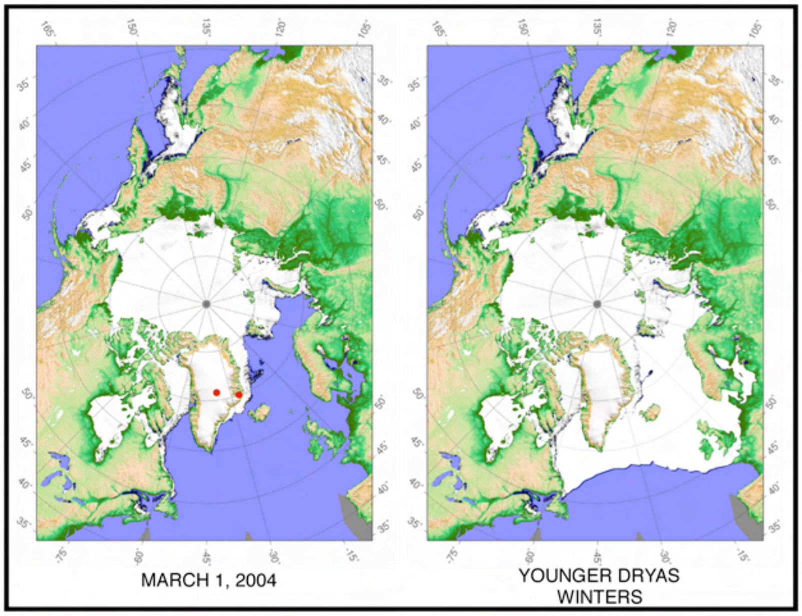
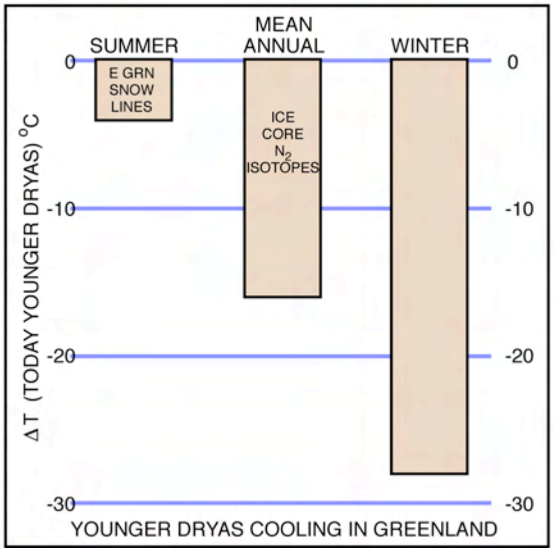


Figure 3-6. Not only were there large ice caps in the Northern Hemisphere during times of peak glaciation (black), but also greatly extended sea ice (blue). Although the Antarctic ice cap didn't change much in extent, winter sea ice extended out 5 or so degrees farther equatorward than it does today. These expansions in ice cover are probably responsible for a 10 to 20° polar cooling. As the tropics cooled by only about 3°C, these expansions increased the equator to pole temperature gradient, leading to more frequent and intense winter cyclonic activity thought to be responsible for the several-fold higher atmospheric dust loading during times of peak glaciation.






JEFF SEVERINGHAUS

Figure 3-7. George Denton realized that there was a large mismatch between the mean annual temperature reduction and summer temperature reduction for the Younger Dryas time interval. The University of California San Diego's Jeff Severinghaus used an ingenious proxy that he developed to estimate the mean annual temperature reduction. It involves the separation of ^{15}N from ^{14}N in firn at Greenland's Summit locale following times of abrupt warming. Denton's summer estimate is based on the YD snowline lowering at Scoresby Sund in eastern Greenland with confirmation from Scandinavian pollen records. Rather than rejecting either of these estimates, Denton proposed that the winter temperature reduction was 6 or so times larger than that for summer. His explanation for this greatly enhanced seasonality is a large expansion of winter sea ice.

turn, prevent heating of overlying atmosphere. It would also reflect away sunlight. This would deprive northern Europe of both ocean and solar heat, making winters much like those in Siberia. Sea-ice melting during the summer would temporarily ease the situation, but, as happens in today's Arctic, the fresh water lid would survive, allowing sea ice to reform during each succeeding winter.

One consequence of the polar cooling would be a steeper pole to equator temperature gradient. The polar region underwent a cooling of at least 10°C. By contrast, the tropical ocean cooled by only about 3°C. The steepened thermal gradient would have increased the frequency of cyclonic storms and hence the pickup of dust. The sudden expansion of winter sea ice is imprinted in Greenland ice by a large and abrupt increase in dust rain (see Figure 3-8). Of course, when the production of deep water in the northern Atlantic was renewed, the situation was reversed. Especially impressive is the abrupt drop in the rain of dust which took place 14.6 kyrs ago. Marine records show that deep water formation in the northern Atlantic resumed at this time eliminating the excess sea ice and initiating the so-called Bølling-Allerød period of near interglacial warmth.

Evidence for anti-correlated sea ice changes in the Southern Ocean comes from the opal record. As shown by Lamont Doherty's Bob Anderson, maxima in the rain of diatoms occurred during the intervals before and after the Antarctic Cold Reversal (the Southern Ocean equivalent to the Bølling-Allerød). The silica supporting this excess diatom production was presumably supplied by enhanced Southern Ocean upwelling. As a consequence, the extent of Southern Ocean sea ice must have been reduced.

So, if this scenario is correct, Earth's thermal equator would have received a double whammy. During episodes like the Mystery Interval and Younger Dryas, expanded sea ice in the northern Atlantic would have given it a push to the south. An addition to this southward push would have been provided by the reduction of sea ice in the Southern Ocean. By contrast a strong push to the north occurred during the Bølling-Allerød when excess sea ice switched from the north to the south.

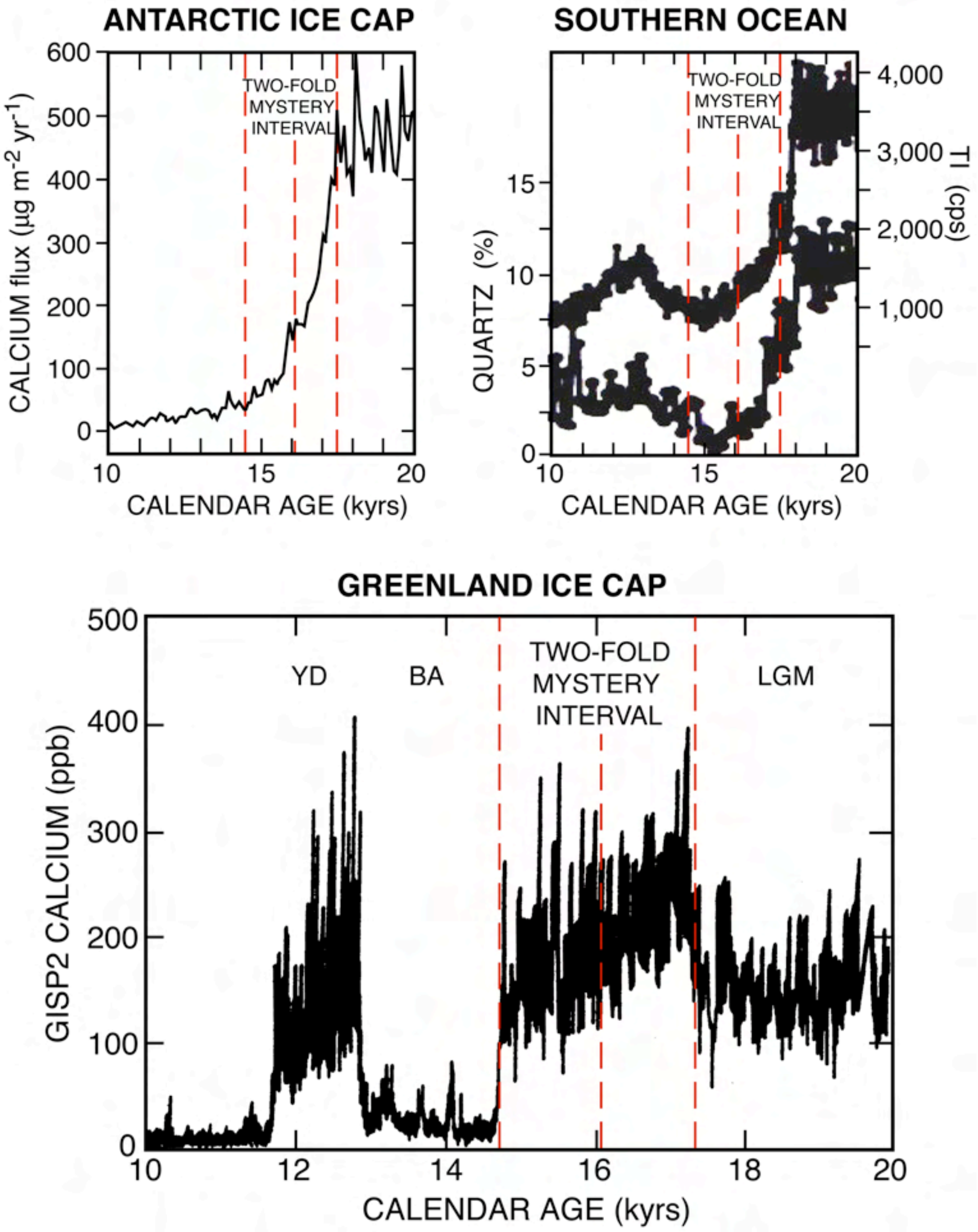


Figure 3-8. Comparison of the records for dust input to the Antarctic and Greenland ice caps for the period of deglaciation. For Greenland, the high dust rain of peak glacial time gives way to an even higher rain during both parts of the Mystery Interval. Then at the onset of the Bølling Allerød, it drops to close to its early Holocene level only to zoom back up again during the Younger Dryas. By contrast, the high dust input to Antarctica and also to the Southern Ocean just south of Australia drops precipitously throughout the first phase of the Mystery Interval, a time when Antarctica underwent a major portion of its post glacial warming. It remains low during the remainder of the deglacial and into the early Holocene.

U.C. Berkeley's John Chiang was the first to demonstrate using ocean-atmosphere models that these shifts in the location of the thermal equator carry with them the tropical rain belts. This prediction was beautifully confirmed by records from the now dry regions surrounding the Amazon rain forest. As shown in Figure 3-9, there are four such records, one to the north, and three to the south of Amazonia.

The northern record comes from the Caribbean's Cariaco Basin just offshore from Venezuela. It is based on the color of the sediment. The soil debris supplied to the ocean by river runoff is dark in color. This terrestrial material is mixes with light-colored $CaCO_3$ produced by marine organisms. As the change in the terrestrial input associated with the changes in Venezuelan rainfall are far larger than those associated with the production of marine $CaCO_3$, the sediment color provides an index of rainfall in the river's drainage basin. The darker the sediment, the larger the amount of debris carried to the sea by rivers and hence the larger the rainfall in the now dry regions of northern Venezuela. This color record has been subsequently confirmed by measurements of the sediment's titanium content (a constituent of soil debris). As shown in Figure 3-9, this record reveals that the river runoff was larger during the Bølling-Allerød than during the latter half of the Mystery Interval. Further, the color transition at the onset of the Bølling-Allerød is extremely sharp, consistent with an abrupt restart of deep water formation in the northern Atlantic.

The three records from south of Amazonia reinforce the conclusion that a pronounced northward shift of the thermal equator (and its associated rain belts) occurred at the end of the Mystery Interval. As shown in Figure 3-9, in the currently hyper-arid southern portion of Bolivia's altiplano, an immense lake, present during the Mystery Interval, dried up. It was three times larger than today's Lake Titicaca. Intense river runoff to the eastern Brazil's continental margin underwent a sharp decline. And stalagmite growth in a cave in eastern Brazil came to a halt.

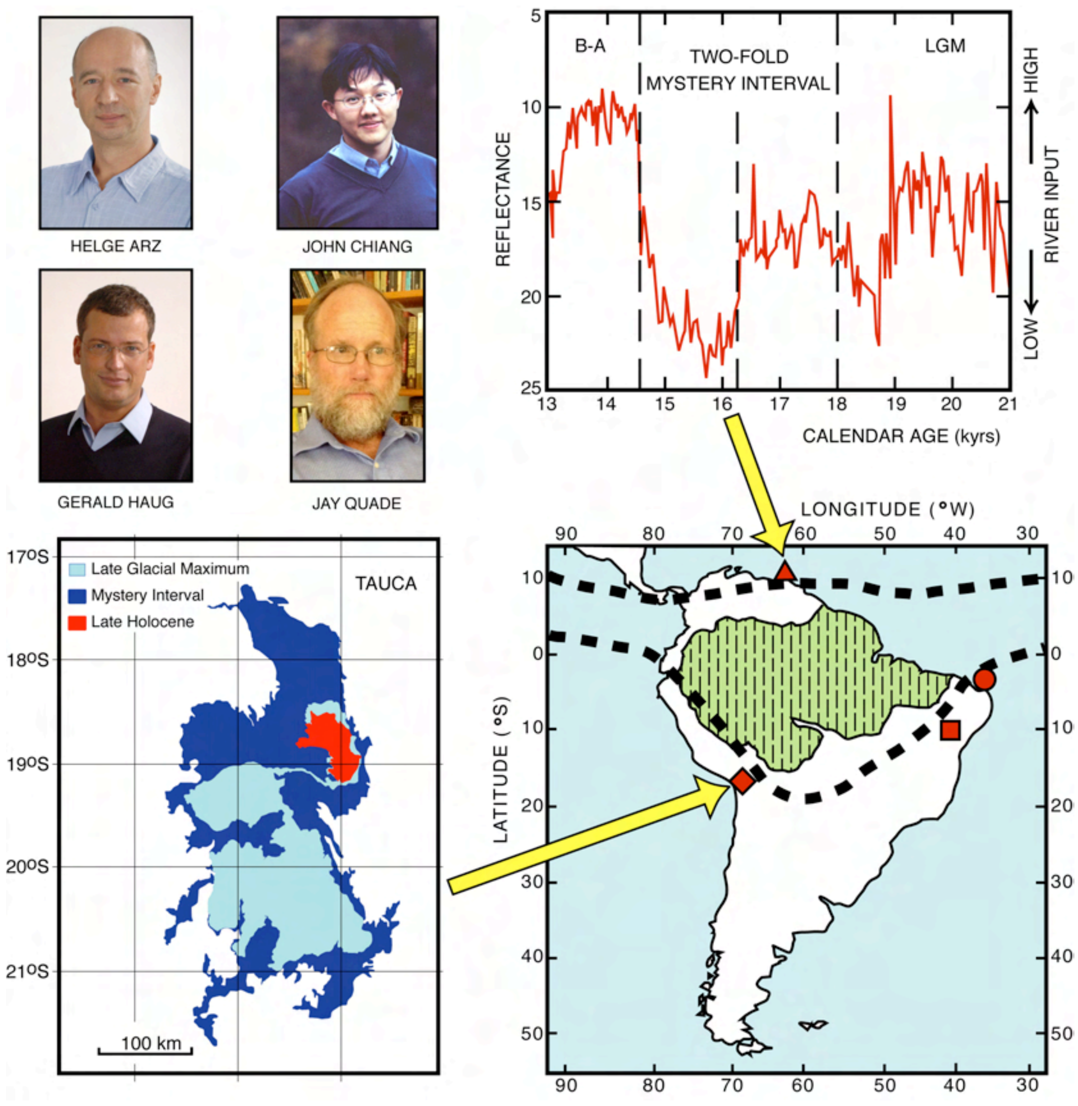


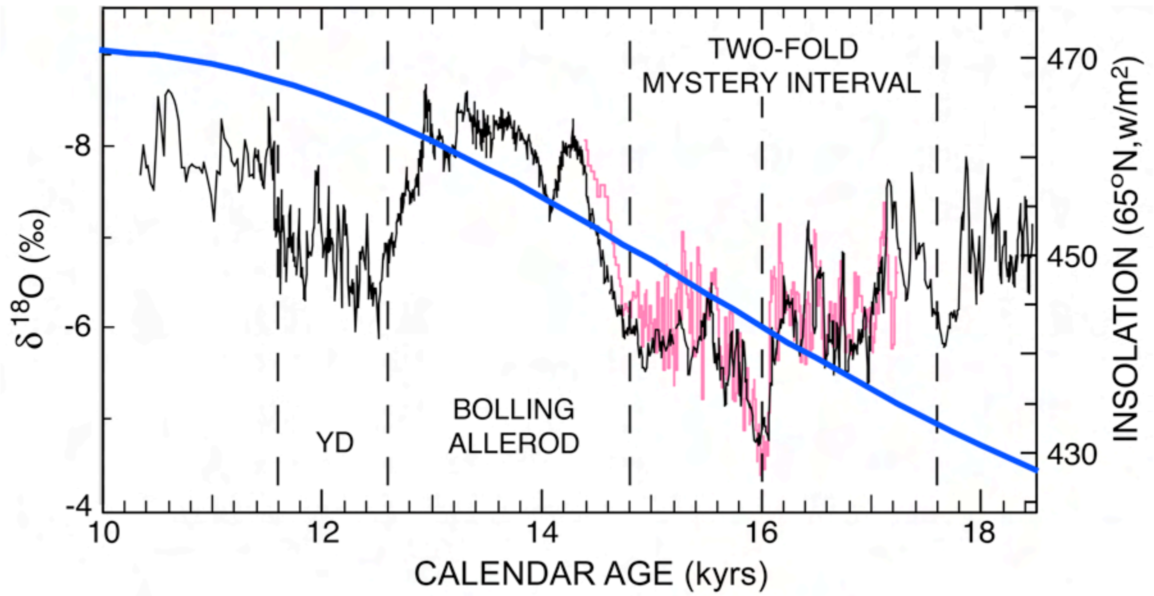
Figure 3-9. The seasonal limits of the tropical rain belt which is narrow over the ocean broadens out over land. The Amazon rain forest is nested between its seasonal limits. Four records clearly demonstrate that during the deglacial time interval, the location of the rain belt changes. During the Mystery Interval and Younger Dryas, it was shifted to the south and during the Bølling Allerød, it was shifted to the north. Records from four locales beautifully record these shifts. A record from the Cariaco Basin, obtained by Gerald Haug, reveals that river runoff from Venezuela was weaker during the Younger Dryas and Mystery Interval than during the Bølling Allerød. To the south of today's limit, University of Arizona's Jay Quade showed that a large lake was present during the Mystery Interval. It dried up during the Bølling Allerød. Two locales in eastern Brazil have records which agree with that from the Bolivian Altiplano. One is from a now dry cave. Xianfeng Wang showed that stalagmite growth occurred only during the Mystery Interval and Younger Dryas. Helge Arz used the record from a continental margin core to demonstrate that the rivers draining easternmost Brazil ran far stronger during these two times. University of California, Berkeley's John Chiang was the first to show that excess sea ice in the north could push Amazonia southward.

Although not as well documented, the situation in equatorial Africa appears to be similar to that in South America. The evidence comes from Lake Victoria which is located on the equator in between the eastern and western branches of the African rift zone. University of Minnesota's Tom Johnson recovered four piston cores from the central portion of the lake. Each bottomed out in a soil. Seismic surveys revealed that reflections from this soil horizon extend to the deepest part of the lake, hence the conclusion that the lake was totally dry when soil horizon formed. Radiocarbon dates on organic material in lake sediment immediately above the soil document that the lake came back into existence at the onset of the Bølling-Allerød. As the lake is located on the northern end of the African rain belt, its rejuvenation is consistent with a northward shift of the thermal equator.

The Chinese stalagmite ^{18}O record reveals sizable departures from the smooth 21-kyr cycle. In particular, as shown in Figure 3-10, a pronounced shift to lower ^{18}O to ^{16}O ratios occurs at the close of the Mystery Interval. Edwards and his associates conclude that at this time the monsoons became stronger. Of course, Battisti concludes instead that the isotope shifts were the result of a reorganization in the Asian wind system.

So we see that, although on time scales of tens of thousands of years tropical hydrology appears to be driven directly by summer insolation, the sub millennial-duration shifts are created by an alternation of sea ice cover in the two polar regions caused by reorganizations of ocean circulation. Clearly these ocean reorganizations were driven by neither orbital cycles nor by CO_2.

Temperate regions shielded by mountains from moisture-laden westerly winds are currently quite arid. In these regions, lakes often occupy topographically isolated basins. The water they receive from river runoff is lost entirely by evaporation. In other words, they never get big enough to overflow to the sea. Among these are: Pyramid Lake in the western United States, the Dead Sea in the Middle East, Lago Cari Laufquen in Patagonia's drylands and Lake Titicaca on Bolivia's altiplano. All three of these inland




LARRY EDWARDS


DAVID BATTISTI

Figure 3-10. Superimposed on the 21-kyr cycle which, as shown in Figure 2-8, dominates the ^{18}O records in stalagmites are pronounced millennial punctuations. Shown here is the record from Hulu Cave in China obtained by Larry Edwards and his coworkers at the University of Minnesota. Of particular interest is the sharp decrease in ^{18}O to ^{16}O ratio which occurred at the onset of the Bølling Allerød time interval and the matching increase at its end. Edwards et al., interpret this as an interval of strengthened monsoon. Battisti et al., disagree. They call on a shift in the pathway followed by the air masses supplying China's precipitation. The solid line depicts the rise in Northern Hemisphere summer insolation.

seas are ringed by raised shorelines representing times when they were larger than present (see Figure 3-11). Clearly, these were times when precipitation was larger than now.

These lakes were far larger during the Last Glacial Maximum than during the Holocene. Further, Lake Lahontan (the name given Pyramid Lake's glacial-age predecessor) achieved an even larger size during the second half of the Mystery Interval. During the Mystery Interval, Lake Lisan (the name given the enlarged predecessor of the Dead Sea) achieved a size similar to that during the Last Glacial Maximum. At the end of the Mystery Interval both Lahontan and Lisan underwent major desiccations.

Although we know from these records that rainfall must have been greater at the times when the elevated shorelines formed, quantifying the magnitude of these precipitation increases remains a challenge. The reason is that the size of the closed basin lakes is not proportional to the amount of rainfall. Twice as much rainfall does not just double the size of the lake. Rather, the magnitude of the change is greatly amplified. The reason is that the fraction of the precipitation falling onto the lakes' drainage basin that reaches rivers increases rapidly with the amount of precipitation. In the wet eastern United States where I live about half of the rainfall runs off to the Atlantic Ocean. In the dry Great Basin of the western U.S. less than 10 percent runs off to the inland seas. A study of 2500 drainage basins by NASA's Randy Koster shows that on the average a doubling of rainfall triples the fraction of runoff. If so, a doubling of rainfall will increase the delivery of river water by a factor of six! The problem associated with deriving past precipitation amounts from past lake size is that the magnitude of this amplification depends on the topography of the basin, on the seasonality of precipitation, on the soil and vegetation types…. And, of course, the rate of evaporation from the lake surface is lower during cold times. As shown by the University of Nevada's Doug Boyle, the range of uncertainty can be narrowed by modeling individual landscape 'pixels' instead of the entire drainage basin. The unfulfilled hope is that the records preserved in these lakes will

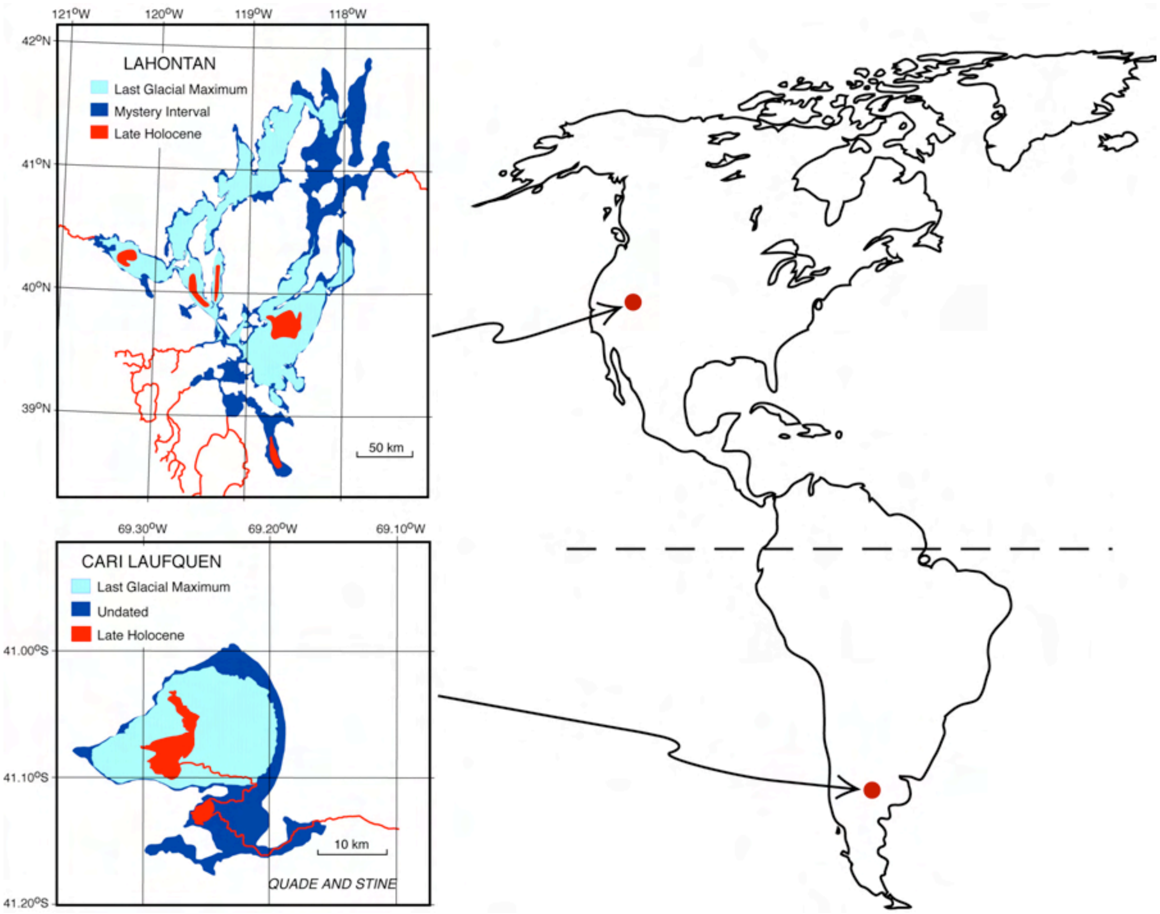


Figure 3-11. Comparison of the Late Holocene and Last Glacial Maximum sizes of Lake Lahontan in the dry lands of the American west and of Lago Cari Laufquen in the dry lands of Argentina. Also shown are the maximum sizes achieved by these lakes. In the case of Lahontan, this occurs during the second half of the Mystery Interval. The high stand of Cari Laufquen has yet to be dated.

allow more reliable precipitation reconstructions than those based on the delivery of soil material to the sea or those based on the ^{18}O to ^{16}O ratio in stalagmites.

Isaac Held at NOAA's Princeton-based research laboratory makes a compelling case that in a colder world, our planet's precipitation will be less strongly focused on the tropics. As a consequence, the extra tropical drylands become less dry. In addition, the Hadley cells may extend further poleward. The record shows us that was indeed the case during times of glaciation.

Mountain glaciers tell us that atmospheric CO_2 is the dominant driver of the Earth's summer temperatures. If Held is correct, CO_2 also controls the extent to which rainfall is focused on the equator. For both, the 100-kyr cycle dominates the record. In contrast, the monsoon isotope record correlates strongly with the 20-kyr precession cycle showing little response to the 100-kyr cycle. Superimposed on both the temperature and the hydrologic record are sharp changes associated with the changes in polar sea ice cover induced by reorganizations of ocean circulation. Of importance to the scenario represented here is that only in response to Heinrich events did these millennial-duration abrupt changes generate measureable changes in the atmosphere's CO_2 content.

Chapter 4

Ocean Reorganizations: A Driver of Climate Change on Both Orbital and Millennial Time Scales

I propose here that the link between orbitally-induced seasonality cycles and Earth climate is related to reorganizations of ocean circulation rather than a direct influence on the growth and retreat of ice sheets. If so, what is the connection? It has to be that these changes in seasonal contrast somehow produce changes in the density of the deep ocean's source waters. In so doing, they influence the state of the ongoing war for space in the deep sea conducted by deep waters formed in the northern Atlantic and in the Southern Ocean. Although in today's ocean the battle is somewhat of a draw, as we shall see, during the time of the Last Glacial Maximum, the battle appears to have shifted in favor of southern source waters. They garnered a greater share of the deep ocean space. If I am correct, these shifts were somehow linked to the drawdown of atmospheric CO_2 by the ocean. But, as no full-scale simulation of the glacial ocean has succeeded in satisfactorily reproducing the observed water mass reorganization, let alone the CO_2 drawdown, the understanding we seek remains beyond our grasp. In the paragraphs which follow, I propose that this war for space led to stratification of the deep sea and, in turn, to a drawdown of the nutrient content of Southern Ocean surface waters.

The majority opinion is that the CO_2 missing from the atmosphere during glacial time was stored in the ocean. It is generally accepted that the drawdown by the ocean involved more efficient use of the plant nutrients, nitrate and phosphate upwelled to the surface of the Southern Ocean (see Figure 4-1). Today only about one third of these nutrients are utilized. The remainder descend, dissolved in newly-formed intermediate and deep water. The organic matter formed in the ocean's surface waters sinks into its interior where it is oxidized releasing CO_2. Of course, as proposed by Huybers and Langmuir, it is likely that changes in the rate at which CO_2 was released from the planet's interior also played an equally important role.

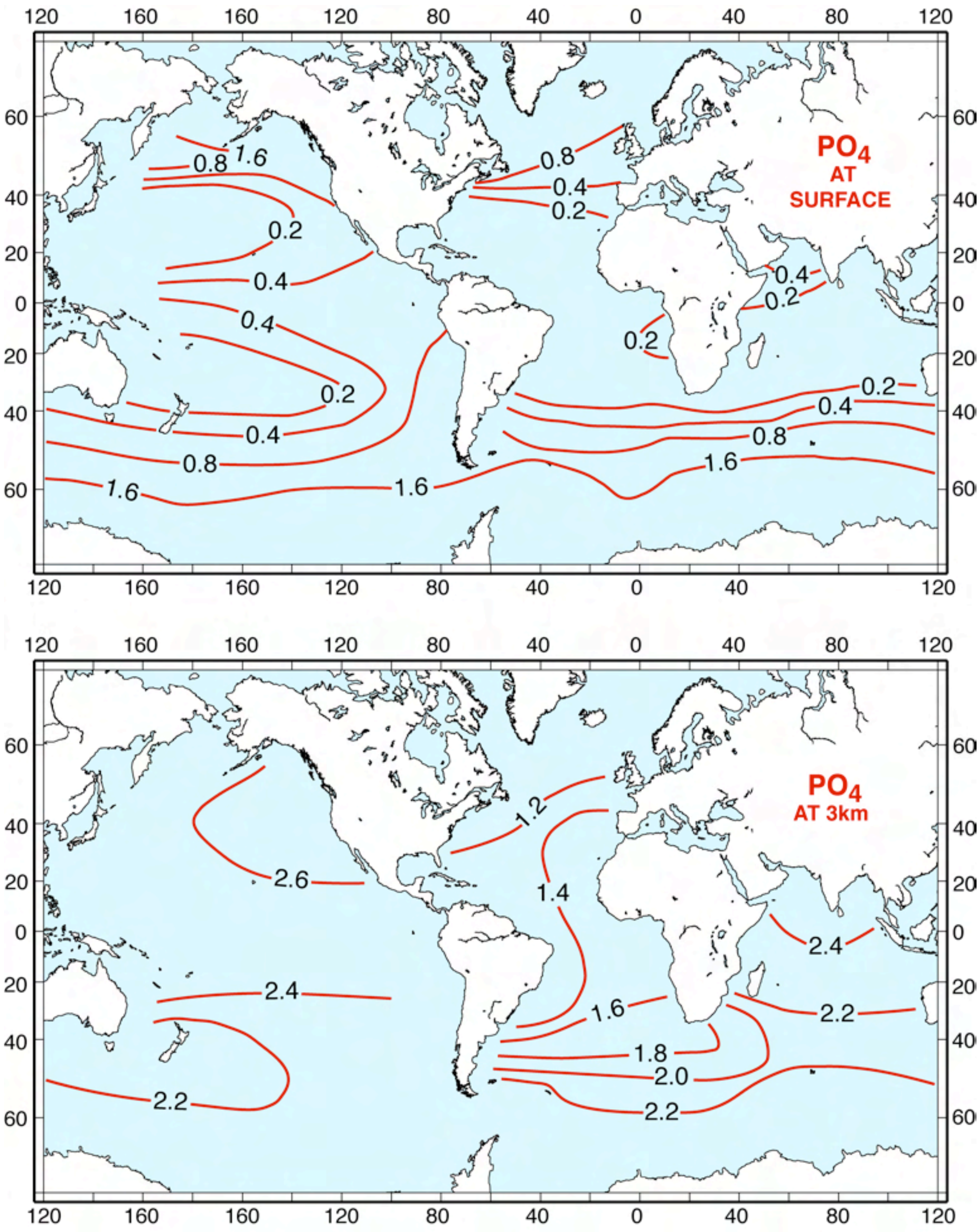
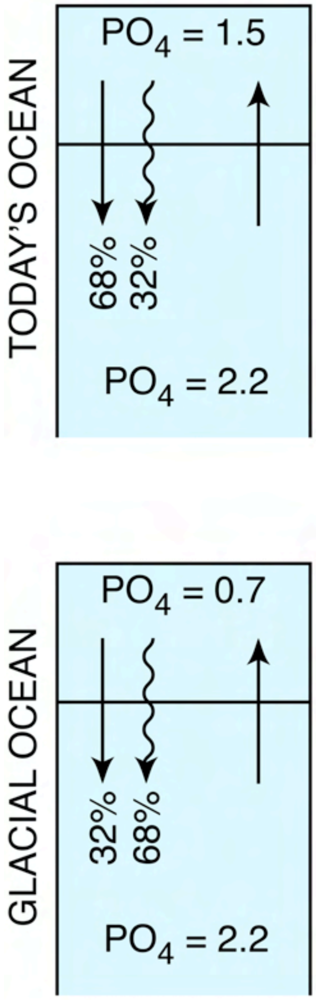


Figure 4-1. The distribution of PO_4 at two levels in today's ocean, i.e., at the surface and at 3 km depth. The Southern Ocean surface waters house the largest inventory of unutilized PO_4. In much of the warm ocean, plants utilize all the nutrients supplied to the surface. Note that the PO_4 content of deep tropical Pacific water is about twice that for the deep tropical Atlantic.

In order to reduce the partial pressure of CO_2 in Southern Ocean surface waters from its interglacial value (~280 ppm) to its glacial value (~190 ppm) requires a Southern Ocean PO_4 drawdown of about 0.8 μmol per liter (see Figure 4-2). It was once thought that measurements of the ^{13}C to ^{12}C ratio in the shells of planktic foraminifera shells would provide a confirmation as to whether this drawdown of phosphate did indeed take place. The idea was that for a 0.8 μmol/l of PO_4 drawdown, the ^{13}C to ^{12}C ratio in surface water would have been increased by 1.2 per mil (see Figure 4-2). The reason for this enrichment is that ^{12}C is utilized in slight preference to ^{13}C during photosynthesis. Of course, to the extent that squelching of planetary CO_2 emissions contributed, the required increase in the utilization of Southern Ocean nutrients would be reduced.

Early on, measurements on planktic foraminifera shells made at Lamont-Doherty by Chris Charles and Rick Fairbanks showed that indeed interglacial-age planktic shells had a higher ^{13}C to ^{12}C ratio than glacial shells. However, companion measurements on benthic foraminifera shells showed more or less the same change (see Figure 4-3). Hence, what Charles and Fairbanks documented was a change in the carbon isotope ratio in the entire Southern Ocean. This put a damper on the nutrient drawdown hypothesis. It took a decade or two to realize that this test was not valid. The reason turned out to be that planktic *N. pachyderma* (left coiling) foraminifera form their shells in the ^{13}C-depleted thermocline rather than in surface waters. As this species is the only shell-forming organism capable of surviving the cold Southern Ocean temperature, there was no other choice.

This was only the first of several chapters in the nutrient drawdown story. The failure of the carbon isotopes approach gave way to the use of ^{15}N to ^{14}N ratios in nitrogen contained in organic matter trapped in the opaline frustules formed by diatoms. Unlike *N. pachyderma*, the diatoms do live in surface water. The findings of each of a sequence of subsequent chapters involving nitrogen isotopes were short lived as their



UTILIZATION EFFICIENCY = 32%

	SURF.	DEEP	
PO_4	1.5	2.2	µmol / L
NO_3	24	35	µmol / L
ΣCO_2	2112	2200	µmol / L
pCO_2	280	450	µatm
$\delta^{13}C$	0.0	-1.2	‰

UTILIZATION EFFICIENCY = 68%

	SURF.	DEEP	
PO_4	0.7	2.2	µmol / L
NO_3	11	35	µmol / L
ΣCO_2	2034	2200	µmol / L
pCO_2	190	450	µatm
$\delta^{13}C$	1.2	-1.2	‰

UTILIZATION RATIOS: $PO_4 : NO_3 : \Sigma CO_2$ = $1 : 16 : 125$

$\delta^{13}C_{\text{ORGANIC MATTER}} = -30‰$

Figure 4-2. Water upwelled in today's Southern Ocean has about 2.2 micromoles of PO_4 per liter. In order to reduce the partial pressure of CO_2 from 280 to 190 µatm, about one third of this PO_4 would have to be utilized and transferred to the subsurface in particulate form. The glacial reduction would lead to an increase in the $\delta^{13}C$ in Southern Ocean surface water-D.I.C. by 1.2 per mil.

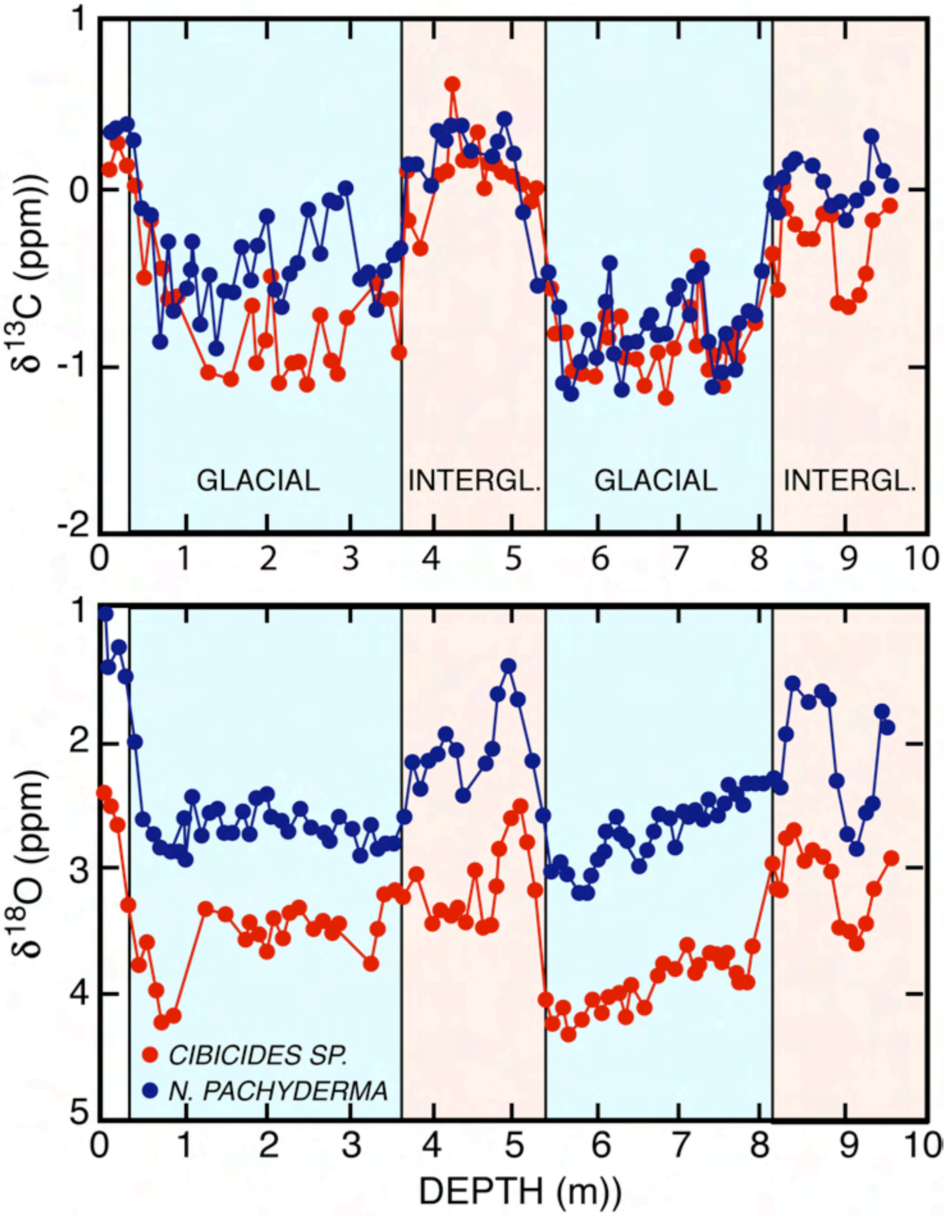


Figure 4-3. Charles and Fairbanks attempted to document the extent of nutrient drawdown in Southern Ocean surface waters during glacial time. They did this by comparing the ^{13}C record for planktic foraminifera with that for coexisting benthics. They chose a core from 43°S and 3°W at a depth of 4.2 km. The record covers the last 200 kyrs. The intervals of glaciation and interglaciation are based on the ^{18}O record in the same shells. As can be seen, the δ^{13}C difference between planktics and benthics is very small. Certainly, the 1.2 per-mil difference required to explain the glacial reduction in atmospheric CO_2 content (see Figure 4-1) did not take place. Years after these results were published, it was realized that this test was not valid. The reason is that the planktic *N. pachyderma* (left coiling) produces its shells well below the surface-mixed layer.

authors struggled to understand the ocean's nitrogen isotope cycle and also to develop the means to remove extraneous sources of nitrogen that contaminate diatom frustules. Only recently has Princeton's Danny Sigman been able to make a strong case that there was indeed a glacial drawdown of Southern Ocean nutrients.

One might ask, why focus on the Southern Ocean? What about the remaining 85 percent of the ocean surface? The answer is that most of this 85 percent currently lacks significant amounts of unutilized nutrients (see Figure 4-1). Further, models of ocean operation suggest that the partial pressure of CO_2 in Southern Ocean surface water dominates that for the remainder of the ocean. If other regions tend toward a CO_2 partial pressure different from that in the Southern Ocean, CO_2 flow through the atmosphere would work against this tendency.

Summarizing, it is clear that surface waters in the Southern Ocean contain the largest inventory of unused nitrate and phosphate in today's ocean. It is also clear that the Southern Ocean's importance in setting the CO_2 content of the atmosphere is much greater than one would expect from its area.

From the very beginning, paleoceanographers pondered why Southern Ocean nutrients might have been more efficiently utilized during glacial time. One might have thought that the opposite was the case. Colder temperatures and more extensive sea ice might be expected to have reduced the efficiency of nutrient utilization. This view prevailed until John Martin showed that a dearth of the element iron was holding back plant productivity. To form their enzymes, marine plankton need iron. Although iron is the most abundant element in our planet, in its oxidized form it is extraordinarily insoluble in sea water. It is rapidly absorbed onto particulates and carried to the sea floor.

Martin's on-deck iron-fertilization experiments were initially pooh-poohed by many bio-oceanographers. It took full-scale open-ocean iron fertilization experiments to convince these doubters. A number of these experiments have now been conducted. All show that in the iron-fertilized patches, the chlorophyll content increases, the plant nutrients are drawn down, and the CO_2 partial pressure is correspondingly reduced.

As has already been mentioned, during peak glacial time the rain of dust onto the Antarctic ice sheet was more than an order of magnitude larger than now. So, the hypothesis is that some of the iron contained in the excess dust rained onto the Southern Ocean, was released and gobbled up by the plankton, allowing them to utilize a larger portion of the nitrate and phosphate. In this way the atmosphere's CO_2 partial pressure was drawn down.

Very important to the scenario presented here is whether or not it was iron fertilization that drove the drawdown of Southern Ocean nutrients. If it were the sole cause, the scenario on which this book is based would be in jeopardy. The reason is that the entrainment of excess dust requires the high wind speeds. These winds are mainly generated by cyclonic storms. As touted by MIT's David McGee, the frequency of such storms is controlled by the equator to pole temperature gradient. At the time of peak glacial conditions, winter temperatures in polar regions decreased by 10 to 20°C, but tropical temperatures decreased by only about 3°C. This is thought to explain why glacial dust accumulation rates were everywhere on the planet greater than today's. If this scenario is correct, then in order to produce an excess rain of iron over the Southern Ocean, the Antarctic continent must already have been cooled. As suggested by U. C. San Diego's Stephens and Keeling, the source of this cooling was likely an expansion of its sea ice apron. Hence, the reduction of CO_2 would have to have been the result of polar cooling. But, if the scenario put forward here is correct, then the opposite must have been the case; CO_2 reduction should have preceded polar cooling.

Fortunately, there is an alternate scenario. Sigman and his colleagues call on stratification of the Southern Ocean rather than iron fertilization to be the driver of the drawdown of nutrients. If so, then perhaps this stratification could have been generated by orbitally-driven reorganizations of ocean circulation. Of course, if the CO_2 drawdown were initiated in this way, it could have been subsequently enhanced by the delivery of iron-bearing dust. Clearly important for the paleoclimate "to do" list is the necessity to distinguish the roles of stratification and iron fertilization in creating a nutrient drawdown.

Before going further with this, it is important to review what is known about the water mass structure and ventilation rates in the glacial ocean. Our knowledge of today's structure is based on the global distribution of deep water produced in the northern Atlantic and that produced in the Southern Ocean. Mixtures of these two sources dominate today's deep ocean. Traditionally they have been distinguished based on their respective salinities and temperatures. Deep water produced in the Atlantic is several degrees warmer and a bit saltier than that produced in the Southern Ocean. Warmth reduces the water's density and salt increases it. But in order to coexist in the deep sea, the two deep water sources must be closely matched in density. Hence the salinity and temperature impacts on density of these two source waters must largely offset one another. Small changes in density of either of these source waters would allow one or the other to occupy a greater portion of the deep sea's volume. I propose that variations in seasonal contrast generated by orbital cycles led to changes in the density of these source waters. Not only would they have created changes in temperature, but likely more important, they would have changed the fresh water inputs and hence the salinities of these source waters. Equally important is the role of salt released from sea ice. Each winter's growth releases brine which sinks into the ocean's interior.

As we have seen, the changes in sea level, in benthic ^{18}O resemble those of Northern Hemisphere summer insolation. This being the case, one might conclude that impacts on the salinity of northern Atlantic surface water dominated.

A more sensitive way to distinguish these source waters is through the use of a property based on the combination of the O_2 and PO_4 contents of deep water. It stems from the observation, by Lamont-Doherty's Taro Takahashi, that for every mole of PO_4

released to subsurface waters as the result of respiration close to 175 moles of O_2 are consumed. Hence in waters isolated from contact with the atmosphere, the sum of the concentration of PO_4 and that of $O_2/175$ remains unchanged. This property is referred to as PO_4^* (phosphate star). It turns out that newly formed deep waters descending along the margins of the Antarctic continent have a much larger PO_4^* concentration than those descending into the deep northern Atlantic (see Figure 4-4, and 4-5). The difference reflects the higher PO_4 concentration in Southern Ocean surface waters (i.e., the unutilized PO_4). The concentration of O_2 in these two sources is similar. If these two water types are taken to be the only contributors to the ventilation of the deep ocean, then based on PO_4^*, the deep water in the Atlantic consists of about 90 percent water produced in the northern Atlantic and about 10 percent that produced in the Southern Ocean. For the deep Pacific Ocean, each contributes close to 50 percent.

In this regard it should be mentioned that modeling conducted by Gebbie and Huybers and also by Khatiwala and his coworkers suggests that only one quarter of the water in the Pacific is supplied from the northern Atlantic. A major difference is that they allow for along isopycnal contributions to deep water formation in the Southern Ocean.

Although no paleoproxy for PO_4^* exists, there is one for PO_4. In today's ocean a strong anti-correlation exists between PO_4 and the ratio of ^{13}C to ^{12}C in dissolved inorganic carbon (see Figure 4-6). The reason is that the photosynthetic uptake of CO_2 leaves behind dissolved inorganic carbon enriched in ^{13}C. And, of course, respiration releases CO_2 depleted in ^{13}C to subsurface waters. Further, it is the difference in PO_4 content that dominates difference in PO_4^* between the two contributors to the ventilation of the deep sea. Hence, the ^{13}C to ^{12}C ratio in bottom dwelling foraminifera provides clues as to how the distribution of source waters in the glacial deep ocean differed from that for the present-day deep ocean. However, the use of this proxy is complicated by the CO_2 added to the ocean-atmosphere reservoir as the result of the reduction in the amount of carbon stored in the terrestrial biosphere during glacial time. As this carbon is depleted

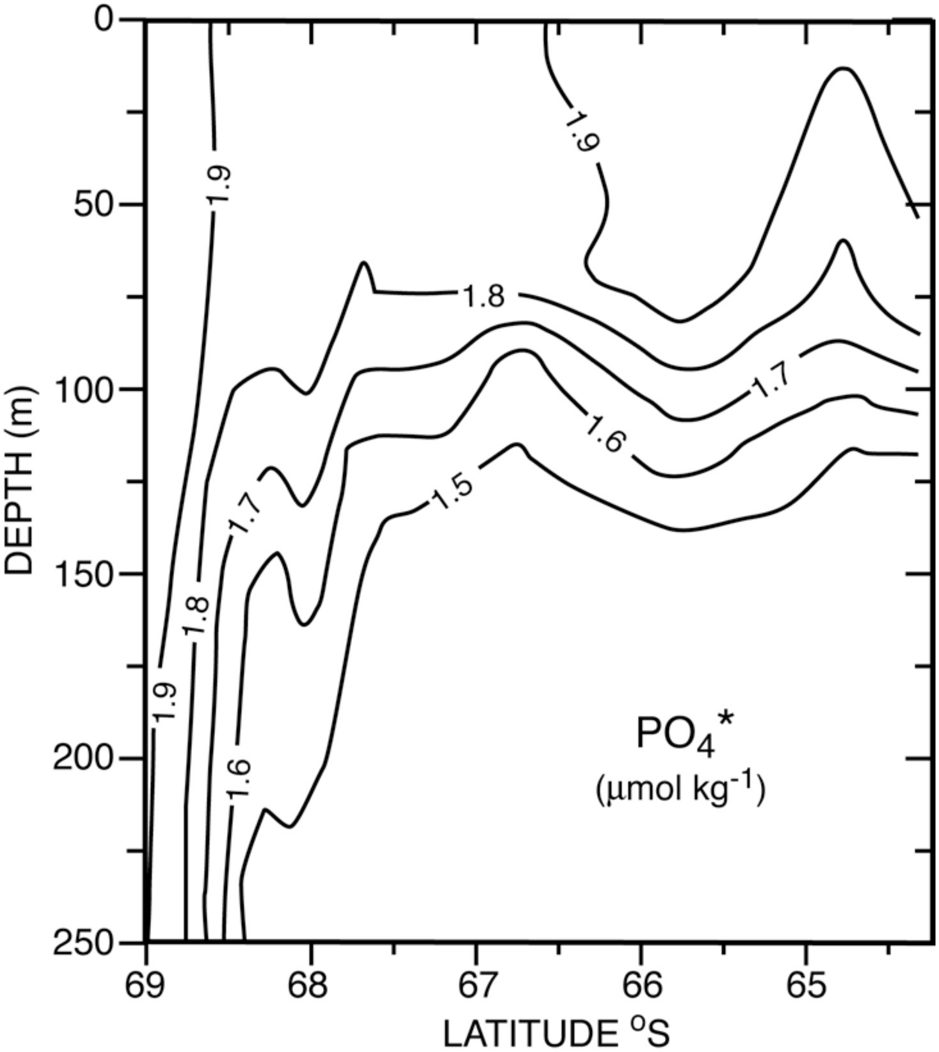


Figure 4-4. Section of winter PO_4^* versus water depth extending from Antarctica out into the Weddell Sea. As can be seen, water with a PO_4^* of 1.9 is cascading down the continental margin into the Southern Ocean.

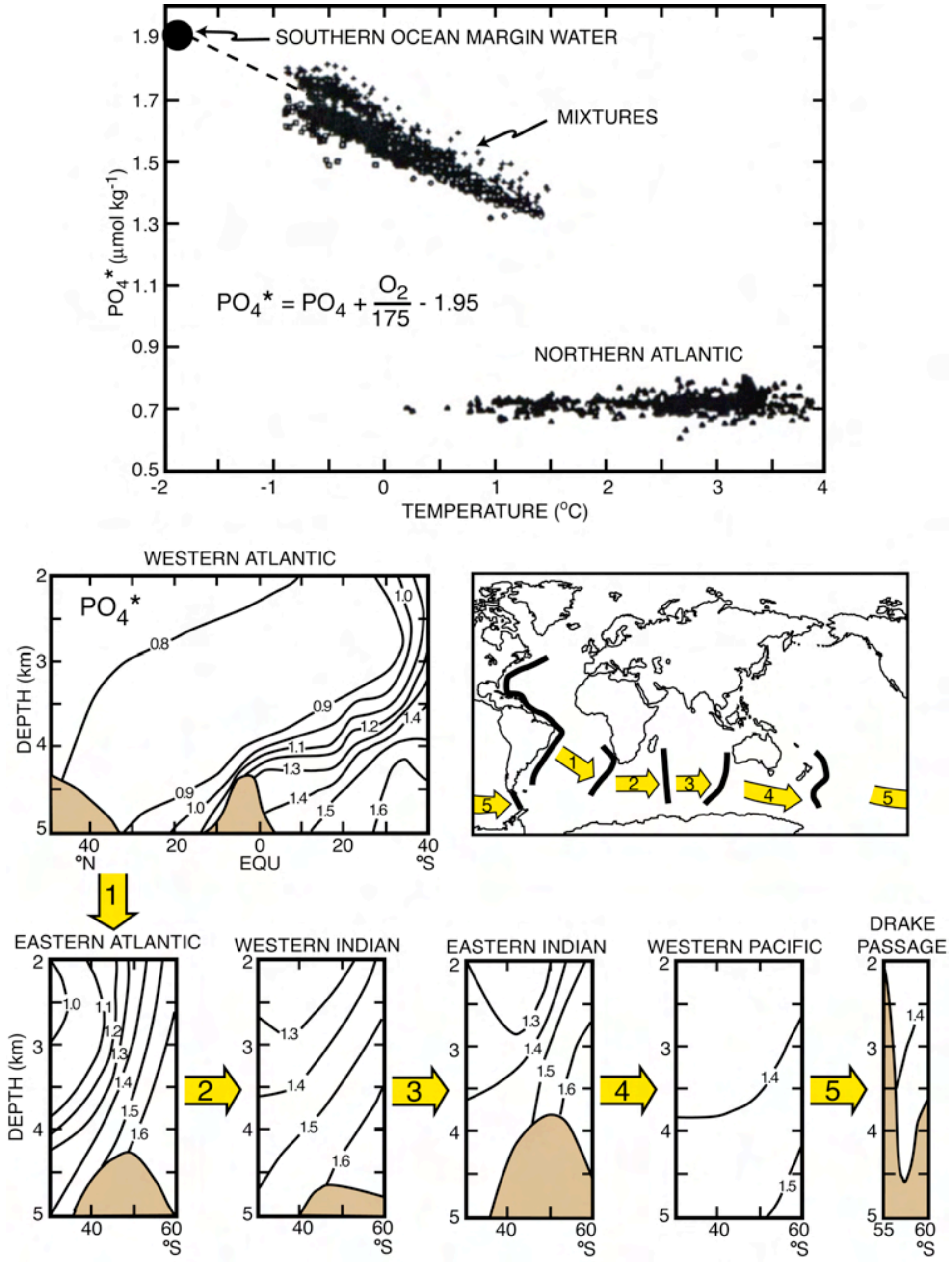


Figure 4-5. The upper panel shows the PO_4^* values for water streaming down the margins of Antarctica (1.9 umol/l) and for newly formed deep water in the northern Atlantic (0.7). Also shown are mixtures in various proportions of these two end member water masses.

Shown in the lower panel are PO_4^* sections for the western Atlantic and for a series of quadrants of the Southern Ocean. The PO_4^* values for the interiors of the deep Pacific and Indian Oceans (1.38) are close to 1.3 (i.e., a 50-50 mixture of the two end members). Note that the low PO_4^* waters entering the Southern Ocean from the Atlantic and the high PO_4^* waters streaming down the margins of the Antarctic continent are nicely blended by the time they reach the Drake Passage.

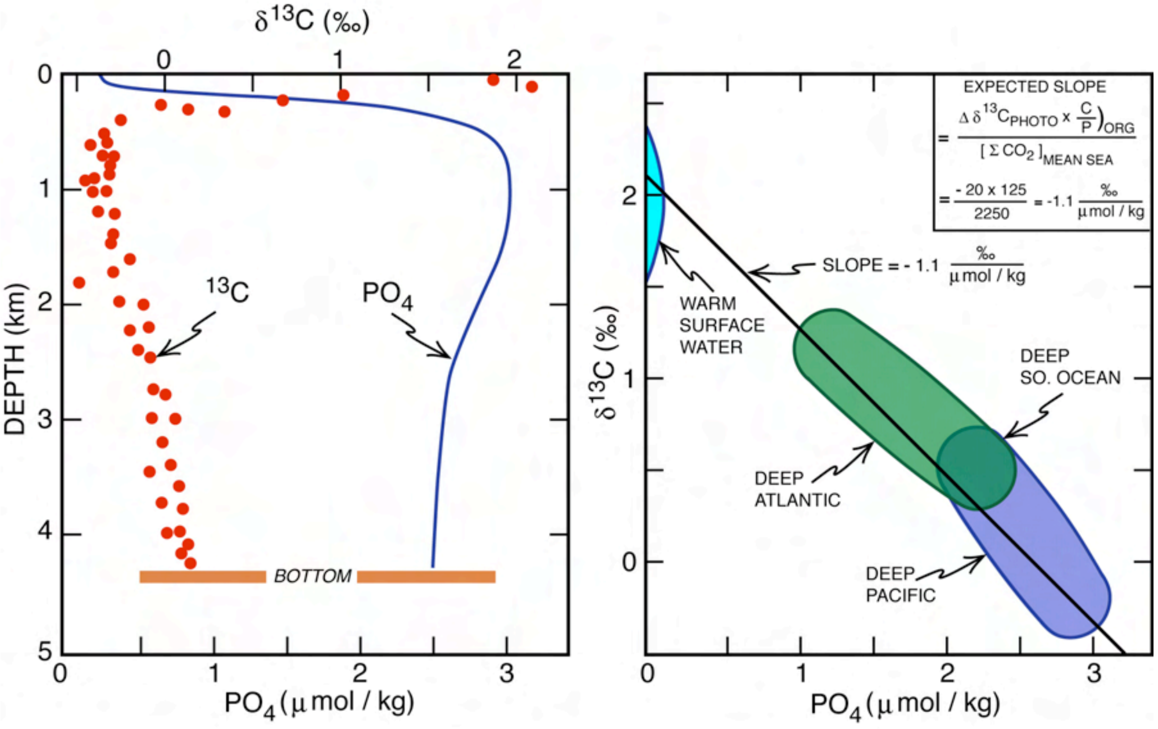


Figure 4-6. Plot of $\delta^{13}C$ versus PO_4 for a station in the eastern North Pacific (28°N, 121°W). As can be seen, as PO_4 rises $\delta^{13}C$ drops. The reason is the CO_2 which is released during respiration has two percent lower ^{13}C to ^{12}C ratio than the ambient ΣCO_2 (left hand panel)

This inverse relationship between $\delta^{13}C$ and PO_4 concentration characterizes the entire ocean. The mean slope is close to -1‰ per μmol.

in ^{13}C, its addition lowered the ^{13}C to ^{12}C ratio in ocean carbon. For example, the destruction of boreal forests by ice caps and permafrost would have led to reduction in $\delta^{13}C$ of about 0.2‰. As the ocean is thoroughly mixed on a time scale far less than the duration of the LGM, this reduction in ^{13}C must have been spread uniformly throughout the ocean. Thus, although it would shift all the ocean's ^{13}C to ^{12}C ratios, it would not have changed the differences among them.

Putting aside the correction for the change in terrestrial biomass, the ^{13}C distribution in the glacial ocean as recorded in benthic foraminifera tells us something very important. Although the distribution of ^{13}C in the deep Pacific and Indian Oceans was similar to todays, that in the Atlantic was quite different. In particular, the distribution of $\delta^{13}C$ with water depth was very different from todays. Rather than being uniform with depth, it was strongly stratified. The water below 2500 meters had a lower ^{13}C to ^{12} C ratio than today's and the water above this level had a higher ^{13}C to ^{12} C ratio (see Figure 4-7).

Boron to calcium measurements on the same benthic forams tell us that the lower water had a lower carbonate ion concentration than todays and the upper water, a higher concentration (see Figure 4-8). As shown by Cambridge's Jimin Yu and Harry Elderfield, the boron contents of core-top shells of *Cibicides* beautifully correlates with the extent of calcite supersaturation. The results of hundreds of such measurements demonstrate that this proxy yields paleo $CO_3^=$ concentration accurate to ± 2μmol per kg. In addition to documenting the $CO_3^=$ stratification in the glacial Atlantic, the B/Ca proxy shows that the carbonate ion concentration in the deep equatorial Pacific remained very close to today's (see Figure 4-9).

These differences suggest the deep glacial Atlantic had two separate water masses (see Figure 4-10). The upper one likely formed in the northern Atlantic much as today's NADW. Two possibilities exist to explain the origin of the lower water mass. One is that it represents a larger influx of Antarctic Bottom Water (AABW). The other is that it

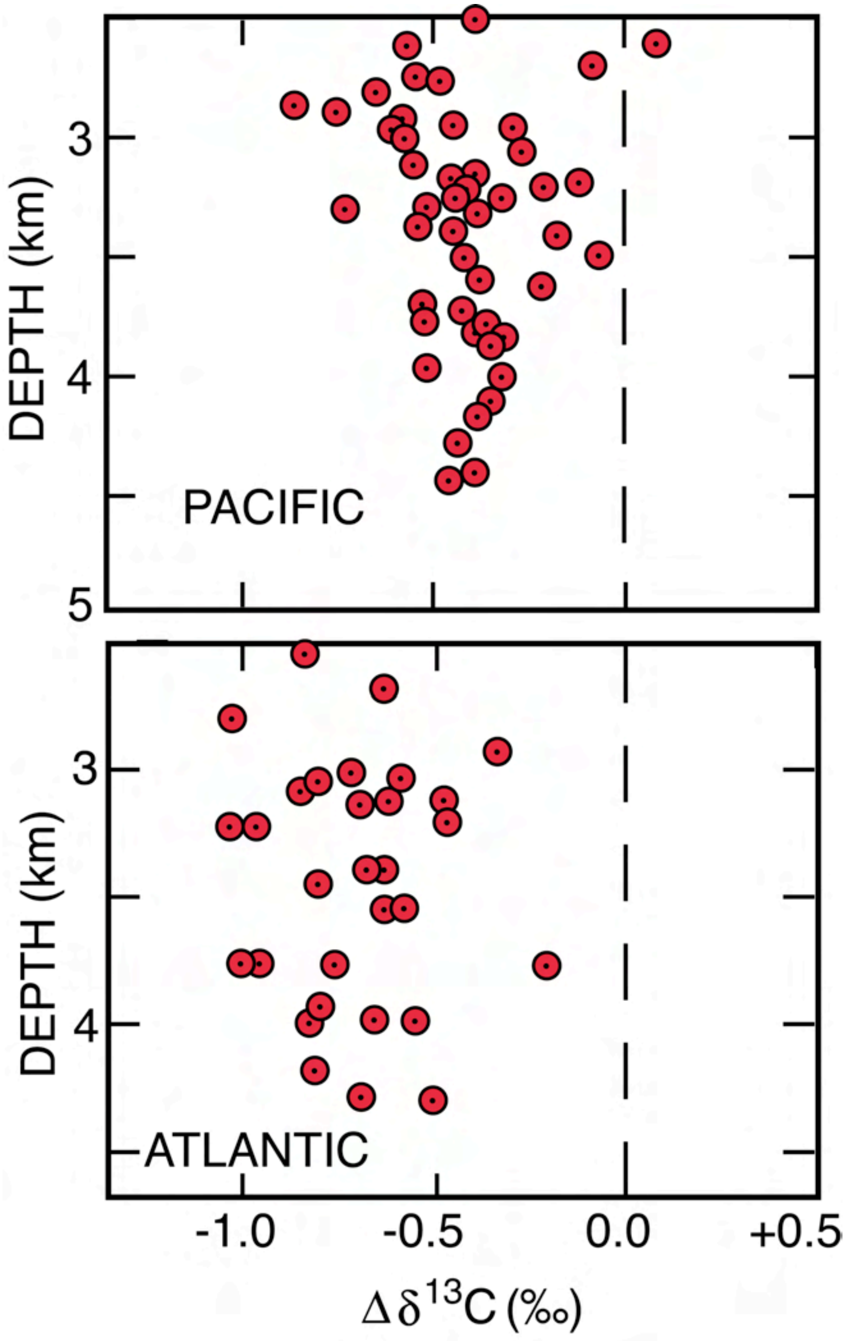
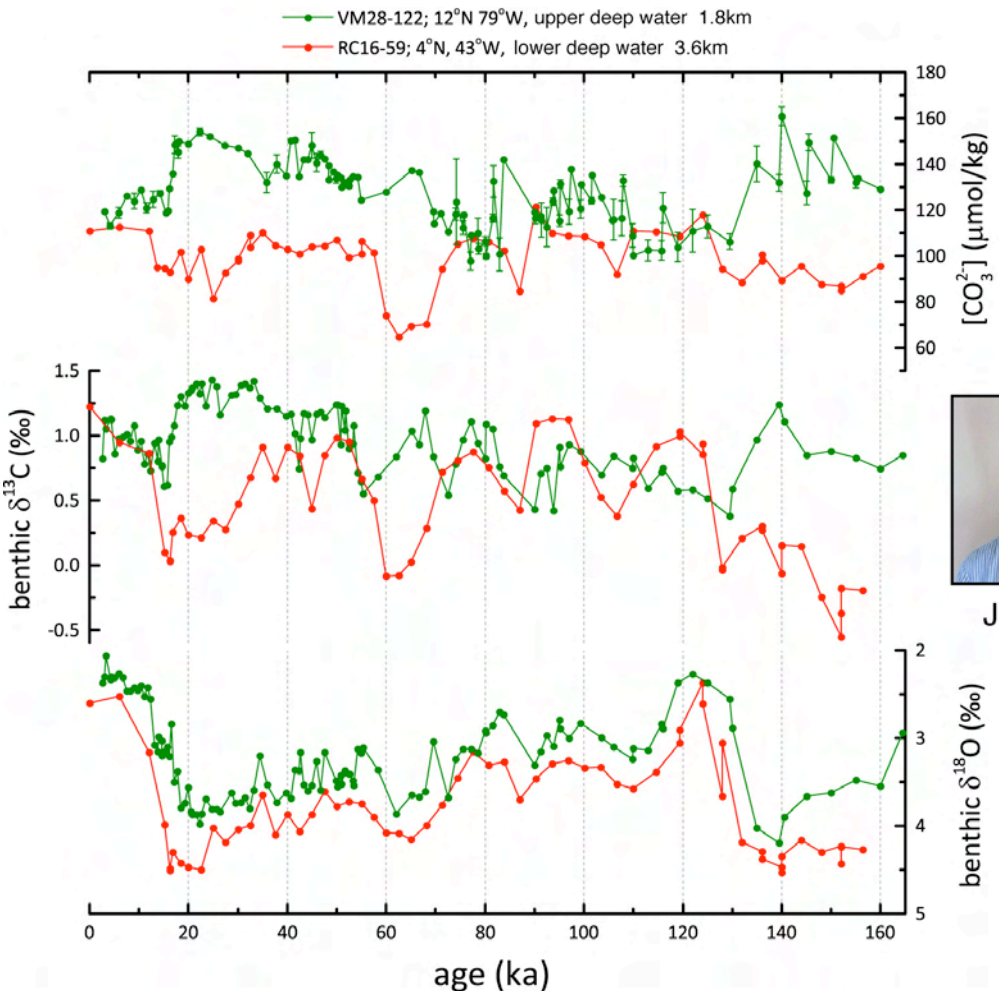


Figure 4-7. Difference between the Last Glacial Maximum (red dots) $\delta^{13}C$ as recorded in benthic foraminifera shells for open ocean sediment cores from deeper than 2.5 km. These values are reference to that for the Holocene $\delta^{13}C$ (dashed lines). For the Pacific, the $\delta^{13}C$ was about 0.4 ± 0.1‰ lower during the LGM. For the deep Atlantic, it was 0.7 ± 0.1‰ lower. As the Atlantic-Pacific difference in today's ocean is 1.2‰, during the Last Glacial Maximum, it was 0.9 ± 0.2‰.



JIMIN YU

Figure 4-8. A comparison of the δ^{13}C and $CO_3^=$ records for the shells of the benthic foraminifera *Cibicides* from a core from the Ceara Rise with those for a core from the Caribbean. The Ceara Rise core (RC16-59) from 3.4 km depth is representative of the lower portion of the deep Atlantic. The Caribbean core (VM 28-122) is representative of the water spilling over the 1.8 km depth sill which separates the Atlantic from the deep Caribbean. It is representative of the upper Atlantic deep water. The time scale is based on the ^{18}O to ^{16}O records for the same benthics. These measurements were made by Jimin Yu at the Australia National University.

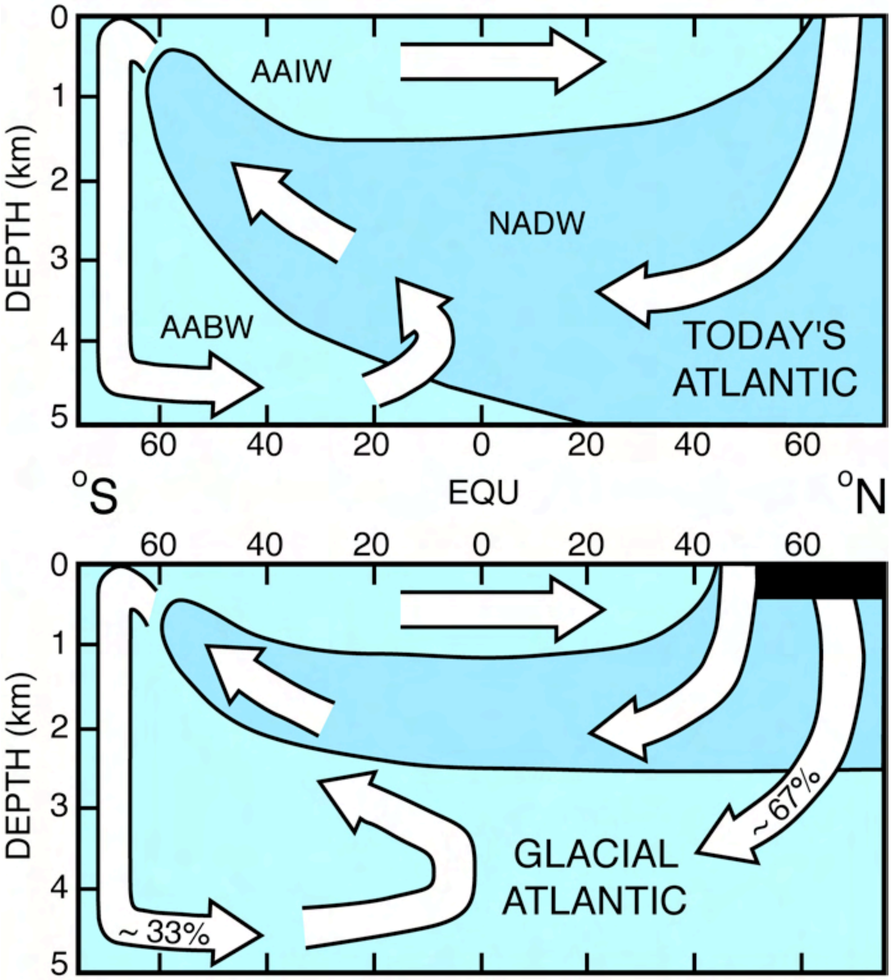


Figure 4-9. Diagrammatic contrast between the water mass structure in today's Atlantic with that for the Atlantic during the peak of the last glacial period. The latter is based on the distribution of ^{13}C and $CO_3^=$ as reconstructed from measurements on benthic foraminifera of glacial age. In order to match both the difference in $\delta^{13}C$ and in $CO_3^=$ in the glacial-age deep water, it is necessary to postulate two sources for the LGM lower deep water (see Figure 4-9), one from the Southern Ocean and one from the northern Atlantic. The former has the same composition as glacial-age abyssal Pacific water and the latter in deep water formed perhaps beneath ice in the northern Atlantic. It differs from today's NADW in that it contains more respiration CO_2 (see Table 4-3).

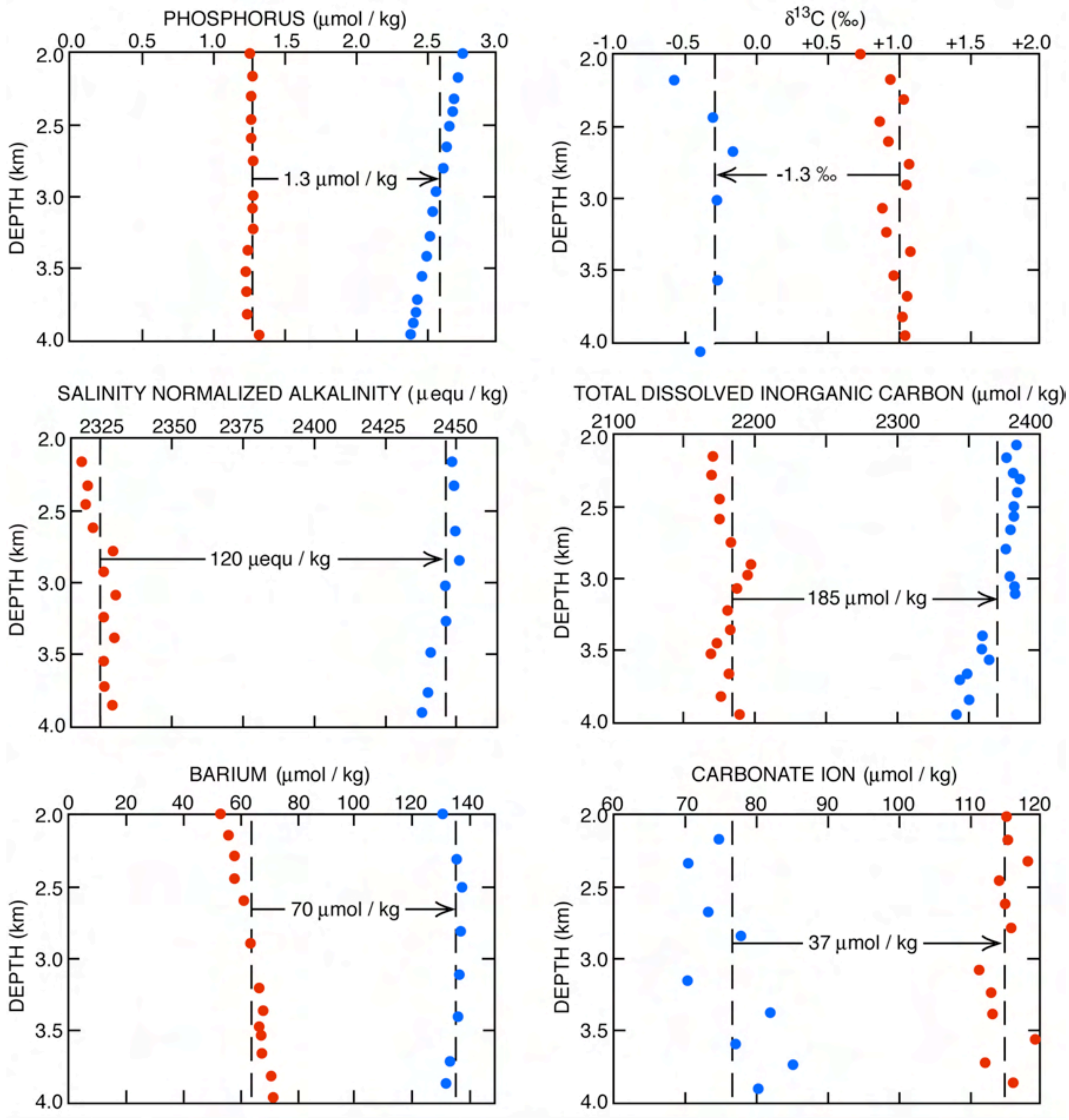


Figure 4-10. Plots of six properties versus water depth in the deep western equatorial Atlantic (red dots) and in the deep western equatorial Pacific (blue dots). These measurements were made during the 1970's as part of the Geochemical Ocean Section (GEOSECS) expeditions.

received a larger contribution of respiration CO_2. This excess must be somehow related to the excess ^{13}C and $CO_3^=$ in the upper deep water (see Figure 4-8). Based on the ^{13}C data (see Figures 4-7 and 4-8). It is clear that expanded AABW contribution alone cannot be the sole explanation. The difference between the $\delta^{13}C$ for Pacific Deep Water (fed by the same source as the Atlantic's AABW) was smaller than today's 1.3‰. A difference of 0.9‰ remained (see Figure 4-11). Rather, it must be a combination of both. Based on the ratio of $\Delta CO_3^=$ to $\Delta^{13}C$ in the lower glacial Atlantic deep water, it appears that about one third of the change is the result of ad mixing of deep Southern Ocean water (i.e., AABW) and two thirds the result of an enhanced respiration contribution (see Table 4-1).

Two other proxies offer additional insight into this question, namely, the cadmium and barium content of benthic foraminifera shells. Shown in Figure 4-12 are the distribution of these properties in today's ocean. As shown by U.C. Santa Cruz', Ken Bruland, cadmium correlates with phosphate and, as shown by M.I.T.'s Ed Boyle, barium correlates with alkalinity. Measurements of cadmium and barium in glacial-age benthic foraminifera shells serve as alternatives to the carbon isotope and boron proxies. The use of these proxies was pioneered by MIT's Ed Boyle and his then graduate student, David Lea. Shown in Figure 4-12, the concentration of these proxies in the abyssal glacial Atlantic differed from that in today's. In today's ocean, the Cd to Ca ratio in the deep Atlantic is also about one half that in the deep Pacific. During glacial time, like ^{13}C, it shifted toward that in the Pacific, but not all the way. In today's abyssal Atlantic the Ba to Ca ratio is about half that in the deep Pacific (see Figure 4-12). During glacial time, the benthic results suggest that the ratio was nearly the same as that for the deep Pacific.

Hence, barium is telling us the same thing as boron. During glacial time the abyssal Atlantic was indistinguishable from the deep Pacific. By contrast, Cd and ^{13}C are telling us that the Atlantic composition shifted only about 25 percent of the way toward that in the Pacific. So the cadmium reconstruction is consistent with that based on ^{13}C and the barium reconstruction with that based on carbonate ion. But, as shown in Table 4-1,

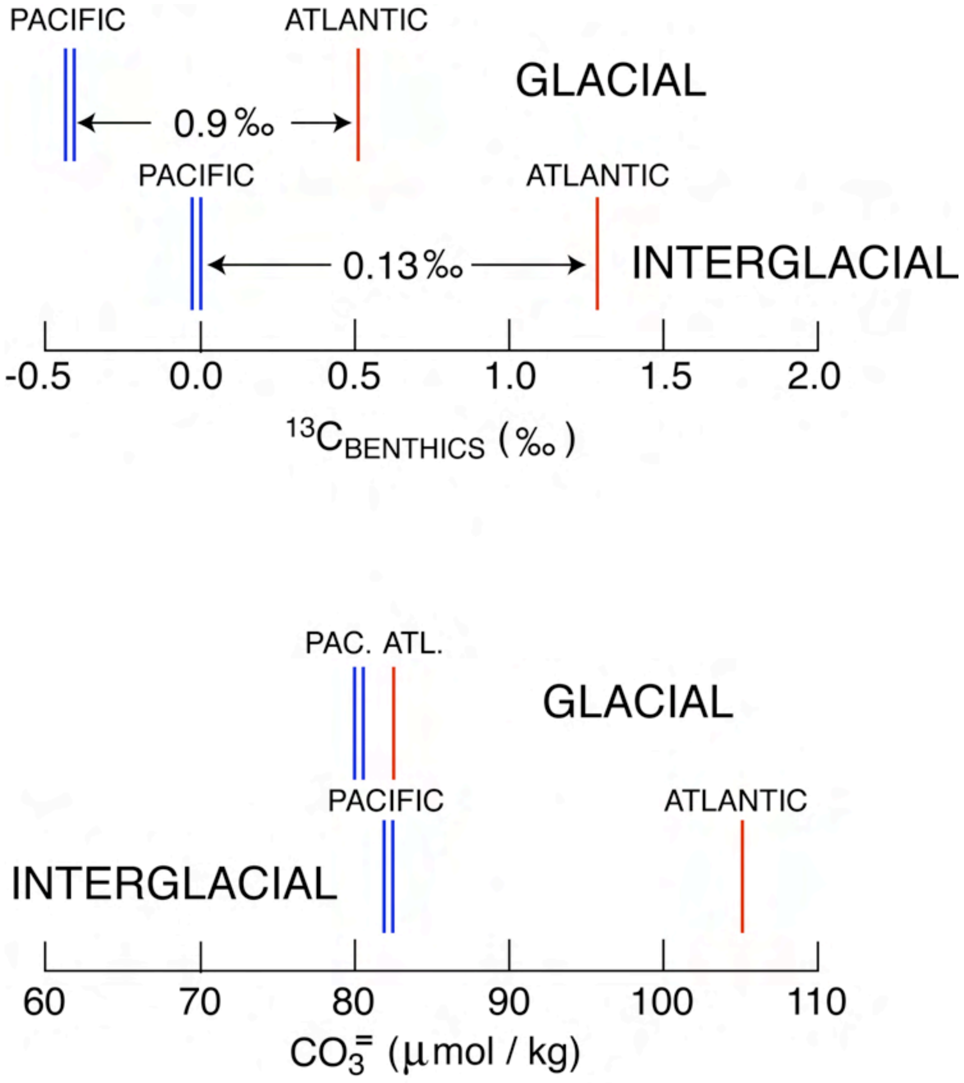
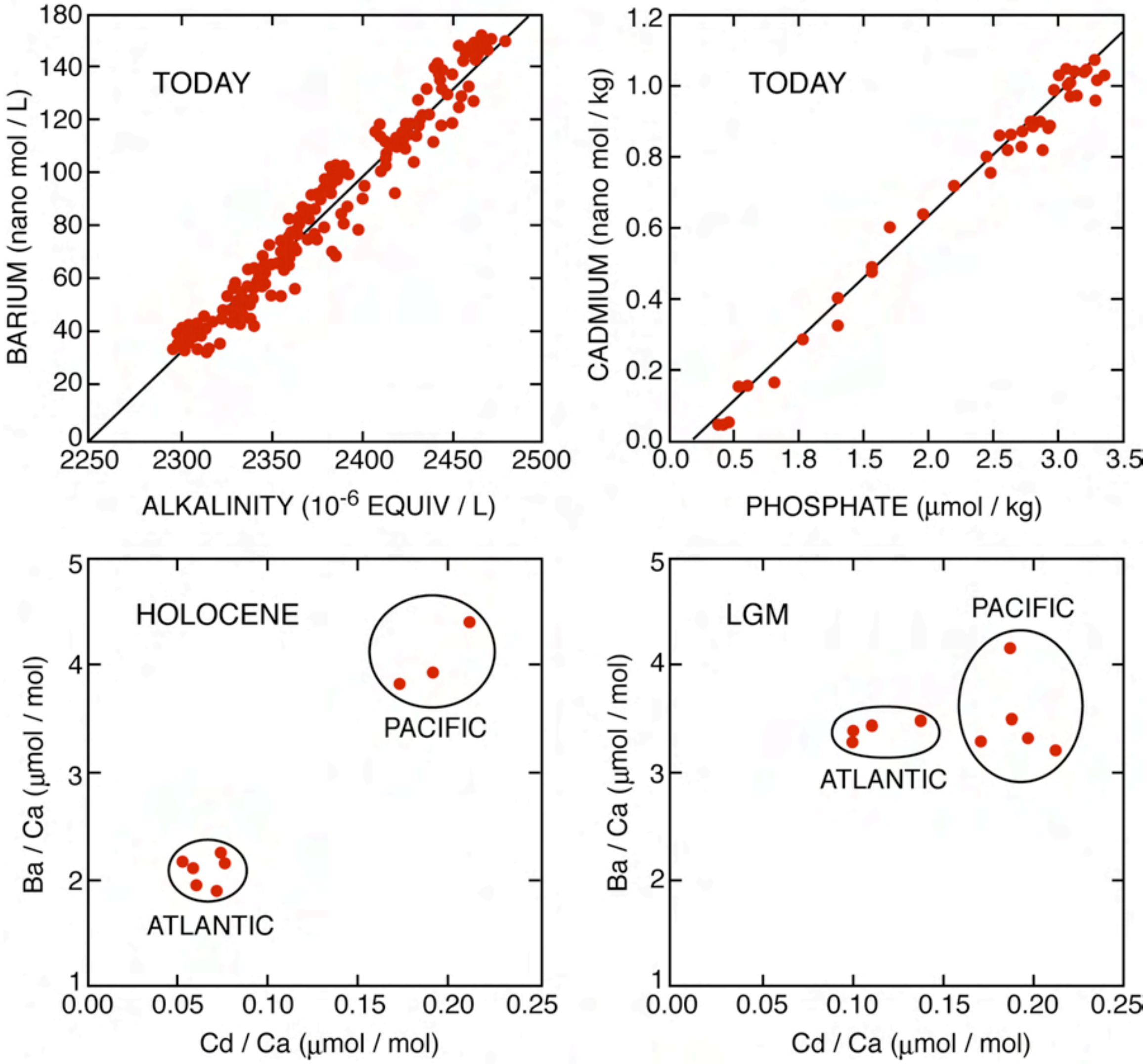


Figure 4-11. Comparison of the Holocene to LGM differences between the $^{13}C/^{12}C$ ratio and for the carbonate ion concentrations for the Atlantic's lower deep water.

Table 4-1. The Holocene to LGM change in the ratio of $\Delta CO_3^{=}$ to $\Delta\delta^{13}C$ in the Atlantic's LGM lower deep water mass suggests that about two thirds can be attributed to an increase in respiration CO_2 and one third to an increase in the contribution of Antarctic Bottom water (AABW).

	$\dfrac{\Delta CO_3\ \mu mol / kg}{\Delta^{13}C\ ‰}$
RESPIRATION	67
LGM LOWER DEEP WATER	$\dfrac{110 - 85}{.75 - .25} = \dfrac{25}{.50} = 50$
AABW	$\dfrac{110 - 85}{2.5 - 0.9} = \dfrac{25}{1.4} = 18$



ED BOYLE

DAVID LEA

KEN BRULAND

Figure 4-12. Shown in the upper panels is the covariance of cadmium with phosphate and that of barium with alkalinity in today's ocean. In the lower panel is a comparison between the barium and cadmium contents of Holocene benthic foraminifera shells (left) with those for the Last Glacial Maximum shells (right).

both are consistent with the two thirds versus one third contributions of extra respiration and ad mixing of AABW.

One other tracer is worthy of consideration. It is the isotopic composition of the element neodymium. One of its isotopes, ^{143}Nd, is produced by the decay of a very long-lived isotope of the element samarium (^{147}Sm; half-life 110 billion years). This decay product proves useful in paleoceanography because the Earth's granitic crust has a lower samarium to neodymium ratio than the Earth's interior. As a result, neodymium in the Earth's crust is deficient in ^{143}Nd relative to that in the Earth's mantle. This deficiency is especially large for the ancient granitic cratons which have been isolated from the mantle for a couple of billion years. As the basaltic and andesitic portions of the crust are quite young, they have ^{145}Nd contents close to that of their mantle source. The reason the isotopic composition of neodymium is of use to paleoceanographers is that the northern Atlantic is surrounded by ancient granitic cratons while the Pacific is surrounded by young volcanic lavas and ashes. The reason is that the Pacific is surrounded by subduction zones and the Atlantic is not. Because of this the neodymium dissolved in deep waters in the Atlantic is deficient in ^{143}Nd relative to that dissolved in the deep Pacific. In this regard paleoceanographers are lucky puppies. For the deep ocean to have this isotopic gradient requires that the oceanic residence time of neodymium be comparable to the mixing time between the Atlantic and Pacific Oceans. If the residence time were far longer, no isotopic gradient would exist. If it were far shorter, the distribution would be highly patchy.

Lamont-Doherty's Sidney Hemming and Steve Goldstein were the first to demonstrate that this isotopic gradient was imprinted in deep-sea sediments. They found that by leaching of the bulk sediment, they could separate the neodymium absorbed from seawater from that trapped in the mineral grains. Measurements on sediment core tops reproduced that the distribution in today's deep ocean. An improvement came when Cambridge's **Alex Piotrowski** showed that coatings on foraminifera shells contained in the sediment gave an even better match.

As shown in Figure 4-13, measurements of neodymium isotopes in LGM-age samples from two cores from the northern Atlantic reveal a significant LGM shift toward Pacific-like values. A detailed record for the last 90 kyrs obtained by Alex Piotrowski for a sediment core from 40°S in the Atlantic's Cape Basin is shown in Figure 4-14. The LGM values are shifted Pacificward by about 2.3 anomaly units. Although the geochemical situation for neodymium is more complicated than that for the other tracers discussed here, it does confirm that during the LGM composition of abyssal Atlantic water shifted part of the way toward that in the deep Pacific (see Table 4-1).

It is also of importance to determine how the rate of ventilation of the deep sea differed during glacial time. In other words, on what time scale were the glacial-age water masses in the deep Atlantic and deep Pacific renewed? In today's ocean, our estimates of renewal times are primarily based on the distribution of radiocarbon. For each 82 years water is isolated in the subsurface ocean, one percent of its ^{14}C is lost to radiodecay. Prior to the addition of the extra ^{14}C created by H-bomb tests, the ^{14}C to C ratio in warm surface waters averaged about 5 percent lower than that for atmospheric CO_2. For deep water in the Atlantic the average was about 10 percent lower, and for deep water in the Pacific it was about 20 percent lower. These differences were generated by the finite rate of CO_2 exchange between the atmosphere and surface ocean and the finite rate of renewal of water in the deep ocean.

These radiocarbon deficiencies can be translated into apparent renewal times. This is done by comparing the ^{14}C to C ratio in subsurface water with that in overlying surface water. This comparison yields an apparent renewal time of about 400 years for water in the deep Atlantic water and of about 1600 years for water deep in the Pacific. I say 'apparent,' because the ^{14}C to C ratio in the source waters which sink to replace those

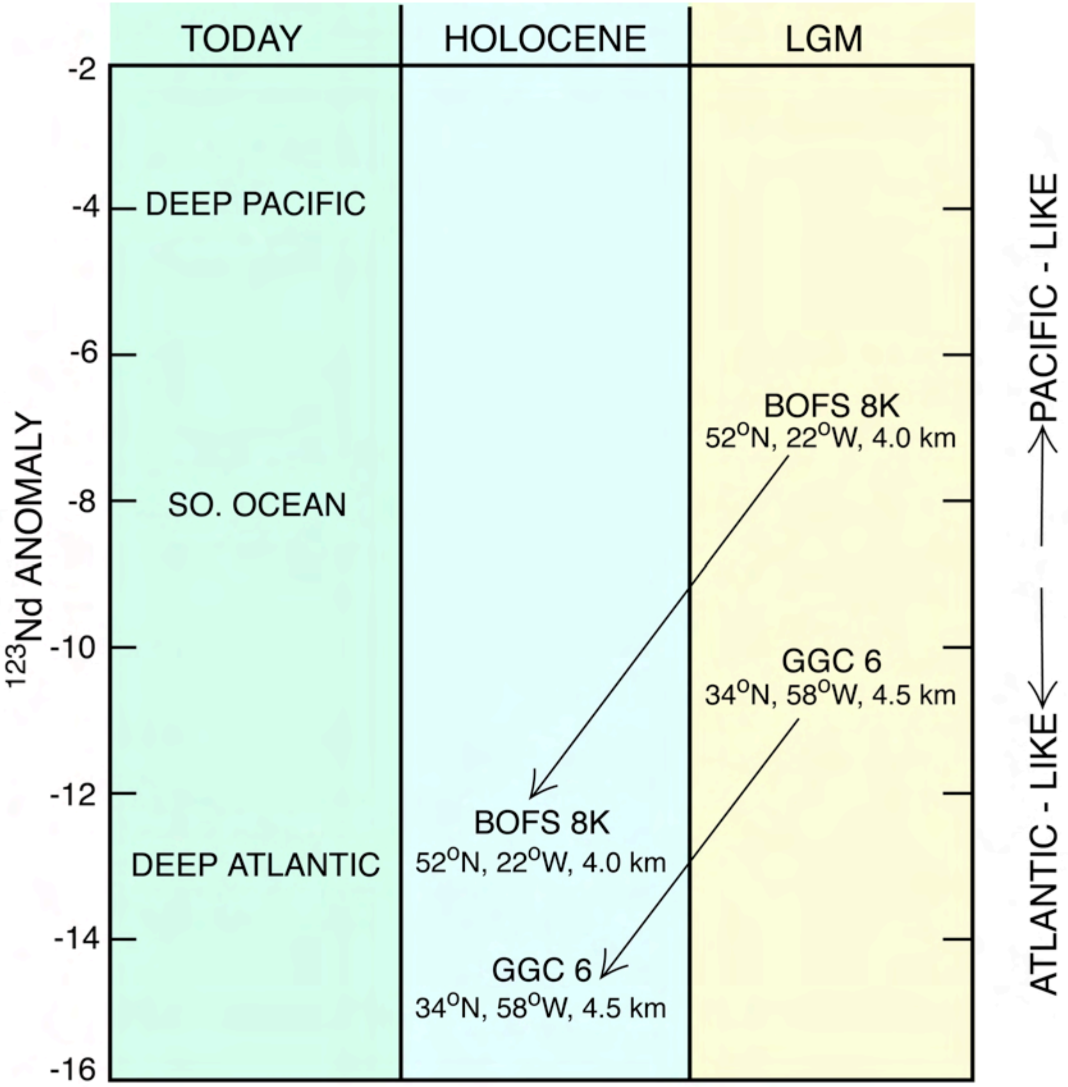
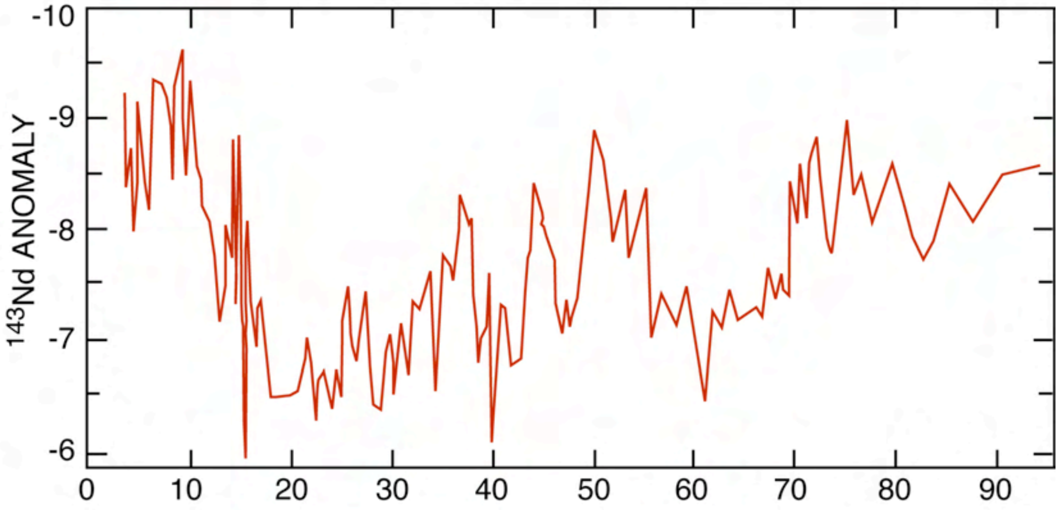


Figure 4-13. Comparison of the LGM to Holocene shift in the ^{143}Nd anomaly for two sediment cores from the deep northern Atlantic. For reference is shown the distribution of ^{143}Nd isotope anomalies in today's ocean.



SIDNEY HEMMING

ALEX PIOTROWSKI

STEVE GOLDSTEIN

Figure 4-14. A detailed ^{143}Nd record for the last 90 kyrs from the Atlantic's Cape Basin (40°S, 4.8 km).

in the deep sea is lower than that in ambient warm surface water. For the Atlantic source water, it is 2 percent lower and for the Southern Ocean source water about 14 percent lower. So it turns out that about 250 of the 400-year apparent residence time of water in the deep Atlantic must be attributed to a combination of the ^{14}C deficiency in its northern source waters and input of ^{14}C-deficient water from the south. Hence, the time scale for renewal by water sinking in the north is about 150 years. For the Pacific, the water entering from the deep Atlantic has an apparent age of 400 years and that produced in the Southern Ocean an apparent age of about 1200 years. Hence, the 50-50 mixture has an initial ^{14}C deficiency equivalent to about 800 years. So about half of the 1600-year apparent renewal time in the deep Pacific is the result of the ^{14}C deficiency in its source waters and half, the result of in situ radiodecay. Hence the water in the deep Pacific is renewed on a time scale of about 800 years.

Fortunately, we have the where-with-all to reconstruct how the warm surface water to deep water ^{14}C to C ratio offset differed during peak glacial time. It involves comparing the ^{14}C to C ratios in coexisting benthic and planktic foraminifera shells contained in deep sea sediments of glacial age. This has now been done for several dozen sites covering a wide range of locations and water depths. The results suggest that, for the deep Pacific, the ^{14}C to C ratio differences for LGM samples are indistinguishable from today's (see Table 4-2). But it must be kept in mind that, as these apparent age differences are the sum of the preformed age of the source waters and the ventilation age, it is possible that both of these changed but their sum did not.

The situation for ventilation-age reconstruction for the Atlantic's LGM abyssal water remains somewhat uncertain (see Table 4-2). The ^{14}C measurements on foraminifera from the equatorial Atlantic (i.e., the Ceara Rise) were made at a time when the precision was not as good as it is now. Hence the measurement errors are larger. The average age difference between planktic and benthic foraminifera shells for the LGM is 700 years with an uncertainty of at least 200 years. Two more recent measurements from

Table 4-2. Summary of radiocarbon-age difference for coexisting benthic and planktic foraminifera shells of Last Glacial Maximum age. For comparison, today's warm surface to deep apparent age difference is about 400 years for the Atlantic and 1600 years for the Pacific.

Latitude	**Longitude**	**Depth**	**Calendar Age**	**ΔB-P**
		km	**kyrs**	**yrs**
Upper Deep Atlantic				
12°N	79°W	1.8		
	Broecker et al., 1990		19.9	255 ± 180
			20.3	85 ± 230
			21.4	285 ± 600
				Mean 210
Lower Deep Equatorial Atlantic				
4°N	43°W	2.8		
	Broecker et al., 1990		17.1	960 ± 665
			18.3	1300 ± 290
			20.6	785 ± 450
			20.6	250 ± 665
5°N	43°W	3.5		
	Broecker et al., 1990		19.3	475 ± 185
			20.4	775 ± 190
			21.3	535 ± 215
			22.2	620 ± 260
5°N	43°W	4.0		
	Broecker et al., 1990		16.4	715 ± 325
			19.5	275 ± 230
			21.3	910 ± 230
			22.0	705 ± 280
			23.3	1165 ± 585
				Mean 730
Lower Deep Northwest Atlantic				
31°N	76°W	2.6		
	Keigwin, 2004		21.3	600 ± 150
29°N	74°W	3.8		
	Keigwin, 2004		18.0	1000 ± 200
				Mean 800

Table 4-2 (continued)

Latitude	**Longitude**	**Depth** **km**	**Calendar Age** **kyrs**	**ΔB-P** **yrs**
		Deep Equatorial Pacific		
1°S	146°E	1.9		
	Breocker et al., 2004		21.5	1950 ± 220
			21.9	1640 ± 250
6°N	126°E	2.1		
	Broecker et al., 2004		19.1	1325 ± 200
			18.7	1170 ± 220
			19.6	1325 ± 200
1°N	130°E	2.8		
	Broecker et al., 2008		17.9	1790 ± 170
			18.6	1510 ± 120
			19.2	1700 ± 130
2°S	140°W	4.4		
	Broecker and Clark, 2010		17.2	1550 ± 300
			22.0	1500 ± 300
			24.2	1700 ± 300
				Mean 1560

the Blake Ridge and Bahamas Outer Ridge, obtained by Woods Hole's Lloyd Keigwin, have smaller errors than those from the Ceara Rise. The average age difference for the cores from 2.6 and 3.4 km water depth is 800 years in agreement with those from the Ceara Rise. This finding reinforces the conclusion based on ^{13}C. The composition of abyssal Atlantic waters shifted only part of the way toward that in the Pacific.

In Table 4-3, I summarize estimates of the extent to which the LGM composition of abyssal Atlantic water shifted toward that in the Pacific based on five different proxies. Although each has a sizable uncertainty, taken together, they point to a one third contribution from the Southern Ocean. The remainder is the result of the redistribution of respiration CO_2 in the deep Atlantic, i.e., more in the lower deep water and less in the upper deep water.

It is instructive in this regard to consider today's Antarctic Bottom Water. It enters the Atlantic from the south under-riding the deep water formed in the northern Atlantic. As shown in Figure 4-15, it is well mixed and is separated from North Atlantic Deep Water by a 0.6 km-thick mixing zone. Importantly, it has the same phosphate content as bottom water entering the Pacific. With the records at hand, it is not possible to say whether a similar mixing zone separated the upper and lower deep water during glacial time. But, records from well south and well north of the equator suggest that the lower deep water was laterally well mixed.

In summary, unlike today's homogeneous depth distribution (see Figure 4-15), during parts of glacial time the deep Atlantic was strongly stratified. Above 2.5 km, the water was more nutrient depleted and below 2.5 km, it was more nutrient enriched than today's. Unlike the Atlantic, the situation for the Pacific did not change.

Turning our attention to another matter, we have seen that in order to explain the large temperature jumps associated with Dansgaard-Oeschger events requires a change in the mode of ocean circulation. Hence, one might suspect that there would be corresponding changes in CO_2 storage in the deep ocean. This didn't happen (see Figure

Table 4-3. Five proxies tell us that during the LGM the composition of the abyssal Atlantic water (i.e., >2.5 km) shifted about one third of the way toward that of the Pacific.

	Fraction Pacific	**Uncertainty**
$^{13}C/^{12}C$ (i.e., PO_4)	25	± 10
Cadmium/Calcium (i.e., PO_4)	25	± 15
$\Delta CO_3^{=}/\Delta\delta^{13}C$	33	± 10
Neodymium Isotopes	40	± 20
$^{14}C/C$	33	± 15
	Mean 31	

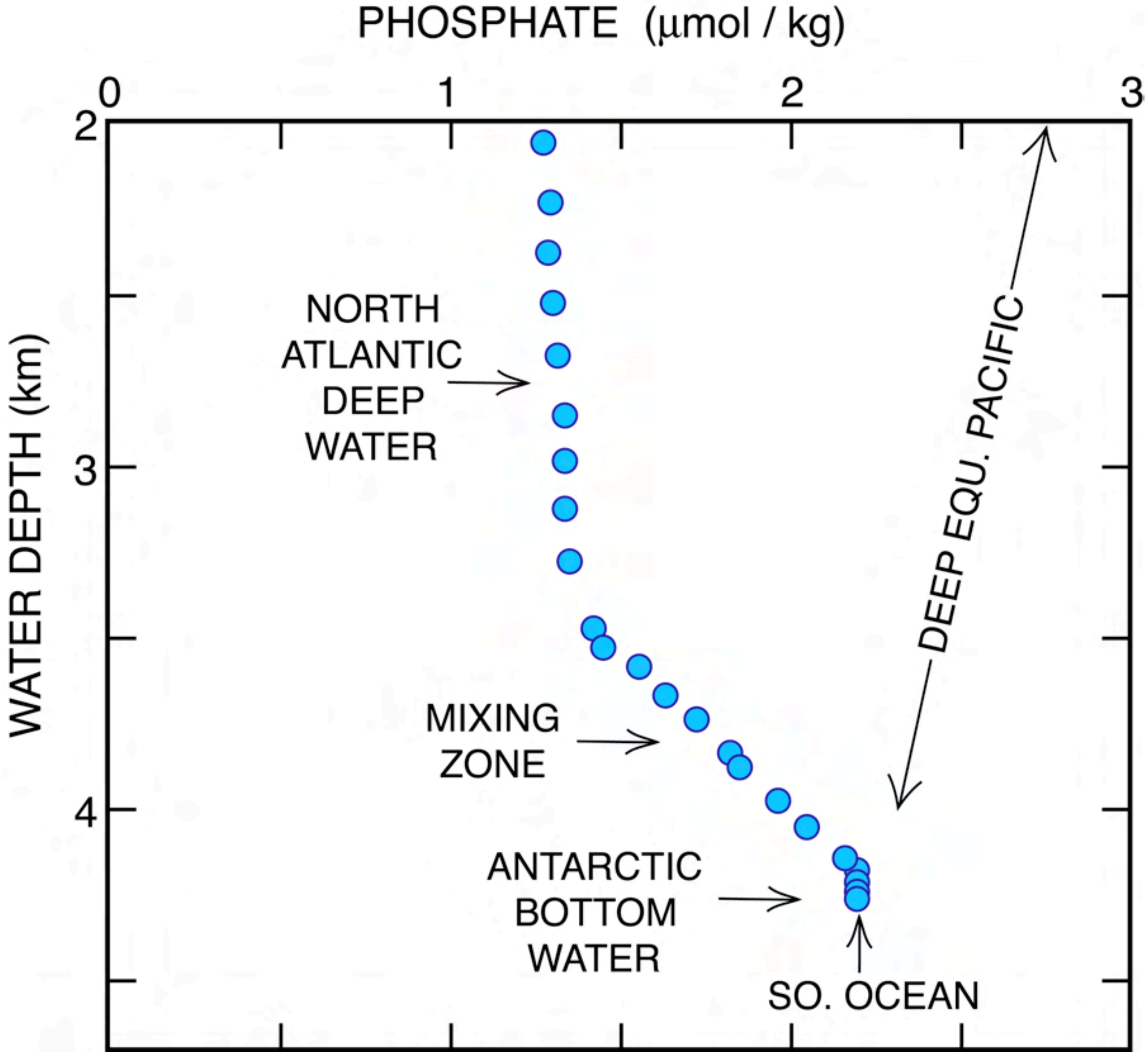


Figure 4-15. Profile of PO_4 concentration at GEOSECS station 57 in the western South Atlantic (24°S, 35°W). A 0.6-km mixing zone separates North Atlantic Deep Water from Antarctic Bottom Water. The latter has the same PO_4 content as that entering the abyssal Pacific. The point is that mixing in the Southern Ocean is so rapid that waters entering the deep Pacific and deep Atlantic have the same composition.

2-6). Perhaps the impacts of the Dansgaard-Oeschger cycles were confined to the water shallower than 2.5 km.

However, significant changes in the CO_2 content of the atmosphere did accompany Heinrich events (see Figure 2-6). At the time of each of these events, the CO_2 content of the atmosphere began to go up. Further, the slope of the increase in each rise was similar to that characterizing the onset of the last deglaciation. The difference is that for each of the Heinrich events, the CO_2 rise was somehow squelched before a full termination was achieved. Once this happened, CO_2 started back down. So, the reorganizations associated with Heinrich events did push CO_2 back and forth between the ocean and atmosphere.

As shown by Lamont-Doherty's Jerry McManus, a Heinrich event accompanied each glacial termination. So it is tempting to postulate that the circulation disruptions triggered by the Heinrich ice armadas led to breakdowns in the stratification of the Southern Ocean allowing the release of CO_2 to the atmosphere. If the system was properly poised, the CO_2 rise continued bringing about deglaciation. If it was not, the stratification re-formed stifling the transition to interglacial conditions.

Chapter 5

Cause of the Cooling Ramp

Each of the climate cycles of the last half million years has the same first order shape. A decline lasting on the order of 100 kyrs is terminated by a recovery accomplished in less than 10 kyrs. This asymmetrical triangular shape is particularly well displayed by the most recent of these cycles. As shown in Figure 5-1, the sea level, the benthic ^{18}O and the CO_2 records show this ramp-like cooling.

The ramps in two of these records (sea level and ^{18}O) are created by the growth of the Northern Hemisphere ice sheets. Although there are fluctuations around this ramp, there is a steady growth which continues until the ice sheets become vulnerable to a reorganization of thermohaline circulation triggered by a Heinrich ice armada. Further, the modulations superimposed on the 100 kyr decline resemble Northern Hemisphere summer insolation.

However, as discussed above, it is CO_2 and not summer insolation that is the primary driver of ice sheets. Hence, the question becomes what drives CO_2? It is tempting to call on the proposal suggested by Huybers and Langmuir. It attributes the ramp-like drawdown to a reduction in planetary CO_2 release. As shown many years ago by Cambridge's Dan MacKenzie, the weight of ice on volcanoes raises the melting point of the underlying silicate rocks. Although the pressure effect is transmitted instantaneously, the temperature response is far slower. Hence, loading and unloading of ice on volcanoes should pulse their eruptions and hence their CO_2 release. This scenario nicely explains the time history of lava flows in Iceland and in the Andes during the last 140 kyrs.

However, complicating the situation is the release of the pressure on mid-ocean ridge crests as sea level drops. It should enhance ridge crest volcanism and hence CO_2

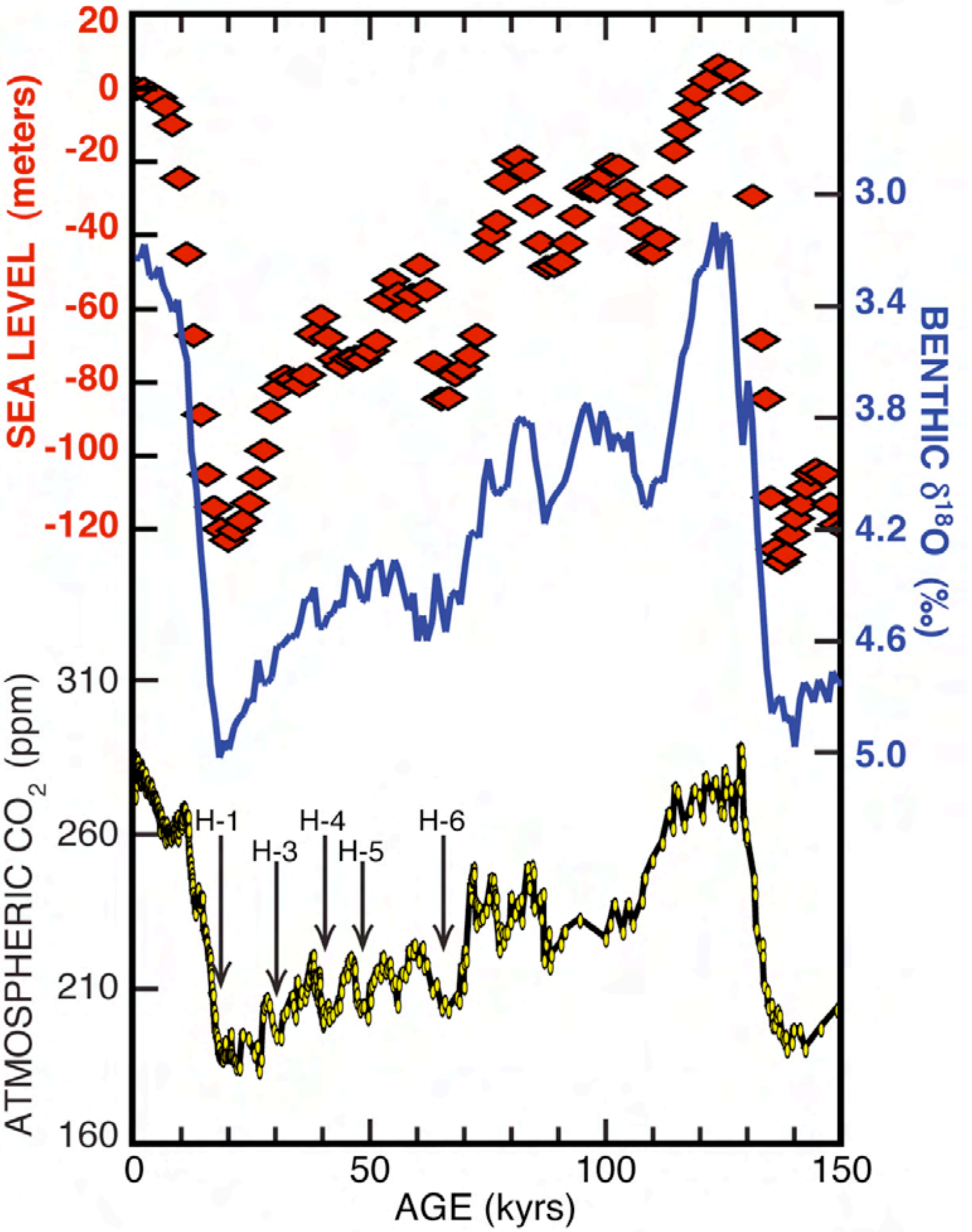


Figure 5-1. The records for sea level benthic ^{18}O and CO_2 are dominated by a downward ramp. Most would call on a continued growth of the Northern Hemisphere ice sheets as the cause for this ramp. I agree, but would like to believe that this growth was driven by the decline in atmospheric CO_2 content.

release. This extra CO_2 should then compensate for the reduction in terrestrial CO_2 release. The CO_2 release for these two sources is thought to be similar in magnitude.

Modeling of magma release from the mantle, carried out by Oxford's Richard Katz, demonstrates that there is a delay between pressure change and the rate of eruption of magma at the mid-ocean ridge crests. He shows that depending on the flow dynamics of the magma, the delay could be as much as several tens of thousands of years. If, as is thought to be the case, this delay mechanism does not apply to magma formed within the Earth's crust, the ridge crest delay could bring the reductions in CO_2 release from ridge crest back into at least partial synchrony with that from terrestrial volcanoes.

There is one source of information that will help to sort this out. It is fluctuations in the elevation of the basaltic sea floor as a function of distance away from the ridge axis. Magma injections should lead to highs and pauses to lows. Preliminary surveys show that the elevation fluctuations away from the ridge crests do indeed have frequencies found in the climate record. But the exact phasing of the two has yet to be established. But clearly it holds information regarding the duration of the delay.

Although a quantitative understanding of the changes in the rate of CO_2 supply to the ocean-atmosphere reservoir over the course of a glacial cycle awaits much more research, it is tempting to attribute at least part of the downward ramp in atmospheric CO_2 content to what could be thought of as supply starvation. If, as I would like to believe, the amount of CO_2 stored in the ocean follows the extent of deep Atlantic stratification, then these changes would modulate the downward ramp.

An even thornier issue is whether the supply of alkalinity to the ocean also varies with climate. Were the alkalinity flux from rivers greater during glacial time than during interglacial time, then the atmosphere's CO_2 content would have been correspondingly drawn down. As is the case for the ocean's DIC, its alkalinity is being replaced on a time scale comparable to the length of a glacial cycle. Unfortunately, there is little agreement on the sense of this glacial to interglacial difference change, let alone its magnitude.

CO_2 is also released from and added to the ocean-atmosphere reservoir, resulting in changes in terrestrial biomass. The late Nick Shackleton was the first to suggest that during glacial time there was less biomass. Much of the carbon in the trees and soils of the boreal lands of the Northern Hemisphere must have been destroyed by glaciers and permafrost. Shackleton attributed much of the decrease in the $\delta^{13}C$ of benthic foraminifera to this loss. However, we now know that part of this $\delta^{13}C$ drop could be the result of the redistribution of respiration CO_2 within the deep ocean. Further, the growth of trees on the shelf areas exposed by the drop in sea level likely compensated for the demise of boreal forests. The uncertainties involved in assessing the climate-induced changes in biomass, in my estimation, are so large that even the sign of its contribution remains in question.

A third contribution must be considered, namely, the changes in surface ocean temperature and salinity. The contribution of salinity is small and reasonably well constrained. The main contributor is the salt left behind as the result of formation of ice sheets. Hence, this part of the salinity correction can be based on the sea level record. The maximum lowering of sea level was about 120 meters. As the mean depth of the ocean is about 3600 meters, the salt content was about 3 percent higher during the LGM. Such an increase would raise the CO_2 partial pressure of CO_2 in surface water by about 10 μatm.

The influence of surface water temperature is likely larger. For each °C cooling, the CO_2 partial pressure drops by about 10 μatm. Evidence is converging that the tropics were about 3 to 4° colder during the LGM. The estimates for 40° north and south are about 6°C colder. So one could conclude that the ocean 40°N to 40°S cooled by about 4°C. However, as the Southern Ocean is thought to have an influence much larger than its area would indicate, it is important to assess its extent of cooling. But as it already is close to its freezing point, it is tempting to conclude that the ΔT was small. However, the presence of excess sea ice complicates the situation. It increased the size of this cold water region. If I had to estimate the contribution of sea-surface cooling to the CO_2 drawdown, I would place it at 25±15 μatm.

One might consider the best index of the time history of the Atlantic Ocean's stratification to be the difference between the $\delta^{13}C$ for the Caribbean benthics and that for the Ceara Rise benthics (see Figure 5-2). But there is a problem with such a choice. Although during the latter half of the last glacial cycle this works well, during the first half it doesn't. At the times of MIS 5e and 5c, the $\delta^{13}C$ for Ceara Rise benthics was greater than that for Caribbean benthics (see Figure 5-2). But this doesn't make sense in connection with the model proposed here. Further, this scenario is incapable of explaining the first half of the CO_2 decline which occurred between 114 and 104 kyrs ago.

In conclusion, although I suspect that changes in the rate of supply of CO_2 and alkalinity to the ocean did play a role in the ramp-like drawdown of CO_2, so far it is not possible to construct a self-consistent scenario that combines it with ocean uptake. To see why this is the case, one has only to ponder the difference between the shape of the CO_2 record and that for sea level.

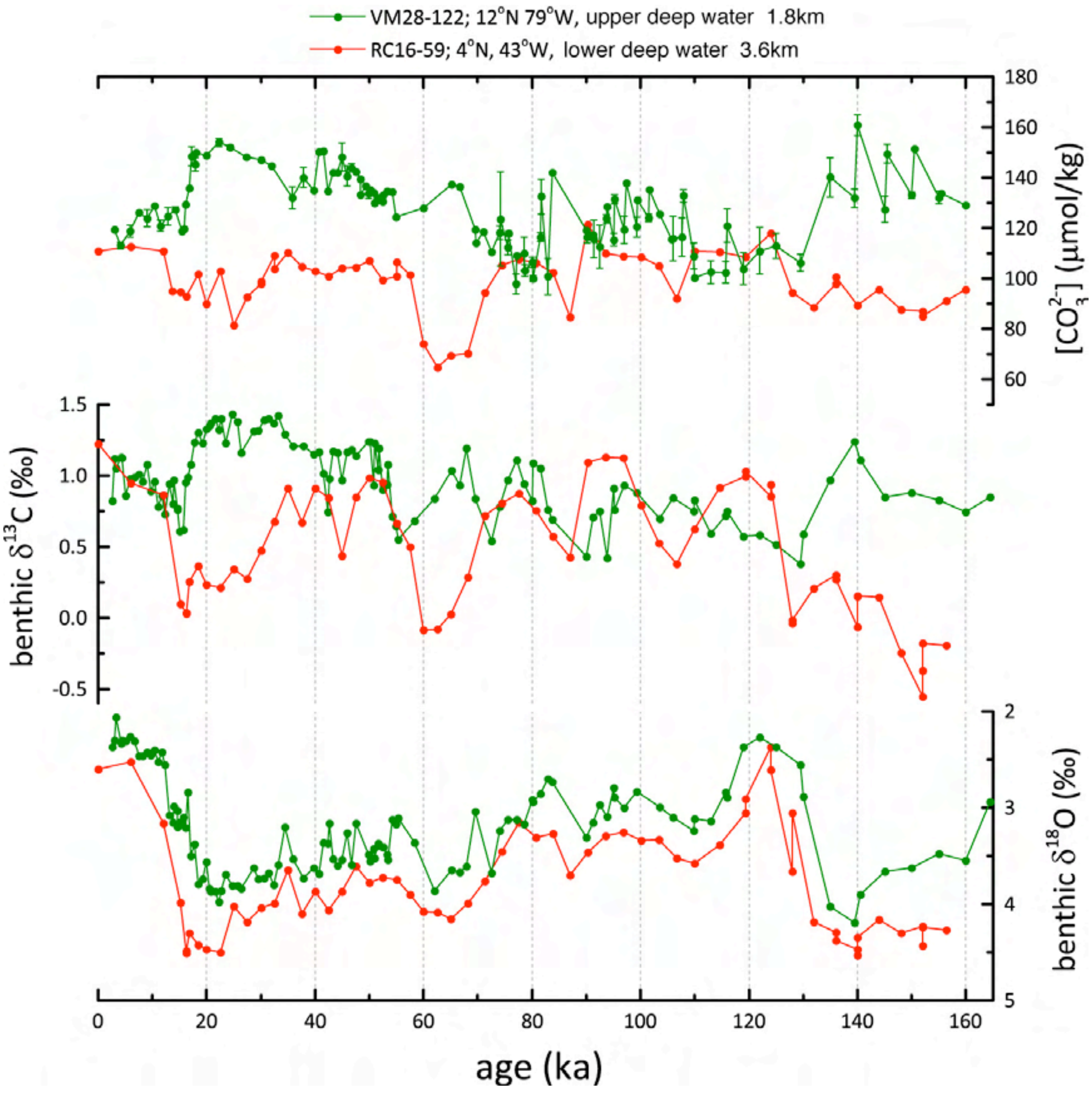


Figure 5-2. If, as I would like to believe, the CO_2 uptake by the deep sea is proportional to the extent of nutrient stratification in the deep Atlantic, then the question arises as to how best to employ the carbon isotope and carbonate ion data from the Ceara Rise and Caribbean cores to this end. For the last 75 kyrs, except for MIS 3, the $\Delta\delta^{13}C$ and $\Delta CO_3^=$ tell the same story; the Holocene Atlantic lacks stratification, the stratification is large and nearly the same during MIS 2 and 4. However, the $CO_3^=$ record suggests an intermediate extent of stratification during MIS 3 and the carbon isotope record suggests only a small extent of fractionation. Prior to 75 kyrs, during MIS 5, the $CO_3^=$ ion stratification is small. The carbon isotope record for this time interval sends no clear message. The prominent $\delta^{13}C$ peaks corresponding to MIS 5a, 5b and 5e. The Ceara Rise cores are not anti-matched by those in the Caribbean core. The $\Delta\delta^{13}C$ and $\Delta CO_3^=$ differences for MIS 6 has about the same amplitude as those for MIS 2 and 4.

Chapter 6

Unresolved Questions

Way back in 1955 when I was a graduate student, I attended a lecture given by the well-known British astronomer, Fred Hoyle. He said something that has stuck with me all these years. It went like this. There are three types of scientists. At one extreme are quacks who are incapable of distinguishing good ideas from crazy ones. At the other are hypercritical types who immediately demolish any idea that enters their head. In between are scientists who tenderly nourish each idea with positive thoughts. But once the idea is firmly in place, they subject it to a blast of criticism. The scenario presented here popped into my head while visiting the University of Arizona in March 2013. As the idea is now well formed, it's time to give it a blast of criticism.

My suggestion that the link between the Earth's orbital cycles and Earth temperature is primarily through their impact on ocean circulation (and in turn CO_2) rests heavily on the record of mountain glaciation for the last 40 kyrs. In both hemispheres, these glaciers stood near their maximum extent from 25 kyrs to 18 kyrs. Further, the snowline lowerings at 40°N and 40°S were similar in magnitude. Were glaciers to have been driven by changes in insolation seasonality, then Southern Hemisphere glaciers should have reached their maximum 10 or so kyrs earlier than those in the Northern Hemisphere and then retreated during the LGM. Further, instead of following the seasonality sinusoid, the Southern Hemisphere glaciers remained near their maximum extent during an entire precession cycle. In contrast, the match with CO_2 couldn't be better.

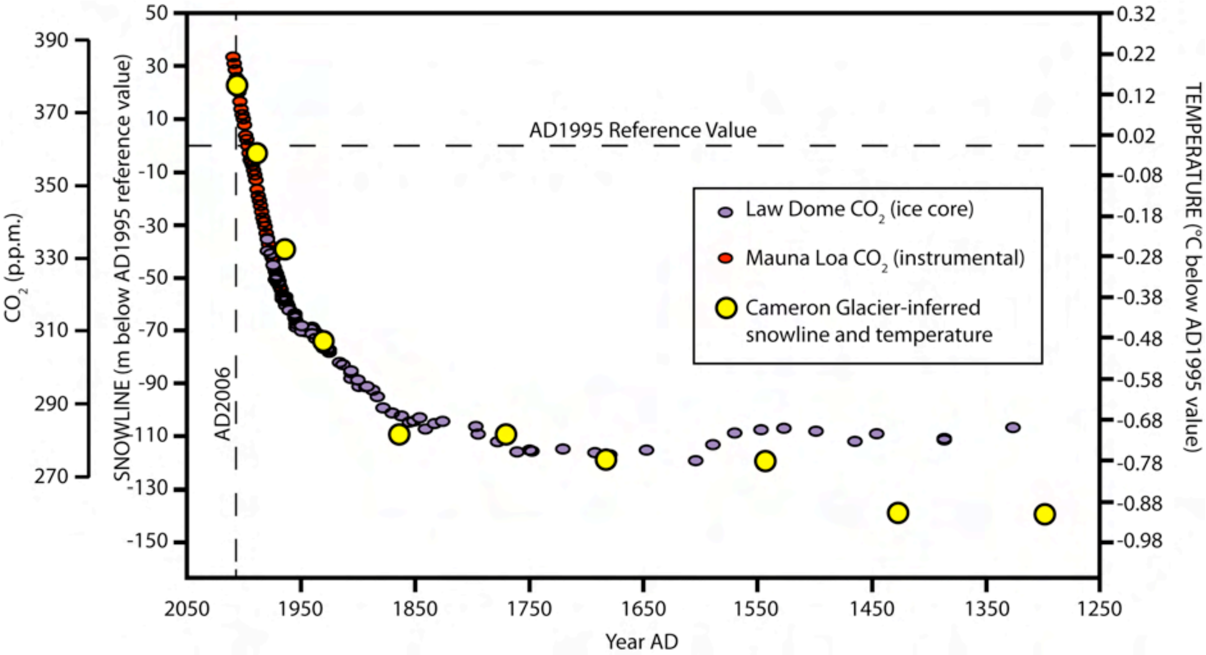
However, there are two important departures from what would be expected if CO_2 dominated the glacial record. First there is a 2-kyr lag in the onset of the rapid retreat of mountain glaciers in the Northern Hemisphere compared to those in the Southern Hemisphere. Mountain glaciers at 40°S began their rapid retreat at the same time as the

CO_2 content of the atmosphere started to rise (i.e., 18 kyrs ago). But glaciers in the western U.S. remained close to their maximum extent until about 16 kyrs ago. The reason for the difference is likely related to shifts in the location of the thermal equator. If so, then CO_2 is not the only thing that impacted glacial extent.

There is also a mismatch between the time of the onset of the LGM in the Southern Hemisphere mountains and those in the Northern Hemisphere. While the extent of Southern Hemisphere mountain glaciers remained nearly the same from 40 to 18 kyrs, those in the Northern reached their near maximum extent 15 kyrs later. They underwent a major expansion between 30 kyrs and 25 kyrs. Perhaps this difference reflects a precession-driven antiphasing of insolation changes. Again, this can't be explained by CO_2.

Starting about 10,000 years ago, the CO_2 content of the atmosphere underwent a small sag which bottomed out about 8,000 years ago. It then underwent an increase which continued right up to the onset of the Little Ice Age. The magnitude of this CO_2 rise was about 10 ppm (i.e., about one tenth of the LGM lowering). As LGM snowlines were about 750 meters lower than today's, one might expect that 8,000 years ago snowlines should have been 75 meters lower than during the Little Ice Age. But there is no evidence that this was the case. In the Northern Hemisphere the expansion of mountain glaciers during the Little Ice Age was as large as that at any other time in the last 8,000 years. One explanation might be that in the Northern Hemisphere the post 8-kyr CO_2 rise was compensated by a decrease in summer insolation. So once again some forcing in addition to CO_2 appears to be necessary.

Interesting in this regard is that during the last thousand years the rise in the snowline for New Zealand's Cameron Glacier has kept pace with the rise in the atmosphere's CO_2 content (see Figure 6-1). Clearly glaciers are taking note of the large rise created by fossil fuel burning. The difference is that during the course of the



JOERG SCHAEFER

AARON PUTNAM

Figure 6-1. Response of New Zealand's Campbell Glacier to the rise in CO_2 caused by the burning of fossil fuels. As are all our planet's glaciers, it is retreating. ^{10}Be ages by Schaefer and Putnam show that the rate of retreat is keeping pace with the CO_2 rise.

Holocene alternate forcings other than CO_2 were available. No such alternates of significant size were available during the last 100 years and the CO_2 rise has been huge.

An interesting test of my scenario is underway. It involves determining what the Northern Hemisphere glaciers did during the Younger Dryas. If summer warming driven by rising CO_2 dominated, these glaciers should have retreated. But, if the winters made frigid by expanded northern Atlantic sea ice dominated, then the glaciers should have become larger. I say 'underway' because there is a renewed interest in carrying out precise ^{14}C and ^{10}Be dating in both Europe and New Zealand. So far, it appears that the late glacial expansion occurred late in the Antarctic Cold Reversal, and there is also growing evidence in support of a glacial retreat during the Younger Dryas. If so, CO_2 wins!

A very serious problem with my scenario has to do with the record for the intervals of peak interglaciation. As recorded in Antarctic ice cores, a mismatch exists between the widths of peaks in the stable isotope (i.e., air temperature) record and the peaks in atmospheric CO_2 record (see Figure 2-1). The CO_2 peaks for each interglacial are wider than those for air temperature. So this means either that CO_2 leads air temperature during the onset of deglaciation or it lags air temperature during the onset of the subsequent glacial period. As already mentioned, the uncertainty in the magnitude of gas age–ice age offset in slowly accumulating Antarctic plateau ice makes it impossible to make a convincing choice between these two possibilities. Further, ice cores with high accumulation rates (and correspondingly small ice age – gas age differences) record only the onset of the rise to the present interglacial peak. As can be seen in Figure 3-5, there is no significant lead or lag between temperature and CO_2. If this applies to the previous glacial cycles, then the difference in peak width tells us that the drop of atmospheric CO_2 content lagged that of Antarctic air temperature. Further, the magnitude of the lag is on the order of one to two thousand years. As the cooling recorded in Antarctic ice preceded the drop in the atmosphere's CO_2 content, CO_2 cannot be called on to create the cooling.

Further, this CO_2 drop which occurred between 114 and 104 kyrs ago accounted for about half of the total CO_2 drop. This drop was not accompanied by a pronounced increase in the deep Atlantic's stratification. Nor was it accompanied by an increase in Southern Hemisphere dust. So what caused it? I have no answer.

In addition to this CO_2 lag, there is a mismatch between the MIS 5 CO_2 record and the records for sea level and benthic ^{18}O. While both of the latter have three distinct interglacial peaks, the CO_2 record has only two. This suggests that the processes that governed the first half of the glacial cycles are not the same as those which governed the second half. This is clearly a serious flaw in my scenario. Something else must have been going on. Perhaps this something was the expansion of the sea ice apron around the Antarctic continent. I consider sea ice to be the glacial cycle's wild card. I would like to believe that the cooling of Antarctica reflects the thermal isolation created by the extension of its sea ice apron. But, if so, what caused it?

The greatest impediment to evaluating my argument lies in our inability to adequately model the CO_2 uptake and release by the ocean. I imply here that the changes in seasonal contrast alter the density of waters in the polar oceans in such a way to change the competition between deep water production in the northern Atlantic and that in the Southern Ocean. This change in competition must somehow lead to a stratification of the Atlantic Ocean. It must also have led to an increase in the utilization of the ocean's phosphate. But, as the details are lacking, modelers have no useful target.

I am also puzzled by the role of dust. If the drawdown of nutrients in the surface waters of the Southern Ocean appears to have been driven by the iron delivered in dust, then what was it that caused the rain of dust to increase? As pointed out by David McGee, dustiness relates to gustiness and gustiness is controlled by pole to equator temperature gradient. If so, somehow the cart got in front of the horse.

If nothing else, my hope is that this book will lead to a greater emphasis on understanding the chain of causation. Most authors have been content to assume that the

CO_2 changes recorded in Antarctic ice were, in a sense, God given. But clearly they must be somehow linked to glaciation. More thought must be given as to just how.

Epilogue

One might ask why I chose to publish this idea as an un-reviewed eBook. The main reason has to do with my age. At 84, I would like to see it out there before I lose my marbles. I would also like to avoid the pangs of anonymous reviews. I find creating a reference list with hundreds of entries an arduous task. Instead, I credit those of my heroes mentioned in the book by including pictures of many of them and a reference to a key paper by each. So maybe I should refer to it as a blog instead of a scholarly book.

Acknowledgements

As many of you know, I am computer illiterate and also a dyslectic. This being the case, I have to solicit help. Joan Totton has converted my pencil scribbles into electronic form. Patty Catanzaro generated the numerous figures. My wife and long-time colleague, Elizabeth Clark, acted as a go-between keeping me linked to the electronic world. Special thanks go to my Lamont-Doherty colleagues: Bob Anderson, Jerry McManus, Leo Peña, Joerg Schaefer, and Aaron Putnam for their willingness to provide help when needed. Also, a day-long discussion with Danny Sigman and Gerald Haug helped me to focus on how the ocean operated during the LGM. Ed Brook kindly provided a composite CO_2 record not yet available in his publications. And, of course, experiencing the stimulation of those who surround me here at Lamont-Doherty has kept me young at heart! Overall I'm a very lucky man.

Without support from the Comer Science and Education Foundation, this project would not have been possible. So, in a sense, it is part of Gary Comer's legacy to abrupt change science.

References

I list here the names of those people mentioned in this book. Each has influenced my thinking. Rather than listing the myriad of papers published on this subject, I reference only one key paper by each of my heroes. I regret that I cannot acknowledge the many, many others who have helped me along the way.

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