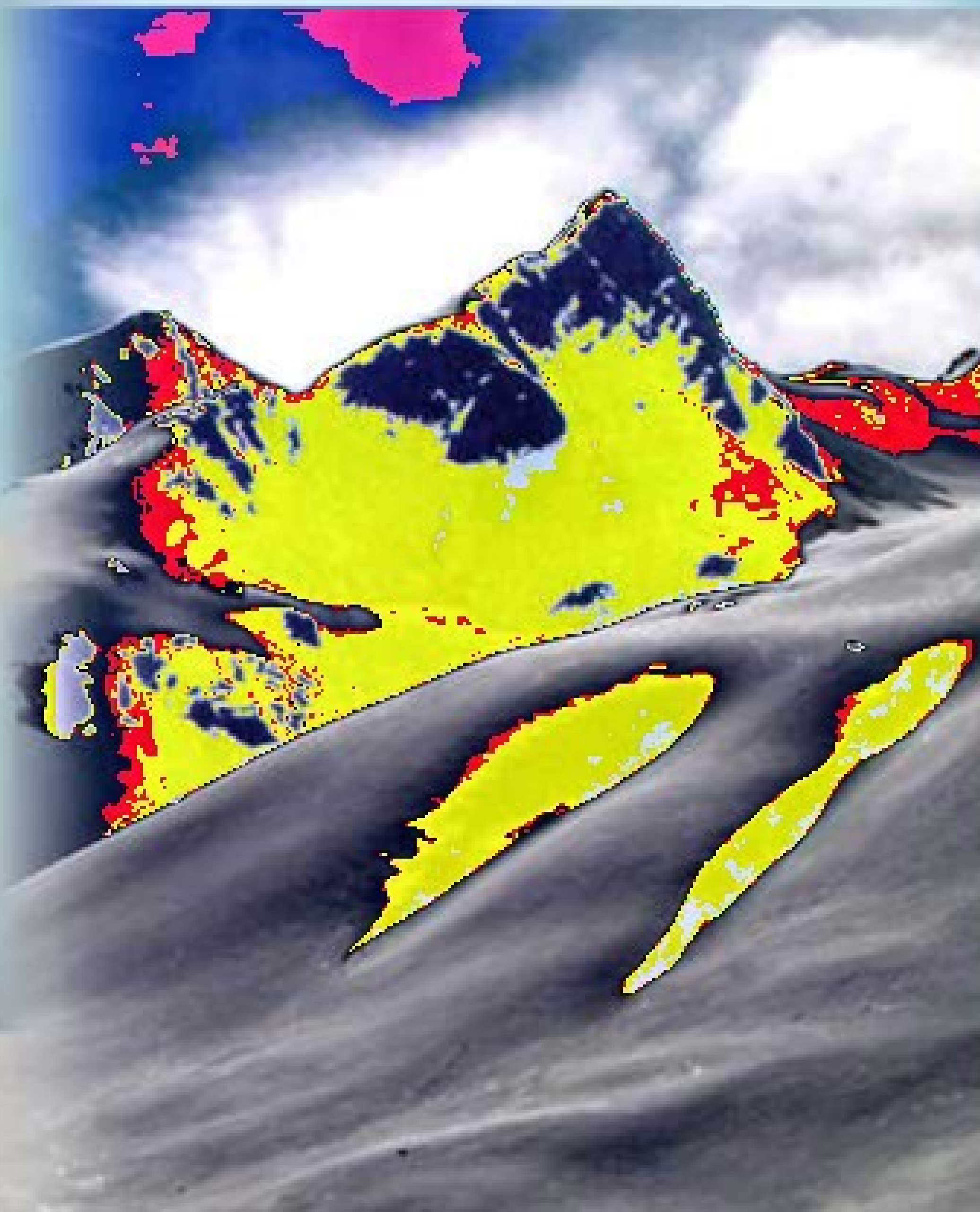

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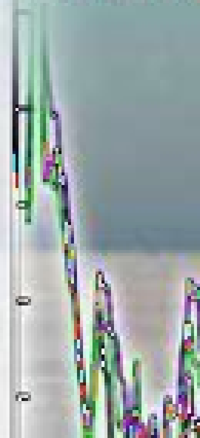

# Ice Ages and Interglacials

Measurements, Interpretation, and Models

(Second Edition)

Donald Rapp

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# Contents

# Preface

The typical description of the past million years would be that the Earth has experienced about 10 major periods of glaciation (ice ages) spaced at roughly 100,000-year intervals. This presupposes that ice ages are unusual departures from normalcy. Actually, it appears as if the natural state of the Earth during this period was an ice age, but there were about 10 interruptions during which the climate resembled something like today's climate for perhaps 10,000 years or so. Each ice age required several tens of thousands of years to develop to its maximum state of glaciation.

During the Last Glacial Maximum, some 20,000 years ago, Canada and the northern U. S. were blanketed by huge ice sheets up to 4 km thick. In addition, there was a large ice sheet covering Scandinavia that reached down into Northern Europe. The Antarctic ice sheet was somewhat more full than today. Local glaciations existed in mountainous regions of North America, Europe, South America, and Africa driving the tree line down by as much as 700 m (800 m in some cases). The temperature of Greenland dropped by as much as 20°C, but the climate was probably only a few degrees colder than normal in the tropics. Conditions were very harsh 20,000 years ago at the Last Glacial Maximum (LGM) when an ice sheet more than 2 miles thick pushed down from Canada into the northern U. S.

These ice sheets tied up so much of the Earth's water that the oceans were as much as 120 m shallower. As a result, the shorelines of continents extended much farther out than today. The Beringia land bridge from Siberia to Alaska was created, allowing animals and humans to cross from one continent to the other. In the upper- to mid-latitudes the climate was semi-Arctic and the flora shifted to tundra. Humidity was reduced and much of the land dried out. The sharp temperature discontinuity at the edges of the ice sheets generated violent winds that swept up dust and dirt from dry regions, filling the atmosphere. This ice age began to wane around 15,000 years ago and dissipated through a series of gyrating climate oscillations, ending in the comparatively benign period that has lasted for the past $\sim$10,000 years called the *Holocene*.

A few geologists in the 19th century were perceptive enough to notice signs of glaciation in rocks and geological formations and concluded that the Earth must have once (at least) been heavily glaciated with massive ice sheets that generated the markings and rock depositions that they observed. They eventually overcame the initial resistance to this new (and shocking) concept in the geological community. But, it was not until the 1970s that extensive studies of marine sediments (followed by polar ice core studies in the 1980s and 1990s) demonstrated the existence, amplitude, and recurrent chronology of multiple ice ages.

During the 19th century several scientists proposed that ice ages could have resulted from the quasi-periodic variability of the Earth's orbital parameters that affect relative solar energy input to higher latitudes. As the theory goes, when summer solar energy input to higher northern latitudes drops below a critical threshold, ice and snow can better survive the summer. Data acquired in the 20th century suggest that ice sheets slowly begin to form over many millennia at latitudes roughly in the range 60°N to 70°N. As the ice cover spreads, the albedo (reflectivity) of the region increases, further adding to the cooling effect. Water increasingly leaves the oceans and gets deposited in the process of building ice sheets, lowering the oceans and extending shorelines. Since land has a higher albedo than the ocean, this provides further cooling. In regions adjacent to the ice sheets vegetation is inhibited, adding still further to increased Earth albedo. As northerly regions cool, the concentrations of key greenhouse gases such as water vapor, $CO_2$, and $CH_4$ decrease, creating a worldwide cooling effect that converts the budding ice age into a global phenomenon. Other effects such as widespread dust storms and the expansion of sea ice and mountain glaciers also contribute. Thus, the runaway expansion of ice sheets develops over many millennia. James Croll formulated the concept of the Sun acting as a trigger for ice ages based on variations of the Earth's orbit in 1875. In the first several decades of the 20th century, M. Milankovitch quantified this theory by carrying out extensive calculations by hand (no mean feat in the pre-computer age). Nevertheless, in the absence of long-term data over many ice ages, the astronomical theory remained an abstract concept. Furthermore, there were no credible mechanistic models to describe how changing solar energy input to higher latitudes could lead to alternating ice ages and deglaciations.

With the advent of marine sediment data in the 1970s, it became possible to compare the astronomical theory with data over many glacial cycles. John Imbrie was a pioneer in this regard. He built up a stack of ocean sediment data—which he dubbed the "SPECMAP" stack—from several sites with the objective of reducing noise and devised models to compare ice sheet volume ($V$) with solar variations. In doing this, he tuned the chronology of the SPECMAP stack using solar variability as a guide. He also used spectral analysis to show that some of the prominent frequency components in SPECMAP variability were in consonance with known frequencies of solar variation. From this, he concluded that the astronomical model explained much of the ice age record—at least for the past $\sim$650,000 years. However, there seems to be some circular reasoning involved and one could construe his procedure as involving curve fitting in addition to physics. More importantly, when modeled ice sheet volume and solar intensity are dispassionately compared today, the results are not quite so overwhelming.

As ocean sediment data were extended backward in time, it became apparent that some features of the sediment record did not fit astronomical predictions. What stands out here was the fact that the period from about 2.7 million years before the present (MYBP) to about 1 MYBP was characterized by relatively rapid smaller amplitude climate cycles, whereas since ~1 MYBP climate cycles have increased in period and amplitude. By contrast, the astronomical theory would not have predicted any such major shift in frequency and amplitude since there is no reason to believe that solar forcing at higher latitudes changed qualitatively during this time period. There were other problems with the theory as well; during some major occurrences of climate change there were no corresponding variations in solar input (e.g., 400,000 years ago). Since the 1990s, a number of studies have attempted to resolve the differences between the data and the astronomical theory. Some of these studies had an obvious and pervasive bias in favor of the astronomical theory—in some cases seemingly an attempt to preserve the theory against all odds. Scientific objectivity seems to have been lost somewhere along the way. For example, a number of investigators suggested that each of the several parameters (obliquity, eccentricity, longitude of precession) acted separately over different eras to produce a changing data record. While there may indeed be strange and unusual nonlinear effects in the way that climate reacts to orbital parameters (e.g., Rial, 1999), as far as the conventional astronomical theory is concerned these parameters do not act separately. They act in concert to change solar intensity, and it is solar intensity that determines the climate—at least according to the astronomical theory.

Yet, despite problems with the astronomical theory, there are several tantalizing similarities between climate data and the historical solar record. These include the correlation of several important frequencies in spectral analyses and certain undeniable rough similarities in the climate and solar records over some periods during the past several hundred thousand years.

Roe (2006) looked at the astronomical theory in a way that is both novel and impressive. Instead of modeling ice sheet volume with a simplistic model, he took the slope of the SPECMAP curve as an indicator of $dV/dt$, the rate of change in ice volume. He then compared this with midsummer solar intensity at 65°N and found a very good correlation. This is perhaps the most convincing evidence in favor of the astronomical theory.

Solar intensity varies with a ~22,000-year period due to precession of the equinoxes. These oscillations vary in amplitude over long time periods due to the variability of eccentricity and obliquity. The temperatures implied by ice core records do not oscillate with this frequency. However, there does seem to be some correlation between the amplitude of solar oscillations and ice core temperatures. In many (but not all) cases, periods with higher amplitude solar oscillations appear to be associated with increasing Earth temperatures and those during which solar oscillations are weak seem to be associated with decreasing temperatures. This would be the case if (1) there were a fundamental tendency toward glaciation and (2) ice sheets grow slowly and disintegrate rapidly. In that case ice sheets would disintegrate and not recover when solar oscillations were large, but would grow when solar oscillations were small. As in AM radio, the oscillating precession signal is amplitude-modulated due to changes in eccentricity and obliquity. The precession cycle merely acts as a carrier wave. All of this is very tenuous and represents a somewhat subjective interpretation of the data. However, the fact that the frequency spectrum shows frequencies for eccentricity and obliquity but not precession suggests that it is the amplitude of solar oscillations that matters and that the precession frequency does not directly contribute to climate change. Only eccentricity and obliquity determine the amplitude of precession oscillations.

Nevertheless, what seems to be most glaringly absent from the astronomical theory is a clear quantitative mechanism by which variations in solar input to higher latitudes produce changes in climate, including various positive feedback effects due to changes in albedo, greenhouse gas concentrations, ocean currents, and north–south energy exchange, although the paper by Hansen and Sato (2011) provides some insights. The Imbrie model for comparing ocean sediment time series with the astronomical theory has the virtues of clarity and simplicity, but it is too simplistic to describe the variable climate of the Earth with all its intricate feedback mechanisms and complexities.

There are other aspects of long-term climate change that further confuse matters. There is some evidence that the termination of ice ages may originate in the Southern Hemisphere—not the Northern hemisphere. In addition, there are alternativee theories that propose that ice age cycles are controlled by cosmic rays penetrating the Earth's atmosphere enhancing cloud formation and producing a cooling effect. However, such theories are very speculative.

The role of greenhouse gases, particularly $CO_2$, in transitions between ice ages and interglacials remains murky despite several attempts to unravel the processes involved. While measurements taken from ice cores clearly show that the $CO_2$ concentration rose and fell from interglacial to ice age in a repetitive pattern, the factors that caused these changes are still only partly understood. There is troubling evidence that past interglacials were warmer than the present one, yet they did not have higher $CO_2$ concentrations. How can that be?

Amidst all this work, both experimental and theoretical, there does not seem to be a single reference work that provides an in-depth review of the data and models. *The Great Ice Age* is a book that does a creditable job in many respects (Wilson, 2000). The closest that anyone has come to a thorough review is Richard A. Muller and Gordon J. MacDonald's *Ice Ages and Astronomical Causes*, published by Wiley/Praxis in 2000 (called "M&M" throughout the current book). M&M covers much of the data that were available at the time the book was written (late 1990s) and discusses the models in some depth. Spectral analysis was the dominant theme in M&M, almost to the neglect of other aspects. While it may be true that, in seeking a relationship between two noisy time series, comparison of the important frequencies in the frequency domain has implications for a possible connection, ultimately, it is the time phasing of the two curves (temperature vs. time and solar intensity vs. time) that is of greatest importance in establishing a cause–effect relationship. I have relied upon M&M as a source of data, analysis, and discussion in a number of places. Their book is an obvious starting point for anyone interested in ice ages.

It is interesting to speculate when the next ice age might occur. This topic is discussed briefly toward the end of this book. Some climatologists believe that global warming induced by $CO_2$ emissions will prevent ice ages from occurring.

Throughout this study of ice ages and climatology, what surprises me most is that climatologists seem determined to draw a dollar's worth of conclusions from a penny's worth of data. Even more amazing to this writer is the certainty and assurance that climatologists have in their conclusions, which are typically based on inadequate data. The most perceptive comment I have found is that of Wunsch (1999):

> "Sometimes there is no alternative to uncertainty except to await the arrival of more and better data."

# Figures

# Tables

# Abbreviations and acronyms

| | |
|---|---|
| AABW | Antarctic Bottom Water |
| ACP | Age Control Point |
| AM | Amplitude Modulated |
| AMO | Atlantic Meridional Overturning |
| AMOC | Atlantic Meridional Overturning Circulation |
| AWS | Automated Weather Station |
| BCE | Before Christian Era |
| C&L | Chylek and Lohmann |
| CAS | Central America Seaway |
| CLIMAP | Climate: Long range Investigation, Mapping, And Prediction project |
| CNES | Centre National d'Etudes Spatiales |
| CRF | Cosmic Ray Flux |
| D-O | Dansgaard-Oeschger event |
| DEW | Distant Early Warning |
| EAIS | East Antarctic Ice Sheet |
| ECM | Electro-conductivity Measurements |
| EDC | Epica Dome C. |
| EDML | EPICA Dronning Maud Land |
| EEM | Previous interglacial period named after the Dutch river |
| ENSO | El Niño–Southern Oscillation |
| EOT | Eocene–Oligocene Transition |
| EPA | Environmental Protection Agency |
| EPICA | European Project for Ice Coring in Antarctica |
| ERBE | Earth Radiation Budget Experiment |
| GCM | Global Climate Model |
| GCR | Galactic Cosmic Ray |
| GICC | Glacial–Interglacial $CO_2$ Cycle |

| | |
|---|---|
| GIGO | Garbage In–Garbage Out |
| GISP | Greenland Ice Sheet Project |
| GISP2 | Greenland Ice Sheet Project 2 (see pp. 113, 137) |
| GRACE | Gravity Recovery and Climate Experiment |
| GRIP | Greenland Ice Core Project |
| GSLR | Global Sea Level Rise |
| GYBP | Billions of years before present |
| H&A | Hargreaves and Annan |
| H&W | Huybers and Wunsch (2004) |
| IPCC | Inter-government Panel on Climate Change |
| IR | InfraRed |
| IRD | Ice Rafted Debris |
| ISI | Information Sciences Institute |
| KYBP | Thousands of years before present |
| L&W | Landwehr and Winograd (2001) |
| LGM | Last Glacial Maximum |
| LIA | Little Ice Age |
| LLS | Laser Light Scattering |
| L&R | Lisiecki and Raymo |
| L&W | Landwehr and Winograd |
| M&M | The book by Richard A. Muller and Gordon J. MacDonald: *Ice Ages and Astronomical Causes*, Wiley/Praxis (2000) |
| M&W | McShane and Wyner |
| MBH | Mann, Bradley, and Hughes |
| MECO | Middle Eocene Climatic Optimum |
| MOC | Meridional Overturning Circulation |
| MPR | Mid-Pleistocene Revolution |
| MPT | Mid-Pleistocene Transition |
| MWP | Medieval Warm Period |
| MYBP | Millions of years before present |
| NADW | North Atlantic Deep Water |
| NASA | National Aeronautical and Space Administration (see p. 370) |
| NGRIP | North Greenland Ice Core Project |
| NH | Northern Hemisphere |
| NHG | Northern Hemisphere Glaciation |
| NOAA | National Oceanic and Atmospheric Administration |
| NSF | National Science Foundation |
| OCO | Orbiting Carbon Observatory |
| OLR | Outgoing Long-wavelength Radiation |
| PAL | Present Atmospheric Level |
| PCA | Principal Component Analysis |
| PDB | Crushed belemnite (*Belemnitella americana*) from the Peedee formation (Cretaceous) in South Carolina |
| PDO | Pacific Decadal Oscillation |
| PETM | Paleocene–Eocene Thermal Maximum |

| | |
|---|---|
| RSL | Relative Sea Level |
| SETI | Search for ExtraTerrestrial Intelligence |
| SH | Southern Hemisphere |
| SMB | Surface Mass Balance |
| SMOW | Standard Mean Ocean Water |
| SOI | Southern Oscillation Index |
| SST | Sea Surface Temperature |
| TIMS | Thermal-Ionization Mass-Spectrometric |
| TOA | Top Of Atmosphere |
| TSI | Total Solar Irradiance |
| UAH | University of Alabama in Huntsville |
| UWESS | University of Washington Earth and Space Sciences Department |
| VEI | Volcano Explosivity Index |
| W&L | Winograd and Landwehr (1993) |
| WAIS | West Antarctic ice sheet |
| WAIS Divide | West Antarctica Ice Sheet Divide |
| WB | Wally Broecker |
| YBP | Years before present |

# 1

# Life and climate in an ice age

What was the global impact of the growth of large ice sheets in the far north during past ice ages? What were the climates of the various continents 20,000 years ago at the height of the Last Glacial Maximum? Why was there a greater diversity of species, higher numbers of animals, more large animals, and larger animals? How did climate changes impact the evolution and migration of humans, animals, and vegetation? These are questions that have been pondered and studied by many researchers. Several scenarios have been put forth. However, it is difficult to draw firm conclusions. All we can do is provide a few fragmentary insights.

## 1.1 CONTINENTAL CLIMATES DURING THE ICE AGE

As we will show in subsequent chapters, based on geological evidence, and data from ice cores and ocean sediments, we know that the Earth was immersed in an ice age over the past ~100,000 years that peaked about 20,000 years ago, began to wane about 15,000 years ago, and ended roughly 10,000 years ago. The immensity of the ice sheets is difficult to comprehend. The maximum volume of the ice sheets—about 18,500 years before the present (YBP)—was about $57 \times 10^6\,km^3$. This huge volume of ice resulted in a lowering of sea level of about 110 m (Zweck and Huybrechts, 2005).[1] Assuming that this ice sheet was built up over ~60,000 years, that would imply that ice was added to the ice sheets at the average rate of about $10^{12}\,m^3$ per year. The lowering of sea level exposed large areas of continental shelves that were (at least initially) barren and susceptible to wind erosion.

Ice core data from Greenland and Antarctica indicate that the atmosphere was heavily laden with dust and salt during periods of high glaciation, suggesting

[1] The removal of water from the oceans was actually about 50 m greater than this because the crust below the ocean rebounded about 50 m when water was removed at the LGM.

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books,
DOI 10.1007/978-3-642-30029-5_1, 

that the world was a stormy place with high winds that whipped up dust from land and salt from oceans. The dustiness would suggest that many areas of the Earth were arid. And indeed, the prevailing view seems to be that the Earth was predominantly arid during ice ages, although some areas, particularly the Southwestern U. S., were extremely wet. Yet, there had to be winds that carried moisture to northern climes in order to drop some $10^{12}$ m$^3$ of ice per year on the growing ice sheets. Since the temperature drop during ice ages at high latitudes was far greater than the temperature drop in the tropics, the temperature differential between the tropics and polar areas was greater during ice ages, creating a greater driving force for flow of atmosphere toward polar areas.

A comparison of the distribution of vegetation for all the continents of the world at the height of the last ice age with the distribution today was provided by Adams and Faure (1997). Their comparison for North and Central America is provided here in Figures 1.1 and 1.2. According to this model, the distribution of flora (and presumably fauna as well) migrated toward the equator during ice ages, and areas adjacent to the ice sheets were converted to tundra and semi-desert. Burroughs (2005) provides a similar flora map of Europe.

Barton *et al.* (2002) provide a window into life, flora, and fauna in North America as the last ice age began to wane:

> "Flying over the ice fields of Canada it is easy to imagine being back in the last Ice Age. There is ice as far as the eye can see. Glaciers roll down the valleys, towering ice sculptures rise out of the mountainsides, and exquisite turquoise pools glisten in the fissures below."

Figure 1.3 shows the Wrangell–Saint Elias ice field on the Alaska–Yukon border. It is the largest non-polar ice field in the world and shows what much of the continent would have looked like at the height of the glaciation around 20,000 years ago. Barton *et al.* (2002) describe this scene as follows:

> "Sheets of ice stretch as far as the eye can see, with strange shell-like patterns scalloped into the surface. Snow clings to mountainsides in great crumbling chunks while in the glaciers below, ultramarine pools glint in the sunlight. Rivers run across this glacial landscape and suddenly disappear through the ice to the valleys below. The ice here is up to 900 m deep and the glaciers move up to 200 m a year as they grind and sculpt the landscape around them."

During the last ice age, glaciers radically changed the north of the continent, leading to the human invasion of North America through the creation of the Bering land bridge. At the peak of the last ice age the land bridge was 1,600 km wide (see Figure 1.4). For the first time since the previous ice age (about 100,000 years prior), animals could travel across the land bridge from Siberia into the North American continent. According to Barton *et al.* (2002):

> "The land bridge was part of a larger ice-free area called Beringia, which

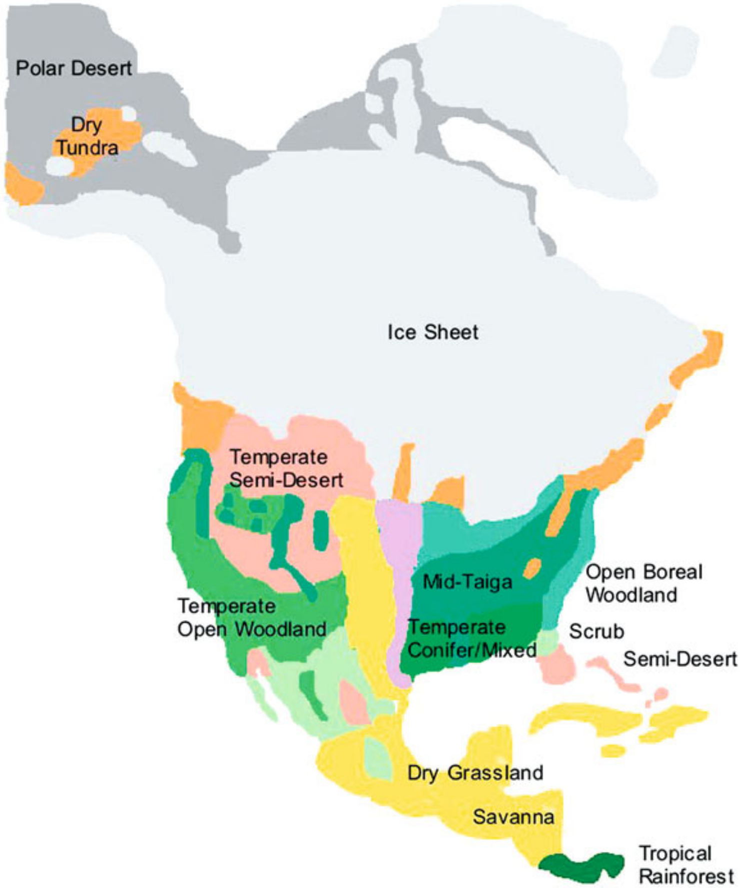


**Figure 1.1.** Distribution of vegetation in North and Central America at the height of the last ice age (Adams and Faure, 1997).

included Siberia, Alaska and parts of the Yukon. Beringia was bounded by the then permanently frozen Arctic Ocean and the continental ice sheets. Rain and snow tended to fall on the high southern ice fields of the Yukon and Alaska, thus reducing the amount that fell on the Beringian side. At the height of glaciation the retreat of the sea meant that most of the land was far from maritime influence and so had an arid, continental climate. The low winter snowfall prevented glaciers from forming and left grass and other vegetation accessible to grazers throughout the winter. This is what made Beringia habitable at a time when much of the land to the south was buried in ice.

As well as creating a dry climate, the ice sheets also made loess—a fine dust produced by the grinding action of the glaciers and deposited on the edge of streams emerging from the ice front. Loess blew across Beringia, establishing a well-draining soil. The result was a land of grassy steppes. An array of tiny plants


**Figure 1.2.** Distribution of vegetation in North and Central America today if there were no agriculture (i.e., conditions circa 500 years ago) (Adams and Faure, 1997).

> including grasses, sedges, herbs, dwarf birch and willow provided a highly nutritious rangeland capable of supporting the [fauna] giants of the past.... This mixture of steppe and tundra plants was unlike the tundra or boggy muskeg found in the region today. Scientists have coined the term 'Mammoth Steppe' (after the enormous herbivore) to describe this unique environment. Some even believe that the grazing action of these massive beasts maintained the grassy landscape, which subsequently disappeared due to the extinction of the megafauna, rather than the other way round. Whatever the reason, Beringia's most impressive inhabitant was of course the woolly mammoth."

Beringia must have been covered with vegetation even during the coldest part of the most recent ice age because it supported large populations of woolly

**Figure 1.3.** The Wrangell–Saint Elias ice field on the Alaska–Yukon border. It is the largest non-polar ice field in the world and shows what much of the continent would have looked like at the height of the glaciation around 20,000 years ago (Barton *et al.*, 2002; reprinted by permission of Random House).

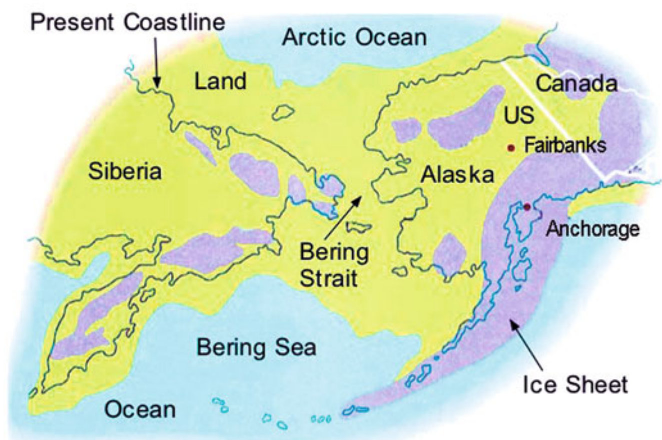


**Figure 1.4.** Beringia—the connecting link between Siberia and Alaska about 18,000 YBP (Barton, *et al.*, 2002; reprinted by permission of Random House).

mammoth, horses, bison, and other mammals. Zazula *et al.* (2003) reported the discovery of macrofossils of prairie sage, bunch grasses, and forbs that are representative of ice age steppe vegetation associated with Pleistocene mammals in eastern Beringia. This vegetation was unlike that found in modern Arctic tundra, which can sustain relatively few mammals, but was instead a productive ecosystem of dry grassland that resembled extant subarctic steppe communities. Evidence was provided that this region might have contained an arid but productive, grass-dominated ecosystem. This mammoth steppe system might have sustained mammalian herds all year round.

According to Barton *et al.* (2002), rainfall in North America was about 50% higher than at present, but most of that rainfall was concentrated in the winters while summers were very dry. They cite the example of the ponderosa pine that requires summer rainfall. It is virtually absent from the fossil record during ice ages. They also cite the absence of the pinyon pine in the fossil record for ice ages. The combination of low temperatures and summer drought is thought to be the cause. Thus, Barton *et al.* (2002) disputed the commonly held belief that the Ice Age was cooler and wetter and that plants simply shifted their distribution by moving south or downwards in elevation. The examples of ponderosa and pinyon pines were cited to support their contention that the differences were far more complex.

Burroughs (2005) shows a map of Australia and New Guinea conjoined as a single continent when the oceans were at their lowest.

Colinvaux (2007) wrote an extraordinary book detailing 50 years of research in an attempt to define the climate of the Amazon region during the past Ice Age. This book begins with an emphasis on the vast difference in the number of species of flora and fauna in the Amazon vs. mid-latitude zones.

The great diversity of species in the tropics:

> "... has long been one of the knottiest problems of ecological theory.... In warmer climates there are more kinds of living things than in the colder north; many, many more kinds. But why should this be? The temptation is to say, 'Obvious! It is nicer in the tropics; more productive; wet and warm; no winter; living is good and lots of species take advantage of it. Next question please.' But that answer is no answer. [There are] lots of living things in Europe and North America, thousands of kinds of animals and plants. The problem is that the wet tropics have more kinds still, many more."

Colinvaux (2007) asserted that the great diversity of flora and fauna in the tropics is not simply explained by its current favorable climate. The impact of ice ages is likely to be related. Mountain ranges in Europe tend to run east–west. As the great ice sheets moved down on Europe during the Ice Age, expanding mountain glaciers moved northward catching the flora and fauna in a "pincer movement". The flora and fauna were prevented from moving southward by the blockade of east–west mountain ranges. Europe never fully expanded its flora and fauna during intervening interglacial periods. By contrast, in North America, mountain ranges tend to run north–south, providing passes for flora and fauna to move southward during ice ages. Nevertheless, North America is endowed with far less diversity than the tropics.

A theory was proposed to account for the huge diversity in the tropics. According to this theory, the climate in the tropics during the Ice Age was arid with far less rainfall than today. As a result of dry conditions over tens of thousands of years, much of the rainforests were transformed to savannas. Only local pockets, here and there, in the tropics stayed wet enough to maintain rainforest conditions. These "refuges" were isolated from one another, and this theory is referred to as the "refuge theory", In order to generate large numbers of new species, it is necessary for species to be isolated to prevent crossbreeding. The refuge theory provided a mechanism for such speciation to take place during ice ages, with consequent spreading of domains during interglacial periods. This theory was widely accepted; however, there was a dearth of data supporting the theory, both in regard to the existence of the putative refuges as well as the belief that the tropics were arid during ice ages.

Colinvaux accepted the refuge theory at first, but he relentlessly went into the Amazon jungles over several decades to seek lake sediments more than 20,000 years old that could provide evidence for the theory. What he found instead was that during the Last Glacial Maximum (about 20,000 years ago) the tropical rainforests persisted; however, they were infused with coniferous trees that do not presently grow in the tropical rainforests. Thus he concluded that the refuge theory was wrong, that tropical rainforests persisted, and the climate change was not aridification, but rather simple cooling. But the cooling was not draconian. The Amazon lowlands were still suitable for most of the species that are common today. But cooling allowed other plants, normally restricted to higher altitudes, to invade the lowlands. Colinvaux estimated the lowering of the mean temperature in the Amazon lowlands to be 4.5°C during the Last Glacial Maximum. However, Colinvaux's viewpoint remains somewhat controversial and his conclusion does not explain the great species diversity in the tropics. Some believe that cooling in the tropics was more like 2°C.

According to Dawson (1992):

> "The presence of extensive sea ice as far south as 40°N to 45°N during winter months drastically reduced moisture evaporation and by cooling the overlying air, resulted in southward extension of high pressure. The formation of a land bridge across the Bering Straits due to lowering of the oceans reduced transfer of warmer water from the Pacific to the Arctic. Summer melt water in the Arctic produced a layer of fresh water that increased salinity stratification and promoted formation of sea ice."

In his classic book, Mithen (2003) describes the world of 20,000 years ago as:

> "... inhospitable, a cold, dry and windy planet with frequent storms and a dust-laden atmosphere. The lower sea level has joined some landmasses together and created extensive coastal plains. Tasmania, Australia and New Guinea are one; so are Borneo, Java and Thailand that form mountain chains within the largest extent of rainforest on planet Earth. The Sahara, Gobi and other sandy deserts are greatly expanded in extent. Britain is no more than a peninsula of

> Europe, its north buried below the ice, its south a polar desert. Much of North America is smothered by a giant dome of ice.''

As a result, Mithen (2003) suggested that human communities were forced to abandon many regions they had inhabited previously while other regions amenable for settlement remained unoccupied because access was blocked by dry desert and ice barriers. People had to survive wherever they could, struggling with freezing temperatures and persistent drought. Burroughs (2005) provides many insights as to how humans survived the ice ages.

The extinction of Neanderthals has been a topic of interest in both scientific discussions and public interest. They lived in western Eurasia until approximately 30,000 years ago, when they disappeared from the fossil record, about 10,000 years after modern humans arrived in Europe for the first time. While competition between these groups is often cited as the cause of Neanderthal demise, it is possible that the Ice Age climate may have played an important role (Finlayson, 2004). Most recently, Kennett *et al.* (2009) found evidence that a comet impact may have induced extinction of species about 12,900 YBP.

## 1.2 THE GLACIAL WORLD—ACCORDING TO WALLY BROECKER

Wally Broecker wrote a treatise on ice age climates. According to Broecker:

> ''Except for the observations made over the last 130 or so years at weather stations and on ships, our knowledge of past climates is based on records kept in sediment and ice. The task of the paleoclimatologist is to decipher the proxies contained in these records. This has proven a complex task for every proxy is influenced by more than one climatic variable. While much progress has been made toward isolating the influence of these competing contributions, the task has proven to be a very tough one. For convenience, these proxies can be divided into five major groups; i.e., those which carry information regarding: 1) ice volume, 2) temperature, 3) aridity, 4) atmospheric composition, and 5) ocean chemistry.''

Broecker went on to say:

> ''Except for high mountain regions, little precise paleotemperature information exists for the continents. The obvious source of such information is the fossil remains of plants and animals. Indeed a wealth of measurements regarding the relative abundances of pollen grains has been collected over the last century. However, the [analysis of] this information has not proven particularly successful. Unlike the sea that is everywhere wet, the topography of the continents strongly influences the availability of water. Plant communities are attuned to these differences in moisture availability. Hence plant communities respond as much to changes in rainfall and humidity as they do to changes in

temperature. Reliable separation of these two influences has proven very difficult. The problem is compounded by the large seasonality in temperature and rainfall. Because of this, two locales with the same mean annual temperature and rainfall may have quite different plant cover. Thus, while in a historical sense pollen abundances have provided very valuable qualitative evidence with regard to changing climates, no means yet exists to convert these results into reliable absolute temperature changes.''

Another problem is that pollen-bearing sediments are found only in lakes and bogs. While providing an excellent record of the post-glacial succession of plants, these lakes and bogs tell us these water bodies had not yet come into existence until after the Ice Age had ended.

Broecker describes efforts to reconstruct precipitation during ice ages as ''an extremely difficult task''. The use of pollen records for this purpose is difficult because of the problem of separating influences of temperature and moisture. An additional problem arises because the $CO_2$ content of the atmosphere was lower during the Ice Age and plants needed more water to take in the $CO_2$ needed for growth. Because of this, a drop in moisture availability suggested by the Ice Age vegetation may not be a valid indicator of Ice Age rainfall because it may reflect in part the atmosphere's low $CO_2$ content. Broecker described the use of the past levels of lakes with closed drainage basins such as the Great Salt Lake, the Dead Sea, and the Caspian Sea as indicators of past rainfall. The water that currently enters these lakes via rain and via rivers must leave by evaporation. Hence, during times of higher rainfall, these lakes expand in area until evaporation matches the enhanced input of water to the lake. Accompanying the expansion in area is a rise in lake level. Thus shorelines marking times when a closed basin lake stood higher record times of greater precipitation. These lakes exist only in desert areas. However, the lake level is likely to be more dependent on precipitation in the neighboring mountains than in the region immediately surrounding the lake. Broecker discusses several complications but concludes: ''despite these complications, the size of closed basin lakes is by far our best paleoprecipitation proxy.'' Finally, Broecker concludes: ''during late glacial time the tropics were less wet and the subtropics less dry than now.''

Nevada's late Ice Age climate was much cooler and wetter than today. The Great Basin's Ice Age was marked by increased precipitation and reduced evaporation, known as a ''pluvial'' climate. This increased stream flow and encouraged lake formation. The Great Basin received its name because rivers and streams which originate in the mountains drain into the basin and end in lakes or sinks within valley bottoms throughout the region. During the Ice Age, the Great Basin region supported two major late Pleistocene pluvial lakes: Lake Lahontan and Lake Bonneville. Lake Bonneville lay almost exclusively in western Utah, and only a small area in eastern Nevada, while Lake Lahontan was mainly restricted to western Nevada. Lake Lahontan reached a maximum depth of over 500 feet and covered over 8,610 square miles.

## 1.3 ICE AGE FORESTS

Bonnicksen (2000) described some of the climatic effects of the great ice sheets in the last ice age. Desert basins in the American Southwest filled with water from heavy rains and meltwater from mountain glaciers, and cold air reduced evaporation. There were more than 100 such freshwater lakes, with the largest being Lake Bonneville in Utah that occupied an area of 19,000 square miles and reached depths up to 300 meters. Even Death Valley, California filled with water. Cold air blew off the sides of the ice sheets at high speed generating gale force winds. In the winter when conditions were dry, these winds produced huge sand and dust storms that blew silt across the central part of America. According to Bonnicksen, Ice Age silt "covers 30% of the U. S. but it lies beneath forests and grasslands."

Bonnicksen provided an elegant description of Ice Age forests. He described the Ice Age as an "alien world of modern and extinct animals living among well-known plants mixed in unusual ways." The territories of cold-weather trees such as spruce, fir, and bristlecone pine spread out during cold periods and contracted when it became warmer. Conversely, warm-weather trees such as oak, hickory, and ponderosa pine spread poleward when the glaciers retreated and moved toward the south when the glaciers expanded. In this process, "the trees shifted and sorted themselves into unique forests while moving around the landscape." The most recent sorting process began when the climate warmed shortly after the Last Glacial Maximum about 18,000 years ago. Prior to that, North America's Ice Age forests endured an uneasy stability for thousands of years. According to Bonnicksen, summers were cooler but differences between seasons were less extreme than today. Exotic mixtures of plants and animals were able to form complex patchworks of communities that had "a greater diversity of species, higher numbers of animals, more large animals, and larger animals than any that existed from then until now. Many of these primeval communities fell apart after the ice sheets melted...."

Bonnicksen described immense tracts of open white spruce forests:

> "The white spruce is a short tree with a thin trunk and low-hanging branches that form a narrow cone of pointed blue-green needles. It grows on relatively dry soils.... Spruce forests grew in a band hundreds of miles wide from the Rocky Mountains to the East Coast. They hugged the southern edge of the tundra and cold steppes at the foot of the glaciers. Occasionally fingers and patches of spruce also protruded into the tundra and worked their way up to the edge of the ice."

As the glaciers expanded, the tree line in the western United States descended by up to 700–800 meters. The continental ice sheets redirected the jet stream southward, causing changes in precipitation patterns. The Puget Sound area became drier while the Southwest benefited from increased rainfall. California's weather became cooler, drier, and more continental. Santa Ana winds also increased, blowing great clouds of sand from the Mojave Desert westward over southern California. However, "California's climate buffered forests from the extreme cold that lay over most of North America during the Ice Age and forests of giant redwoods probably grew along the northern California coast at this time just as they had done for at least the past 5 million years."

Bonnicksen (2000) also described the fauna of the Ice Age:

> "No single plant or animal symbolizes the Ice Age better than the woolly mammoth. It evolved in Eurasia and migrated across the Bering land bridge into North America about one-half million years ago. The smaller and more primitive mastodon, a forest dweller that lived on shrubs and trees, joins the mammoth as a symbol of the Ice Age. Coarse golden-brown hair covered the animal, but it was not as shaggy as the hair of the woolly mammoth. It roamed North America and parts of South America for several million years before the woolly mammoth arrived. Woolly mammoths plodded through cold steppes and tundra in the far north and at the southern edge of the glaciers. They also flourished within the open spruce and pine forests, and the Columbian and Jefferson mammoths lived as far south as northern Florida, southern California, and Central America. Mammoths looked something like a modern elephant. However, instead of rough gray skin, thick brown hairs covered their entire body, even the trunk. A 6-inch woolly undercoat provided additional protection from the cold. Their eyes were like protruding saucers, and their dull white tusks stuck out 12 feet and curled sharply upward. They swung their tusks back and forth to scrape away snow so that they could eat the underlying grass much like bison use their noses for the same purpose. Their ears were small and round, and long hair draped over their dome-shaped heads like a bad toupee. Wide padded feet designed for snow or marshy ground supported the 8-ton weight of the shaggy beasts as they lumbered along in search of food."

He also described other extinct herbivores, such as shrub-ox, stag-moose, 7-foot-long armadillos, and a beaver the size of a black bear, giant ground sloths weighing several tons, western camel, horse, and long-legged and short-legged llamas, a giant condor-like vulture with a 15- to 17-foot wingspan, the dire wolf, saber-toothed cats, the American lion, and the American cheetah. The most terrifying extinct carnivore of all was the giant short-faced bear. It stood as high as a moose and it used its long legs to run swiftly after prey across the tundra and cold steppes. These animals are described further and illustrated by Barton *et al.* (2002).

## 1.4 THE LAST GLACIAL MAXIMUM (LGM)

The Last Glacial Maximum (LGM) refers to the time of maximum extent of the ice sheets during the last glacial period, roughly 20,000 years ago. According to Wikipedia:

"At this time, ice sheets covered the whole of Iceland and all but the southern extremity of the British Isles. Northern Europe was largely covered, the southern boundary passing through Germany and Poland, but not quite joined to the British ice sheet. This ice extended northward to cover Svalbard and Franz Josef Land and eastward to occupy the northern half of the West Siberian Plain, ending at the Taymyr Peninsula, and damming the Ob and Yenisei rivers forming a West Siberian Glacial Lake. In North America, the ice covered essentially all of Canada and extended roughly to the Missouri and Ohio Rivers, and eastward to New York City.

In the Southern Hemisphere, the Patagonian Ice Sheet covered Chile and western Argentina north to about 41 degrees south. Ice sheets also covered Tibet (scientists continue to debate the extent to which the Tibetan Plateau was covered with ice), Baltistan, Ladakh, the Venezuelan Andes and the Andean altiplano. In Africa, the Middle East and Southeast Asia, many smaller mountain glaciers formed, especially in the Atlas, the Bale Mountains, and New Guinea.

Permafrost covered Europe south of the ice sheet down to present-day Szeged and Asia down to Beijing. In North America, latitudinal gradients were so sharp that permafrost did not reach far south of the ice sheets except at high elevations.

The Indonesian islands as Far East as Borneo and Bali were connected to the Asian continent in a landmass called Sundaland. Palawan was also part of Sundaland, while the rest of the Philippine Islands formed one large island separated from the continent only by the Sibutu Passage and the Mindoro Strait. Australia and New Guinea were connected forming Sahulland. Between Sundaland and Sahulland, Wallacea remained islands, though the number and width of water gaps between the two continents were considerably smaller.

In warmer regions of the world, climates at the Last Glacial Maximum were cooler and almost everywhere drier.... Most of the world's deserts expanded. Exceptions were in the American West, where changes in the jet stream brought heavy rain to areas that are now desert and large pluvial lakes formed, the best known being Lake Bonneville in Utah. This also occurred in Afghanistan and Iran where a major lake formed in the Dasht-e Kavir. In Australia, shifting sand dunes covered half the continent, whilst the Chaco and Pampas in South America became similarly dry. Present-day subtropical regions also lost most of their forest cover, notably in eastern Australia, the Atlantic Forest of Brazil, and southern China, where open woodland became dominant due to drier conditions. In northern China—unglaciated despite its cold climate—a mixture of grassland and tundra prevailed, and even here, the northern limit of tree growth was at least twenty degrees further south than today."

Ruddiman (2007) provided an extensive description of the LGM. Only a few excerpts are given here. He emphasized the dustiness during the LGM:

"The ice sheets were prolific producers of debris in all sizes from large boulders to fine clay. Ice sheets grind across the landscape, scraping and dislodging soils and relatively unconsolidated sedimentary rocks. The weight of the ice sheets provides a pressure force that uses debris carried in the bottom layer of ice to grind and gouge out small pieces of even the hardest bedrock. In areas where basal layers of ice alternately freeze and thaw through time, water trickles down into cracks in bedrock when the ice melts and then expands when it freezes again, breaking off large chunks of bedrock. This freeze–thaw process quarries large slabs of bedrock and incorporates them in the ice for further grinding and fragmentation. These and other processes at work in ice sheets erode huge volumes of bedrock debris in all sizes. The ice sheets carry this material out toward their margins and deposit it along their edges, where the ice melts.... Winds then rework these deposits, creating a gradation of grains away from ice margins. The coarsest debris remains in place but strong winds can transport medium to fine sand over short distances. Winds also lift and carry finer silt-sized sediment farther from source regions.... Winds can carry even finer (clay-sized) dust completely around the world. Glacial-age layers in the Greenland ice sheet contain ten times as much fine dust as interglacial layers. Chemical analysis of this dust indicates that the main source region was Asia rather than nearby North America. Dust transport was also greater at lower latitudes during the LGM.''

Ruddiman (2007) also said:

> ''Despite the harshness of this environment, the steppe and tundra supported a diverse population of large mammals, including woolly mammoths and rhinoceroses. It is not clear how the creatures found enough food to survive during the cold winters.''

Ruddiman discussed at length the conflicting views on the climate in the tropics during the LGM. CLIMAP (Climate Long-range Investigation, Mapping, and Prediction) results from ocean sediments indicated that tropical oceans were just 1 to 2°C cooler than today, with a few regions in the Pacific being slightly warmer than today. However, other data suggest much cooler temperatures. Tropical mountain glaciers descended 600 to 1,000 meters, indicating a temperature drop of 4 to 6°C. Tropical vegetation on the flanks of mountains also indicates a larger temperature drop during the LGM. Ruddiman went on to discuss the pros and cons of both sides of the controversy, and concluded that perhaps the ''truth lies somewhere in the middle''.

Mix *et al.* (2001) discussed the terminal climate during the LGM about 20,000 years ago when the ice sheets of the last ice age reached their maximum. As they pointed out, the LGM is important because (as they stated):

- The LGM represents a global climate state dramatically different from that of today, and thus provides a useful test of climate models' sensitivity to change.
- The LGM is reasonably close to an equilibrium state of climate (to the extent that equilibrium is ever obtained in the recent geologic past).

- Primary boundary conditions for the LGM climate, such as continental geography, orbital configurations, and atmospheric $pCO_2$ are well known. Other factors, such as sea level, ice area, and ice sheet heights are reasonably well known.

The CLIMAP project in the early 1970s attempted to describe the state of the Earth at the time of the LGM using all the data available at that time. The CLIMAP project culminated in a series of maps that emphasized seasonal sea surface temperatures, but also included the distribution of ice on land and in the ocean, as well as vegetation and albedo of the land surface.

Mix *et al.* (2001) provided an update to the CLIMAP study based on more recent work, mainly with advanced climate models. Their estimate of sea surface temperatures during the LGM is shown in Figure 1.5.

A number of investigators used climate models to describe the climate at the LGM. Kim *et al.* (2008) and Oglesby and Maasch (2009) provide reviews.

Schneider von Deimling *et al.* (2006) analyzed the LGM using climate models. In their model, they estimated the global distribution of various forcings (change in vegetation, effect of dust, $CO_2$, and ice sheet albedo) at the LGM relative to modern pre-industrial times. Unfortunately, despite a great deal of verbiage in the paper ("... the main glacial forcings are relatively well known"), they did not actually specify their best estimates of the global average forcings for these factors, although they did mention that dust and vegetation were estimated to contribute a total of about 2 W/m$^2$, and the total of all forcings was in the range 8.0 to 8.5 W/m$^2$. This suggests that $CO_2$ and ice sheet albedo were each roughly 3 W/m$^2$ although that was not explicitly stated. Having estimated the forcing, they proceeded to estimate the temperature difference from modern pre-industrial times. For the tropics, they estimated a cooling of 2.7°C and for the global

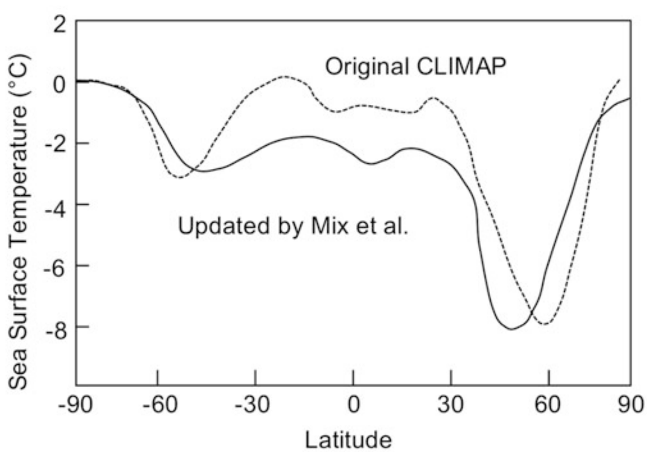


**Figure 1.5.** Estimates of sea surface temperatures during the LGM (Mix *et al.*, 2001; Woillez *et al.* 2011).

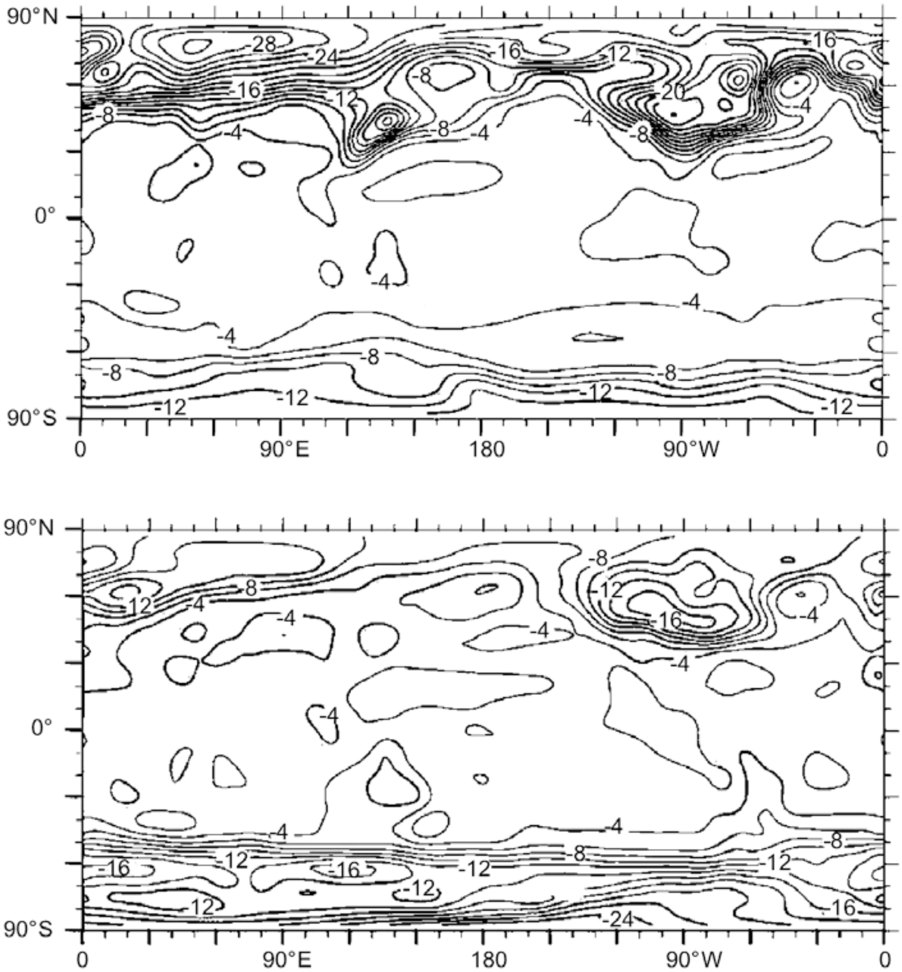


**Figure 1.6.** Estimated temperatures at the LGM relative to recent temperatures. The upper figure is for December–January–February while the lower figure is for June–July–August (Shin *et al.*, 2003).

average, a cooling of 5.9°C. About one quarter of this cooling was attributed to dust and vegetation changes.

Shin *et al.* (2003) analyzed the LGM using a climate model. They found that during northern winter (December–January–February) temperatures over the ice sheet area in Canada and Europe were typically 16 to 20°C colder than current temperatures, while in the tropics, temperatures were typically roughly 4°C colder, and near Antarctica they were about 8°C colder. In northern summer (June–July–August) the inverse occurred with Antarctic temperatures 16 to 20°C colder and Arctic temperatures typically 8°C colder than today. A simplified version of their result is shown in Figure 1.6.

# 2

# Variability of the Earth's climate

## 2.1 FACTORS THAT INFLUENCE GLOBAL CLIMATE

The geothermal gradient delivers about 61.5 $mW/m^2$ from the interior of the Earth to the surface. Since the surface area of the Earth $= 5.1 \times 10^8$ $km^2$, the rate at which energy is released from the interior of the Earth is $3.1 \times 10^{10}$ kW. The solar power that impinges on the Earth is 342 $W/m^2$. If all of this were absorbed, the Earth would receive $1.7 \times 10^{14}$ kW. Actually, only about 70% of the incident solar energy is absorbed by the Earth; nevertheless, the solar input far exceeds that which derives from the interior. Therefore geothermal energy may be ignored in dealing with the heat balance of the Earth.

The Earth is suspended in a vacuum. Hence the only way that it can lose energy is via radiation. The Earth's surface climate derives from a tenuous balance between the rate of solar energy input and the rate at which the Earth loses energy by radiation to space. Since the Earth has a significant heat capacity, it does not respond immediately to changes in solar input or radiant output.

The overall heat balance of the surface of the Earth is dictated by a number of factors. Three important elements are:

- Rate at which solar energy impinges on the Earth.
- Fraction of solar energy reflected by the Earth into space (albedo).
- Effect of greenhouse gases (particularly, water vapor, $CO_2$, and $CH_4$) in the atmosphere in preventing escape of radiation emitted by the Earth.

The rate at which solar energy impinges on the Earth is 342 $W/m^2$ averaged over the whole Earth. A fraction of this (called the albedo) is reflected back into space. Ice and snow have high albedos (0.5 to 0.9) while land ($\sim$0.3) and oceans ($\sim$0.1) have lower albedos. Clouds have an important effect on albedo and the

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presence of clouds tends to reduce differences in net albedo above land and oceans. Albedo is very important in determining the Earth's heat balance. The global average albedo depends on the state of the Earth. During an ice age, it is relatively higher than during an interglacial, due to the reflectivity of ice sheets, and the spreading of sea ice, the extending of mountain glaciers, as well as the fact that the smaller oceans are replaced to some extent by land, and, there are changes in vegetation as well. Averaged over the whole Earth, the present albedo is currently a little over 0.3, so the net solar input to Earth, independent of the greenhouse effect, is about $0.7 \times 342 \sim 239\,\mathrm{W/m^2}$. This net irradiance warms the Earth and, if there were no greenhouse effect, the temperature of the Earth would increase to the point where it would radiate enough energy to just balance this solar input. The average temperature of the Earth would be something of the order of –18°C. All the water on the Earth would freeze, and the resultant high albedo of the ice-covered Earth would further reduce temperatures until the entire Earth became a veritable snowball. In fact, it seems likely that the Earth may have passed through such a snowball state in its distant past.

The presence of greenhouse gases in the atmosphere acts as a barrier to escape of radiant energy emitted by the Earth. Greenhouse gases absorb some of the radiant energy emitted by the Earth, and then reradiate this energy. The transfer of this radiant energy through the atmosphere is highly complex but, ultimately, some of the reradiated energy finds its way into space while the remainder heads downward to Earth. Thus, greenhouse gases act as filters for some parts of the infrared spectrum emitted by Earth, reducing the net flux of radiant energy emitted by the Earth to space. The Earth must then warm until it radiates enough energy to achieve equilibrium.

Water vapor is the most important greenhouse gas. After water vapor, carbon dioxide and methane are the next most important greenhouse gases. A sharp decrease in the concentrations of these gases in the atmosphere could trigger a cooling trend that would be amplified by lowered water vapor pressure and increased albedo as snow and ice spread. Alternatively, an increase in the concentration of greenhouse gases will tend to increase the heat retained by the Earth, leading to global warming. The temperature increase due to an increase in a greenhouse gas concentration depends upon (a) the absorption characteristics of the greenhouse gas (absorption bandwidth and degree of saturation of absorption bands) and (b) concentration of the greenhouse gas. As the concentration of any greenhouse gas increases, the additional warming produced gradually diminishes as the absorption bands become saturated. At present concentrations, the main absorption band of $CO_2$ is quite saturated, and further increases in concentration produce diminishing increases in global temperature due to increased absorption at the edges ("wings") of the absorption band. However, water vapor and methane are not as saturated, and increases in these concentrations produce significant heating. When greenhouse gases produce a warming, secondary effects can act as feedbacks to either further increase the warming or oppose it. Climate models have been used to estimate the warming produced by increasing $CO_2$ concentrations. As the Earth warms, climate models assume that the average humidity in the atmosphere will increase due to the higher vapor pressure of water with increasing temperature. Depending on where the humidity increases, an additional greenhouse effect due to water vapor can amplify the greenhouse effect of rising $CO_2$. Increases in humidity in dry areas will have a much greater effect than humidity increases in humid areas. Climate models tend to make simplistic assumptions in the absence of data on how humidity changes as the Earth warms. Other important feedbacks include clouds, aerosols, wind patterns, ocean currents, and dust. As the water vapor content of the atmosphere increases, more clouds are likely to form. Some clouds may produce a net heating effect via absorption of IR emitted by Earth, while others may produce a cooling effect by reflecting incident solar irradiance out to space. The treatment of clouds remains one of the major uncertainties in climate models.

The concentration of $CO_2$ in the atmosphere is reached as a balance between opposing forces: $CO_2$ is supplied to the atmosphere by emissions from volcanoes and other geological processes. (All of the above is prior to human production of $CO_2$). $CO_2$ is removed from the atmosphere by what is called "silicate rock weathering" which stores the $CO_2$ in $CaCO_3$ (limestone). Rainwater strips out $CO_2$ from the atmosphere, and the rain thereby becomes slightly acidic. The acidified rain reacts with rocks chemically, forming carbonates that store $CO_2$ in the rocks (Walker, 2003). $CO_2$ is also removed by burial of organic matter in sediments.

Over very long geological times, continental drift rearranges the positions of the landmasses on Earth, and, depending on whether the continents are separate or conjoined and also depending on their latitudes, the capability of the land to take up $CO_2$ may increase or decrease. Silicate rock weathering is enhanced by warm wet landmasses. Thus, landmasses located in the tropics enhance uptake of $CO_2$. An additional factor is the placement of the landmasses. If they are conjoined, the humidity in the interior is likely to be low, thus reducing $CO_2$ uptake by the land. Conversely, if the land is distributed as separate bodies with close access to moisture from nearby oceans, $CO_2$ uptake by the land is enhanced. Finally, large eruptions of basalt lava provide a rich source of calcium ions that can readily remove $CO_2$ from the atmosphere to produce $CaCO_3$. Hence, the $CO_2$ concentration in the atmosphere can go through wide variations over geologic time as continental drift rearranges the continents, volcanoes pass through active and passive periods, and occasional large emissions of basalt lava take place. It is likely that variable $CO_2$ concentration has been an important factor in determining the Earth's climate over many millions of years.

Methane is supplied to the atmosphere by microbes (methanogens) that live in poorly drained soils (e.g., tropical wetlands) and in organic-rich sediments below the sea floor. It is removed via oxidation by the oxygen in the air. Methane has a rather short lifetime in today's atmosphere and must be continually replenished or its concentration will fall. In the early Earth prior to about 2.4 billion years ago, the oxygen concentration was very low, so presumably the concentration of methane was higher than today, producing a significant greenhouse effect that counteracted the weaker Sun that prevailed at that time.

Another factor affecting the climate of the Earth is ocean circulation. Ocean currents from the tropical zones toward polar areas transfer heat to higher latitudes, thus helping to prevent the equatorward spread of ice. As this ocean water moves poleward, its density increases due to evaporation and cooling, and the dense brine eventually sinks and returns toward tropical zones at deeper levels. One theory is that this "great ocean conveyor" can on occasion be shut down, leading to increased cooling of high latitudes and expansion of glacial conditions there. This, in turn, produces an increase in global albedo, and ice ages may result. Thornalley *et al.* (2011) found evidence of such shutdowns as the Earth came out of the last ice age. The ocean conveyor is affected by the placement of the continents and the connectivity of the oceans. There is some evidence, for example, that the conveyor changed about 3.2 million years ago when the Isthmus of Panama became closed off, leading to a long series of repeated ice ages and a gradual cooling of the Earth. Spencer Weart asserted that the Earth's climate is largely governed by the oceans, because the main ingredients of climate are not in the Earth's tenuous atmosphere but in the oceans, where the top few meters alone store as much heat energy as the entire atmosphere, and the average depth of the oceans is 3.7 km. Most of the world's water is there too, of course, and even most of the gases, dissolved in the water. However, as Figure 8.4 shows, the atmosphere actually delivers a higher heat flux to high latitudes than the oceans.

If the irradiance of the Sun were to change, that would also affect the Earth's climate. We know that solar irradiance has gradually increased over billions of years but we don't know the degree to which the "solar constant" has been constant over the past few hundred thousand years. Variations in sunspot count and solar cycle period over the past four centuries suggest that solar irradiance may have wavered but there is no definitive analysis.

As the Earth moves in its orbit about the Sun, subtle changes in the orbital characteristics occur over many tens of thousands of years. These changes can affect the yearly input of solar energy to higher latitudes on a secular basis. It is widely believed that the ebb and flow of ice ages is tied to this phenomenon whereby variations in the solar energy input to high latitudes act as "triggers" to initiate feedback mechanisms that produce climate extremes. However, this theory remains difficult to validate exactly.

The biosphere also affects climate by generating greenhouse gases (principally $CO_2$, but also $CH_4$) and by uptaking these gases as part of the natural life/death cycle of the plant kingdom. Land clearing reduces the ability of the biosphere to absorb $CO_2$ and acts as a virtual source of $CO_2$.

Hence, variations in the Earth's climate are due to many (sometimes conflicting and opposing) factors, some of which provide positive feedback to enhance trends, once started. Understanding climate variations is very challenging because it is difficult to separate out and quantify the various contributing factors.

The Earth has gone through incredibly wide climate changes over hundreds of millions of years. A number of factors contributed including a gradually strengthening Sun, drift of continents, incidence of volcanism, etc. But it is widely believed that the Earth's thermostat was controlled mainly by prevailing $CO_2$ concentrations in the tug-of-war between $CO_2$ emissions and $CO_2$ burial. Thus, over geological time, variability of $CO_2$ is believed to be the main controller of the Earth's climate. For example, 500 million years ago, the $CO_2$ concentration was some 20 times greater than it is today and the Earth was very balmy. There is little doubt that if we again increased $CO_2$ to 20 times the pre-industrial value most of the Earth would become tropical. The question before us now is how the Earth's climate will respond to a much smaller increase in $CO_2$: a mere doubling from 280 to 560 ppm?

## 2.2 STABLE EXTREMES OF THE EARTH'S CLIMATE

Solar energy input to the Earth is the principal driving force that determines the Earth's climate. This input is controlled by the Earth's albedo. The overall average albedo of the Earth is determined by the amount and geographical distribution of land, sea, and snow/ice across the globe. Over very long time periods, continental drift has reorganized the landmasses on Earth. Since the greatest amount of solar radiant input is to the tropics and water has the lowest albedo, in ancient times when there was not much landmass in tropical zones the Earth would have absorbed a significantly higher proportion of solar irradiance and would have become much warmer as a result. Conversely, it is possible that the Earth may have gone through very cold periods in which the high albedo of snow and ice caused positive feedback that spread the ice and snow until the entire Earth became sheathed in snow and ice.

As nuclear fusion progresses with time in the Sun, the conversion of hydrogen to helium increases the mean molecular weight and reduces the number of particles. Increased gravitational energy is then converted to heat. The increase in central temperature and pressure results in an increase in the rate of generation of energy as the Sun evolves. Models for evolution of the Sun from its early beginning indicate that solar luminosity has risen steadily over the past ~4.5 billion years from about 70% of its present value.

If the composition of the Earth's atmosphere in antiquity had been the same as today, the Earth's mean surface temperature would have been below the freezing point of water before 2 GYBP and global glaciation would have been the likely result.

The earliest rock records from western Greenland, dated approximately 3.8 GYBP, provide a record of waterborne processes of erosion, transport, and sedimentation. Liquid water must have existed at least locally. The earliest record of glaciation is 2.7 GYBP. The temperature sensitivities of the diversity of life since 3.8 GYBP are additional evidence for moderate temperatures. This diverse life would be difficult to imagine on a frozen Earth. Despite the lack of Archaean climatic data, the absence of ice with a substantially reduced solar luminosity presents a well-posed problem for climate modeling. This problem has been termed the "faint young Sun paradox" (Gough, 1981).

Sagan and Mullen (1972) showed that, for an early Earth with an emissivity of 0.9 and an albedo of 0.35, the faint young Sun would produce a frozen Earth prior to 2.3 GYBP. They suggested that the discrepancy between the Archaean record and their model requires changes in atmospheric composition with a strong greenhouse effect to counteract the weak Sun. They rejected $CO_2$ abundance because the strongest absorption bands are nearly saturated; however, they did not consider extremely high $CO_2$ concentrations. They suggested that the answer might lie in enhanced concentrations of reducing gases such as methane and ammonia.

However, the paradox only occurs if one assumes that the composition of Earth's atmosphere has remained constant. Kasting (1993) claimed that the paradox disappears if either the Earth's albedo was lower in the past or the atmospheric greenhouse effect was larger, or some combination of the two. The argument given by Kasting is based mainly on the presumption of extremely high $CO_2$ concentrations in the primitive atmosphere. In terms of the *present atmospheric level* (PAL) of $CO_2$ (between 300 and 400 ppm), Kasting suggested that the $CO_2$ concentration may have been >300 PAL on the early Earth, fading down to perhaps 10 PAL at about 0.6 GYBP. However, he said: "These predictions are entirely theoretical: There are no reliable paleo-$CO_2$ indicators that would allow them to be tested empirically." Others have postulated $CO_2$ concentrations as high as 30 bar ($10^5$ PAL).

In a later paper, Kasting (1997) commented on Sagan and Chyba (1997) who revived the discussion of "how liquid water was maintained on early Earth and Mars despite a solar luminosity 25 to 30% lower than that at present." He pointed out that "geochemical constraints on early atmospheric $CO_2$ abundances fall well below the levels needed to warm the surface." Other greenhouse gases ($NH_3$ and $CH_4$) have been proposed but they too lead to problems.

Veizer (2005) claimed that $CO_2$ atmospheric concentrations up to 10,000 times greater than today's value are at odds with the geologic record. Such high partial pressures of carbon dioxide would reduce seawater pH, and therefore

> "... ancient limestones would be enriched in $^{18}O$ relative to their younger counterparts, yet the secular trend that we observe in the geologic record shows exactly the opposite. Factors more complex than a massive $CO_2$ greenhouse would have to be invoked to explain the warming of this planet to temperatures that may have surpassed those of the present day. A plausible alternative is a change in the cloud cover ... bringing forward again the role of cosmic ray flux (CRF) as the potential solution. Considering that young stars of the same category as our sun would have been characterized by a stronger solar wind that muted the CRF, the resulting reduction in cloudiness may have compensated for the sun's reduced luminosity."

If the Earth ever enters a warm state where the polar ice is all melted and the glaciers are all gone, it can remain in that state for a long period because (a) the global albedo will be minimized due to the absence of ice and snow, (b) when the polar ice is all melted, the oceans will cover additional landmasses, thus reducing global albedo further, (c) the water vapor concentration will be high due to the fact that the vapor pressure of water increases with temperature, enhancing the greenhouse effect (although the effect of clouds is difficult to evaluate), and (d) globally warm conditions are likely to increase emissions of greenhouse gases $CO_2$ and $CH_4$ from deposits on land and sea (as evidenced by past variations in greenhouse gas concentrations across ice age–interglacial transitions).

Therefore, if the Earth can enter a *hothouse Earth* state where the polar ice is all melted and greenhouse gas concentrations are high, it could conceivably remain that way stably for some time. Only a drop in greenhouse gas concentrations would restore polar ice. Geological evidence suggests that during the Cambrian period (about 570 to 510 million years ago) the Earth was a hothouse with essentially no polar or high-altitude glaciers. It is conjectured that there were much higher concentrations of greenhouse gases in the atmosphere compared with the present day. During this period, most of the continents as we know them today were either underwater or part of the so-called Gondwana "supercontinent." The oceans were all interconnected, bringing warm water to polar areas. About 85% or more of the Earth's surface was covered with water (compared with approximately 70% at present) and there was a lack of significant topographic relief. Chemical weathering was at a minimum because the landmasses were minimal and they were all conjoined. Toward the end of the Cambrian period, this supercontinent began to break up—dispersing the landmasses—and the greenhouse gas concentration dropped markedly, leading to a cooling trend.

The theory of *snowball Earth* first originated when Harland and Ruddick (1964) observed that glacial deposits from ~600 MYBP were widely distributed on almost every continent. Magnetic orientation of mineral grains in these glacial deposits indicated that the continents were clustered together near the equator in this era. They therefore suggested that there might have been a great global ice age at the time.

Around the same time that Harland publicized his theory, Budyko (1969) developed a mathematical energy–climate model that explained how tropical glaciers could form. Budyko estimated that if Earth's climate were to cool, and ice were to form at lower latitudes, the planetary albedo would rise at a faster rate because there is more surface area per degree of latitude as one approaches the Equator (Hoffman and Schrag, 2002). It was found that at the critical latitude of 30° north or south, the positive feedback became overwhelming, and once having passed through 30° the freeze becomes irreversible, yielding an entirely frozen Earth.

Walker (2003) published a book that provides an excellent summary of the scientific rationale for snowball Earth, if one can get past the interminable descriptions of the personalities of the players and the travelog descriptions of geological localities that are interspersed with the science. First, why might a snowball Earth occur at all? Walker (2003) pointed out that magnetic traces in rocks suggest that at the time period suggested for snowball Earth, the continents drifted into a band near the Equator. As Walker emphasized: "tropics soak up most of the heat that arrives on Earth from the Sun. Because land is more reflective than ocean, putting all available land in the tropics could reflect more of the incoming sunlight, and help the planet to cool." Walker provided an additional argument. The concentration of $CO_2$ has an important effect on global climate. This concentration is reached as an equilibrium between sources (volcanoes) and sinks (burial of carbonates in rocks). When there are continents at fairly high latitudes, they act in opposition to the spread of ice toward the equator because as the ice spreads southward, it covers land and removes that land from the realm that acquires $CO_2$ into carbonate rocks. As a result, the $CO_2$ concentration in the atmosphere builds up and the ensuing warming counteracts the further spreading of ice. When the continents are grouped around the Equator, this effect will not oppose southward spreading of ice as the Earth cools. Whether this qualitative argument can be backed up by convincing quantitative analysis remains unclear. Budyko's analysis (as well as several other more recent studies) suggests that a snowball Earth or at least a *slushball Earth* may be theoretically possible.

A good deal of Walker's book is concerned with the efforts of several geologists to find evidence that a snowball Earth actually occurred. She points out how rocks transported by ice are distinguished, either by uniform scratches or by their anomalous placement. When the theory of continental drift was established, some argued that these rocks might have been deposited when their continents had been in polar regions, thus contradicting the snowball Earth hypothesis. However, when rocks are formed, they often carry a magnetic signature that is horizontal near the Equator and vertical at high latitudes, following the field lines of the Earth's magnetic field. The evidence from many ice-deposited rocks indicated that they were equatorial in origin.

Next, the question arises that if the snowball Earth formed, how did it disappear? The answer provided by Kirschvink (1992) is that during a global glaciation, shifting tectonic plates would continue to build volcanoes and supply the atmosphere with carbon dioxide that would leak out into the atmosphere through fissures in the ice. If the Earth were completely frozen over, the processes that remove carbon dioxide from the atmosphere via acid rain forming carbonate rocks would essentially cease, allowing carbon dioxide to build up in the atmosphere to extremely high levels. Eventually, this would produce so much heating that it would reverse a snowball Earth. Once melting begins, the ice–albedo feedback would be reversed and this, combined with the extreme greenhouse atmosphere, would drive surface temperatures rapidly upward. The warming would proceed rapidly because the change in albedo begins in the tropics, where solar irradiance and surface area are maximal. With the resumption of evaporation, the addition of water vapor to the atmosphere would add dramatically to the greenhouse effect. $CO_2$ would remain in the atmosphere for many thousands of years. Calculations cited by Hoffman and Schrag (2002) suggest that tropical sea surface temperatures would reach almost 50°C in the aftermath of a snowball Earth, driving an intense hydrologic cycle. Sea ice hundreds of meters thick globally would disappear within a few hundred years.

Another intriguing aspect of a snowball Earth is the question of how life survived through this period. Another related question is whether the rapid trans-

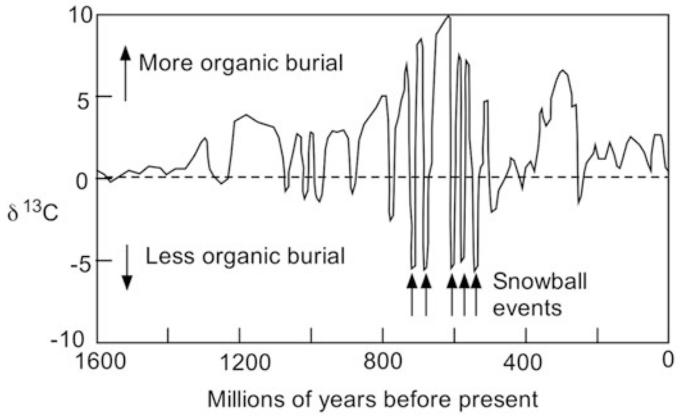



**Figure 2.1.** Variation in carbon isotope composition of shallow marine carbonates with $\delta^{13}C$ measured in ‰ (i.e., parts per 1,000; Purdy, 2003).

formation of one-celled life to multi-celled life that occurred soon after the snowball Earth was coincidental or a byproduct of snowball Earth. As Walker pointed out, when life is flourishing, ocean water and the carbonates that it produces are enriched in $^{13}C/^{12}C$ compared with periods when life is less extensive. Kerr (2000) provided a commentary on the theory of snowball Earth. As Hoffman and Schrag (2002) have explained, carbon supplied to the oceans and atmosphere from outgassing of carbon dioxide by volcanoes contains about 1% $^{13}C$ and 99% $^{12}C$. Carbon is removed by the burial of calcium carbonate in the oceans, in addition to terrestrial removal by silicate weathering. If removal by burial of calcium carbonate in the oceans were the only process in effect, calcium carbonate would have the same $^{13}C/^{12}C$ ratio as the volcanic output, but carbon is also removed from the ocean in the form of organic matter, and organic carbon is depleted in $^{13}C$ (2.5% less than in calcium carbonate; Purdy, 2003). In a snowball Earth scenario, snowball events should drastically decrease the levels of biological productivity. This drop in biological productivity should trigger decreased levels of $^{13}C$ in sediments. Figure 2.1 shows several periods of extremely low $^{13}C$ in the era near 600 MYBP.

Schrag *et al.* (2002) discussed the possible role of methane in the pre-glacial buildup of $^{13}C$ during the snowball era.

The website *http://www.snowballearth.org* provides a good summary of data and theory regarding putative snowball states of the Earth. Macdonald *et al.* (2010) found new evidence that sea ice extended to the Equator 716.5 million years ago, supporting the theory that a snowball Earth event occurred at that time.

Another possible explanation for snowball Earth is that the Earth may have undergone a larger tilt for a short time, thus cooling the equator while warming polar areas. However, no credible mechanism has been offered for how the Earth's tilt could change so remarkably in a short time.

Kasting and Ackerman (1986) investigated whether a runaway greenhouse could have occurred on the early Earth. A runaway greenhouse was defined "as an atmosphere in which water is present entirely as steam or clouds; no oceans or lakes are present at the surface." They concluded that the Earth is "apparently stable against the development of a runaway greenhouse." Their models indicated that as the $CO_2$ pressure is increased up to $\sim$100 bar (about 300,000 PAL) the temperature of the Earth reaches about 233°C, the water vapor pressure rises to about 29 bar, and the atmospheric pressure is about 130 bar. Since 233°C is lower than the boiling point of water at 130 bar, the oceans would not boil but would remain as high-temperature liquids under high pressure. If the early Earth had a pressure of 10 to 20 bar of $CO_2$, the oceans would have been even more stable at 85 to 110°C with a vapor pressure of 0.6 to 1.5 bar, which is far less than the atmospheric pressure.

While it may be comforting to know that the Earth will not go through a runaway greenhouse in which the oceans boil, nevertheless, oceans at 233°C with an atmospheric pressure of 130 bar are somewhat challenging to the imagination!

## 2.3 THE RELATION BETWEEN ANCIENT CLIMATES AND $CO_2$ CONCENTRATION

### 2.3.1 Background

The current holy grail of climatology is to seek an estimate of how much the global average temperature will increase if the $CO_2$ concentration doubles from the pre-industrial value of 280 ppm to 560 ppm. Attempts to estimate this directly are difficult due to uncertainties in secondary factors that accompany warming from increased $CO_2$ (humidity, cloudiness, winds, ocean currents, glaciers, ice sheets, etc.). Some climatologists have sought to estimate the dependence of the climate on $CO_2$ concentration by analyzing paleoclimatic data on climate and $CO_2$ concentration, with the intent of using the climate sensitivity derived from this to estimate the global average temperature increase if the $CO_2$ concentration doubles from the pre-industrial value of about 280 ppm.

Over the past couple of million years in which we have had alternating ice ages and interglacials, there is fairly good evidence that the trigger to set the cycles in motion is solar input to higher northern latitudes. But what does it mean to set the cycle in motion? Presumably, it means that an albedo effect begins in the $\sim$60°N latitude range as snow and ice accumulate, causing a regional cooling. As the ice sheet builds, sea ice expands, and the ocean drops, other albedo effects occur and a greater regional cooling takes place. Dust is stirred up and this further amplifies the cooling. Then as the cooling spreads, the $CO_2$ concentration in the atmosphere decreases, producing additional negative forcing worldwide, which lowers the worldwide temperature. However, changes in humidity and cloudiness are unknown and may be very large factors. At the height of the Last Glacial Maximum (LGM) some 20,000 years ago, the negative forcing produced a global average temperature decrease of roughly 4.5°C. Hansen and Sato (2011), Chylek and Lohmann (2008), and Kohler *et al.* (2009) all independently estimated the forcing at the LGM (see Table 2.2 on p. 33). The contribution of the diminution of $CO_2$ at the LGM to total cooling was estimated by these studies to be in the range 16% to 33%. While it seems likely that solar input to higher latitudes triggered the cycles, the variability of $CO_2$ concentration is believed to have played a part in determining the extremity of the temperature cycle that resulted from this trigger. The changes in $CO_2$ concentration between glacial maxima and interglacials (~180 to ~280 ppm) are well documented in ice core records, although no one seems to have a satisfactory explanation for why the $CO_2$ concentration changed this much (simple solubility in the oceans does not suffice). However, the estimates of forcings, particularly due to dust, vary considerably from investigator to investigator and it is difficult to pin down climate sensitivity to $CO_2$ change. There are reasonably good estimates available of the global average temperature and the $CO_2$ concentration at the LGM 20,000 years ago, and if these data are compared with values in the pre-industrial era (a few hundred years ago) one can thereby estimate the sensitivity of the climate to $CO_2$ concentration over the range ~180 to ~280 ppm. Using this estimated climate sensitivity, one can then estimate the global average temperature rise in going from 280 to 560 ppm. Various investigators have come up with a range of projections. It is noteworthy that the estimates for the real world $\Delta T_G$ due to doubling $CO_2$ from 280 to 560 ppm range from ~1 to ~3°C. However, these estimates do not take into account possible differences in humidity and cloudiness.

Over much longer time periods (up to 540 million years ago) the evidence from benthic sediments (and other geological evidence as well) indicates that there have been periods of great warmth with no glaciation at all on Earth, with occasional periods when the Earth was heavily glaciated. The widely held view amongst geologists and climatologists alike is that the primary cause of these climate changes was variability of $CO_2$ concentration due to long-term imbalances between $CO_2$ degassing at spreading centers and the conversion of atmospheric $CO_2$ to mineral carbon through long-term silicate weathering and oceanic carbonate formation. The argument goes (more or less): "If it wasn't $CO_2$, what else could it have been?" Foster *et al.* (2009) described this as the "accepted paradigm" that requires global temperature to vary in unison with $CO_2$. So, paleoclimatologists have been trying for decades to establish a relationship between climate and $CO_2$ concentration over many millions of years. The more audacious of these have attempted to establish a quantitative relationship between climate and $CO_2$ concentration in order to try to estimate Earth system climate sensitivity. Unfortunately, the proxy data for $CO_2$ over many millions of years are very widely scattered and the results are equivocal. There is a general tendency for warmer climates to be associated with higher $CO_2$ concentrations, but this mainly relates to very large temperature excursions, and even then there are many exceptions. The supposed one-to-one correspondence between $CO_2$ and climate is fuzzy and sometimes contrary. Evidently, other factors than $CO_2$ must also influence the climate. In his "Perspective" article, Ruddiman (2010) emphasized that there is no present explanation for the fact that there was no significant drop in $CO_2$ concentration over the past 22 million years while the climate cooled substantially. Nevertheless, it is noteworthy that many paleoclimatologists are so convinced from the start that $CO_2$ is the main driver of long-term climate change that, even with noisy data, they claim support for their theory. Royer (2010) began his commentary with the statement:

> "Global temperatures have covaried with atmospheric carbon dioxide ($CO_2$) over the last 450 million years of Earth's history."

It is noteworthy that prior to 2004, a number of climatologists pointed out discrepancies between the geological records of climate and $CO_2$ over 500 million years, whereas after 2004, most published papers emphasized the correlation of climate and $CO_2$ over that period. It is not clear whether new data makes the difference, or whether it is now necessary to support orthodoxy to obtain research funding. Our conclusion here is that $CO_2$ is probably an important factor in long-term climate change, but other factors are also influential such as the placement of the continents on Earth, the functionality of ocean currents, worldwide distribution of clouds and aerosols, the past history of the climate, the orientation of the Earth's orbit relative to the Sun, the luminosity of the Sun, the presence of aerosols in the atmosphere, volcanic action, land clearing, biological evolution, etc. Hence, there is probably no single curve relating global average temperature to $CO_2$ concentration, but rather, a set of curves that depend on the above factors.

From the limited accuracy of analyses of ancient climates conducted so far, we still cannot pin down the expected $\Delta T_G$ due to doubling $CO_2$ from 280 to 560 ppm very precisely, but the rough indication from the LGM is that it may be in the range 1 to 3°C. The merit of these estimates is highly questionable.

### 2.3.2 Introduction

One of the most pressing issues of our time is the possibility that rising $CO_2$ concentrations in the atmosphere might lead to significant global warming in the future that could produce deleterious impacts on humankind. Hence, the relationship between $CO_2$ concentration and climate has become a very central and critical scientific issue. However, in addition to being a scientific issue, rising $CO_2$ has also become a political issue as well. This is due to several factors:

(1) In the process of consuming fossil fuels, cement production, and other industrial activities, the world produces large amounts of $CO_2$. If the world continues in a business-as-usual scenario, $CO_2$ production will continue to rise in the 21st century, leading to higher $CO_2$ concentrations in the atmosphere. The potential cure for too much $CO_2$ requires a draconian change in the way that energy is generated and used by the world, and this change may not be technically feasible and, even if it turns out to be technically feasible, it will likely be extremely costly. Indeed, it is possible that it may not be possible to provide the people of the world

with energy to run the industrialized world if $CO_2$ emissions must be cut as dramatically as alarmists claim.

(2) A significant number of climatologists have adopted an "alarmist" view in which they believe that continuation of business-as-usual energy policies in the 21st century will be disastrous to humankind. Many of them have voiced this viewpoint via the Internet, meetings, and media. Furthermore, this bias has crept into scientific publications published in peer review journals. A smaller number of climatologists have been skeptical of the certainty expressed by alarmists. Liberal politicians have been swayed by alarmists into enacting severe constraints on future $CO_2$ emissions. These constraints require that by such-and-such a future year, we must emit considerably less $CO_2$. It is not clear that these constraints can be met technically or financially. Indeed, the benchmark used by several governments is an 80% reduction in $CO_2$ emissions by 2050—a goal that almost certainly cannot and will not be met. Conservative politicians tend to lean toward the skeptical view.[1]

(3) Quite a few prominent climatologists in their zeal to save the world from overheating (and possibly to secure more funding for climate research) have engaged in unprofessional activities in an attempt to exclude skeptics from science publications. They have also manipulated data to exaggerate the threat of rising $CO_2$ and they have presented their results in a biased and one-sided manner. Some have prevented others from checking their results by holding their data in secret. In many cases, they have drawn conclusions from sparse and noisy data, yet made bold claims of certainty in their conclusions. The exposure of these shenanigans has hurt their credibility in some quarters; nevertheless, science questions remain regarding the impact of rising $CO_2$.

(4) Under the auspices of the United Nations, the *Inter-government Panel on Climate Change* (IPCC) has been co-opted by alarmists regarding the effect of $CO_2$ on climate, and they have widely promulgated the belief that "the debate is over" regarding the impact of rising $CO_2$, yet considerable uncertainty remains in all the issues.

Characterizing the Earth's climate is not a simple matter. The common approach taken by contemporary climatologists is to characterize the complex climate of the Earth using a single global average temperature ($T_G$) of the Earth's surface. During the past ~120 years, direct temperature measurements have been made over a network of stations on land, and at sea via buckets or intakes on ships. Climatologists have attempted to average these to estimate $T_G$. However, there are limitations to such procedures that are discussed in detail in Rapp (2008). Nevertheless, we can state with some confidence that the Earth has warmed on average, roughly 0.7°C over the past 120 years, albeit not continuously

[1] Governments have not been clear whether this means an 80% reduction from present emission levels or an 80% reduction from that expected on the basis of a business-as-usual scenario. If, as seems likely, it is an 80% reduction from present levels, that is equivalent to approximately an 88% reduction from a business-as-usual scenario.

and not uniformly over all regions. Most of the warming occurred in the higher northern latitudes. Warming has not been in lockstep with rising $CO_2$ levels.

Climatologists have also attempted to estimate $T_G$ using proxies over geological time periods as long as hundreds of millions of years. Proxies are indirect indicators of past temperature based on some natural process that occurred in the past that was dependent on temperature. Many proxies have been proposed and utilized. The proxies that are of the greatest value in estimating global temperatures over tens or hundred of millions of years are oxygen isotope ratios in benthic ocean sediments in which the $^{18}O$ concentration is an inverse measure of $T_G$. While the conversion of the direct signal $\delta^{18}O$ to $T_G$ is only approximate, the $\delta^{18}O$ measurements appear to be reliable and we have rough estimates of how $T_G$ varied over the past 500 million years, even though absolute values are less certain.

Believing that every effect has a cause or causes, climatologists have searched for possible causes of these long-term climate changes and inevitably, after eliminating all other candidates, they have assumed that variability of $CO_2$ concentration was the major factor that caused long-term climate changes over many millions of years:

> "The major transitions between climatic icehouse and greenhouse conditions are ultimately most probably driven by the deep Earth processes of plate tectonics, as a function of the long-term balance between $CO_2$ degassing at spreading centers and the conversion of atmospheric $CO_2$ to mineral carbon through long-term silicate weathering and oceanic carbonate formation" (NAS, 2011).

The argument goes (more or less): "If it wasn't $CO_2$, what else could it have been?" This argument has some merit. We can estimate from first principles the heating effect that rising $CO_2$ will produce in the atmosphere. If that was the only thing that occurred—that is, only the $CO_2$ concentration changed and no secondary effects took place—we would be able to predict the effect of changing $CO_2$ with some precision. The problem is that other effects do take place as a consequence of the climate changes induced by changing $CO_2$, such as changes in humidity, cloudiness, winds, ocean currents, land cover, ice sheets and glaciers, etc., and these secondary changes may be of greater magnitude than the original stimulus of $CO_2$ change, and they are very difficult to predict.

While the current principal interest is in the climate change induced in the 21st century by increasing the $CO_2$ concentration from 280 to 560 ppm, multiple efforts by many climatologists cannot seem to overcome the uncertainties inherent in performing this analysis, and their models still lack credibility and consistency. It has therefore occurred to several climatologists that perhaps by studying the past (tens of thousands of years ago to hundreds of millions of years ago) and finding relationships between $CO_2$ and climate during those periods, they might be able to obtain real world data on how climate and $CO_2$ are connected. This real world data will presumably have built into it all the secondary processes that take place.

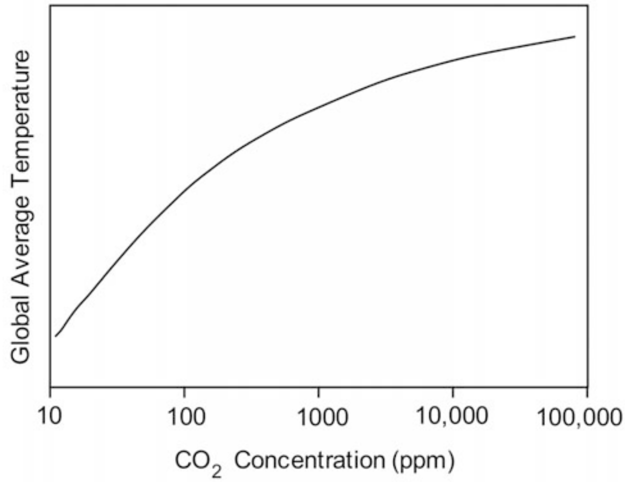



**Figure 2.2.** Hypothetical single curve relating $T_G$ to $CO_2$ concentration.

For example, we have good data on $CO_2$ concentration during the Last Glacial Maximum, some 20,000 years ago, so that is one important historical point for further study. In addition, there are also a variety of estimates of $CO_2$ concentration that go back as far as 500 million years, but unfortunately such data are very scattered and do not appear to be very reliable. But, climatologists are a sturdy lot, and they are willing to derive a dollar's worth of conclusions from a penny's worth of data.

What we seek is a relationship between $CO_2$ concentration and the Earth's climate over long geological periods during which the $CO_2$ concentration varied over a wide range. There is evidence that the $CO_2$ concentration may have been well over 20,000 ppm in the distant past, and it has been as low as $\sim$180 ppm only 20,000 years ago. It would be very nice if there were a single curve relating $T_G$ to $CO_2$ concentration such as that shown in Figure 2.2. In that case, if we could find several points on the curve, we could attempt to map out a good portion of the curve.

However, over long time periods, the variation of $T_G$ with $CO_2$ concentration depends on various factors such as the placement of the continents on Earth, the functionality of ocean currents, the past history of the climate, the orientation of the Earth's orbit relative to the Sun, the luminosity of the Sun, the presence of aerosols in the atmosphere, volcanic action, land clearing, biological evolution, etc. Hence, there is probably no single curve relating $T_G$ to $CO_2$ concentration but, rather, a set of curves that depend on the above factors (see Figure 2.3).

Over the past few million years, the Earth has vacillated between alternating ice ages and interglacial periods, probably driven by variations in the Earth's orbit about the Sun, accompanied by variations in $CO_2$ concentration and other global and regional changes. Over the past $\sim$10,000 years (the Holocene), the Earth has been in a relatively quiescent interglacial period with only moderate variations in

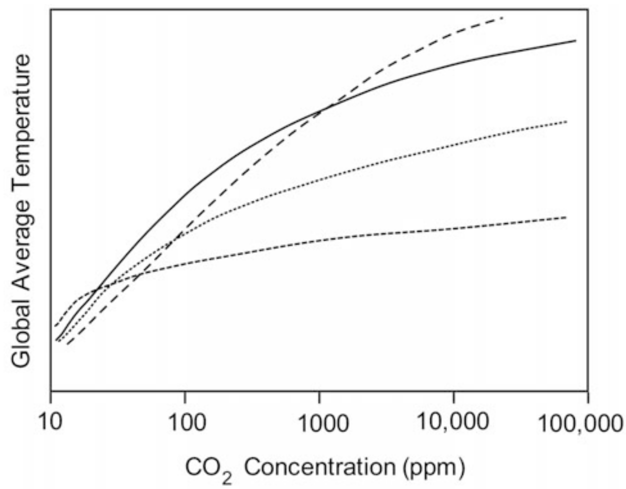



**Figure 2.3.** Hypothetical curves relating $T_G$ to $CO_2$ concentration.

climate. There is a tendency amongst the public, and even amongst many climatologists, to downplay variations within this relatively stable period and consider the climate during this limited period to be relatively constant and "normal". There is evidence that the $CO_2$ concentration remained in the range 270 to 290 ppm during the Holocene, and variations in $T_G$ for the most part were probably less than $\pm 1^\circ$C. With the advent of the industrial age, power plants, cement production, and other industrial activity spewed out more $CO_2$ than the Earth could absorb, and the $CO_2$ concentration rose steadily in the 20th century, recently reaching about 395 ppm. Depending on future world consumption of fossil fuels and energy policy, the $CO_2$ concentration appears poised to grow in the 21st century, and may reach some level in the range ~500 to ~800 ppm by year 2100. There is little doubt that this will produce further warming of the climate, but how much? Climatologists have selected a benchmark of a doubling of the pre-industrial level (280 ppm to ~560 ppm) as the standard basis for estimating the future rise in $T_G$. The holy grail of climatology is thus to seek an estimate of how $T_G$ varies with $CO_2$ concentration over the range 280–560 ppm. To put this in perspective, we show this range in Figure 2.4. Not only do we not know *a priori* which curve applies to our present situation, but the vertical slice of greatest interest is a very narrow one in the total scheme of things.

Climatologists have mainly concentrated on the realm of $CO_2$ concentration between 280 and 560 ppm, with some concern for higher concentrations up to ~900 ppm. In this regard, we can magnify the gray slice from Figure 2.4, and combine this with known values of $T_G$ over the past ~120 years, as shown in Figure 2.5. Curves 1 to 4 show various estimates of the temperature rise that will be induced by further increases in $CO_2$ concentration.

The estimates of temperature rise due to increasing $CO_2$ concentration shown in Figure 2.5 ultimately depend on the following analysis. If we start with the pre-

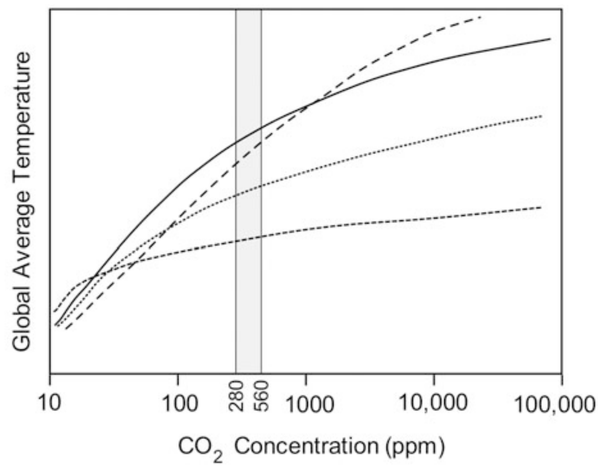



**Figure 2.4.** Range of $CO_2$ concentration (280–560 ppm) for 21st century climate change (gray slice).

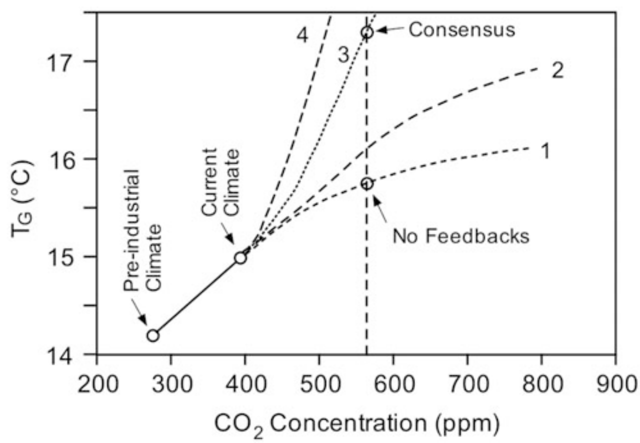



**Figure 2.5.** Variation of $T_G$ with $CO_2$ concentration.

industrial climate ($T_G \sim 14.3°C$ and $CO_2 \sim 280$ ppm) and allow the $CO_2$ concentration to increase with no other changes to the Earth, we can calculate the additional absorption of upward IR radiation emitted by the Earth due to increased $CO_2$ concentration, and thereby estimate from the laws of radiant heat transfer, how much the Earth needs to warm in order to establish a new equilibrium whereby incident heat input from the Sun is counterbalanced by heat radiated by the Earth to space. This calculation has been carried out, and it is widely accepted that if feedbacks are neglected an increase in $CO_2$ concentration from 280 to 560 ppm would increase $T_G$ by roughly 1.2°C.[2] This is represented by curve 1 in Figure 5.2.

As the Earth warms due to increasing $CO_2$, various secondary processes take place. Additional evaporation from bodies of water will tend to increase the humidity of the atmosphere, ice sheets (with their high reflectivity of sunlight) will shrink, cloudiness might increase or decrease in some regions, aerosol concentrations might vary in unknown ways, precipitation patterns will vary, ocean currents may change somewhat, and other changes may take place in the Earth's biota. These so-called feedback processes will also affect $T_G$. There is considerable uncertainty in the magnitude (and, in the case of cloudiness, even the sign) of such feedback effects and, as a result, there have been many diverse estimates of $T_G$ due to a doubling of $CO_2$ when feedbacks are included. Some of these are shown in Figure 2.5 as curves 2, 3, and 4. Curve 3 represents a rough estimate that has been adopted as a consensus by climatologists of the alarmist persuasion. Some skeptical climatologists believe that the truth lies nearer to curves 1 and 2.

It is not our purpose herein to review the many estimates of warming due to an increase in $CO_2$ concentration from 280 to 560 ppm. Rapp (2008) reviews much of this literature. Instead, we are concerned here with the broader picture as shown in Figure 2.4. Can we somehow estimate the shape of the broad curve of $T_G$ vs. $CO_2$ concentration over a very wide range of $CO_2$ concentration and, thereby, find where this curve passes through the gray region in Figure 2.4? Therefore, our intent is to review the literature on the broad dependence of $T_G$ on $CO_2$ concentration over a very wide range of $CO_2$ concentration over geologic time spans.

A few comments of caution need to be made at this point. One comment is that if feedbacks prove to be as amplifying as the consensus would advocate, this would indicate that the effect of $CO_2$ on climate is greatly changed by secondary factors, and the use of data and models from hundreds of millions of years ago may produce misleading results since we may currently be on a very different curve in Figure 2.4 than they were a few hundred million years ago. Of particular importance in this regard is the arrangement of the continents. In addition, the Sun was some 6% reduced in intensity 500 million years ago. These, and other changes, add uncertainty as to whether such data can properly be extrapolated to the 21st century. Another comment is that proxies for $T_G$ and $CO_2$ concentration over geologic time spans are not likely to be very accurate, and these should be critically reviewed before relying on them. As Zeebe (2011) said:

> "By studying the relationship between greenhouse gas forcings and global

[2] This estimate derives from two factors. The forcing due to the change in $CO_2$ concentration from 280 to 560 ppm is estimated to be about 4 W/m$^2$ based on spectroscopic absorption of outgoing IR emitted by the Earth (see Figure 2.8). If the Earth acts as a blackbody with feedbacks neglected, climate sensitivity is calculated to be about 0.3°C/(W/m$^2$). The product of these two numbers is 1.2°C.

temperature changes during past climate episodes, palaeoclimatology currently has a unique opportunity to fundamentally contribute to understanding climate sensitivity. At present, one of the standard tools for estimating climate sensitivity is the use of numerical climate models. Unfortunately, model-derived climate sensitivities are subject to large uncertainties .... Studying past climates to estimate climate sensitivity inarguably has one great advantage over theoretical computer models: it is based on actual data. Unfortunately, palaeo data-derived climate sensitivities have large uncertainties as well. Errors can arise from issues such as dating, alteration of the climate signal after deposition, insufficient spatial and/or temporal coverage, and various uncertainties associated with the proxies for environmental variables such as temperature and past atmospheric $CO_2$ concentrations."

Climatologists use two different definitions of climate sensitivity. The *political definition* is the temperature rise ($\Delta T_G$) in the 21st century resulting from doubling $CO_2$ from the pre-industrial level of ~280 ppm. The *scientific definition* is the temperature rise ($\Delta T_G$) resulting from a forcing of 1 W/m$^2$ at the top of the atmosphere. The scientific definition is applicable for both short- and long-term periods.

It is common for paleoclimatologists to distinguish between two different types of *political climate sensitivity*: *fast feedback sensitivity* and *Earth system sensitivity* (Royer *et al.*, 2011; Zeebe, 2011). The former includes "water vapor, clouds, snow, and sea ice" operating on timescales of less than 100 years, whereas the latter includes these fast feedbacks as well as longer term "changes in non-$CO_2$ greenhouse gases, vegetation, dust/aerosols, ice sheets, ocean circulation, marine productivity, weathering and more" (Zeebe, 2011). Climate models are aimed at estimating the temperature rise due to doubling $CO_2$ from the pre-industrial level of ~280 ppm during the 21st century, and thus deal with the political fast feedback sensitivity. However, consider this hypothetical scenario. Suppose climate models indicate that doubling $CO_2$ in the 21st century will produce an increase in $T_G$ of $X$ degrees (we need not specify $X$, except that it is a relatively large number). Suppose further (as some climatologists believe) that this temperature increase will gradually erode the ice sheets on Greenland and to some extent Antarctica, and produce other long-term effects that will be manifested well after the 21st century. These changes will add further warming leading to a higher long-term political Earth system sensitivity than the short-term political fast feedback sensitivity. However, *scientific climate sensitivity* is the same in both eras. The only thing that changes from the short term to the long term is the magnitude of the forcing.

Royer *et al.* (2011) provide a list of previous attempts to estimate the long-term political Earth system sensitivity from paleoclimatic data on climate and $CO_2$ levels. In the present chapter, I have attempted to provide insights and assessment of various models for paleoclimatic estimates of scientific climate sensitivity.

### 2.3.3 The transition from the Last Glacial Maximum (LGM) to the pre-industrial era

A fundamental dictum in climatology is that the Earth's climate does not change arbitrarily and capriciously but, rather, as a consequence of changes in its heat balance caused by either external changes such as changes in the Sun's power output, changes in the Earth's orbit around the Sun, changes in the Earth's surface producing changes in albedo, and changes in the atmosphere, principally greenhouse gas concentrations. Each of these potential changes is described by an equivalent "forcing" which is a hypothetical heat flux uniformly distributed across the spherical Earth, measured in W/m$^2$. According to this dictum, the Earth will only settle into an equilibrium climate when there is no net forcing and the heat flux radiated out from the top of the atmosphere balances the solar heat input to the Earth's surface. When a change takes place, producing a net forcing, the Earth will respond by warming or cooling (depending on the sign of the forcing) until a new radiative balance is achieved. There is also a possibility of self-induced climate change due to internal variability such as changes in ocean flows and winds that may produce internal feedbacks resulting in climate change. These changes are generally thought to be smaller than the major climate changes of the past such as ice age–interglacial transitions, and the great cooling that took place since about 50 million years ago. Over time spans of millions of years, or even tens of thousands of years, the Earth's climate will have time to reach a series of quasi-equilibrium states in response to forcings. Over short periods such as decades, the Earth may lag in its response to forcings, or the effect of forcings may be hidden by short-term fluctuations due to various feedbacks or internal fluctuations.

About 20,000 years ago, the most recent ice age was at its maximum extent with gigantic ice sheets in the higher latitudes of the Northern Hemisphere. There is reliable evidence from ice cores that the $CO_2$ concentration at that time was roughly 170–180 ppm. The first question is what was $T_G$ at the LGM?

Dwyer *et al.* (1995) utilized the ratio of magnesium to calcium (Mg/Ca) in fossil ostracods from Deep Sea Drilling Project Site 607 in the deep North Atlantic to infer that bottom water temperature changed by $\sim$4.5°C in going from the LGM to pre-industrial times.

According to Leroux (2005), the difference in temperature between an ice age and an interglacial was about 10°C in the Antarctic and about 6°C globally.

Taylor *et al.* (2001) carried out an analysis in which they took into account the reduced $CO_2$ concentration and the extended ice sheets of the LGM in climate models to estimate the amount of global average cooling at the LGM compared with pre-industrial times. Using six different climate models, they obtained values of 3.5, 3.7, 3.8, 4.4, 5.2, and 5.9, for an average of 4.4°C.

Crucifix (2006) provided a less optimistic view of the precision to which this is known: "The global temperature change is therefore estimated to be comprised between 3°C and 9°C with 95% confidence." He also estimated that the tropical ocean sea surface temperature decreased between 1.7 and 2.7°C, and Antarctic

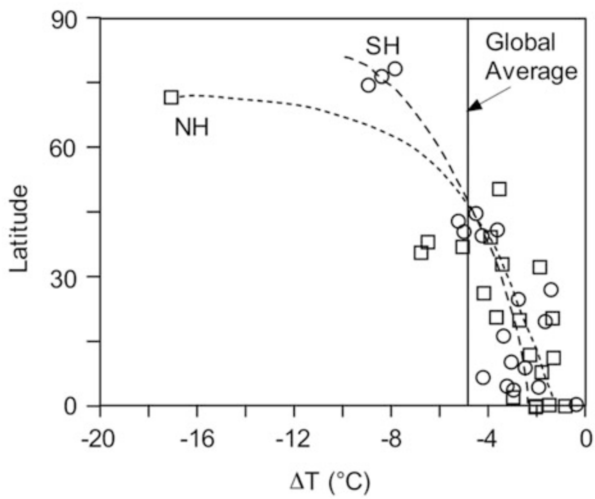



**Figure 2.6.** Variation of $\Delta T_G$ with latitude (adapted from Shakun and Carlson, 2010).

surface air temperature decreased by 7 to 11°C at the LGM compared with pre-industrial times.

In addition, Schneider von Deimling *et al.* (2006) estimated a global cooling of 5.9°C during the LGM and a total of all forcings in the range 8.0 to 8.5 $W/m^2$.

Shakun and Carlson (2010) carried out an extensive review of the LGM–interglacial transition. They found, as would be expected, that the $\Delta T$ in this transition varied with latitude as shown in Figure 2.6. Their estimate of $\Delta T_G$ (the temperature at the LGM minus the pre-industrial temperature) was −4.5°C. If we couple the temperature during the LGM (14.3°C − 4.5°C = 9.8°C) with an estimated $CO_2$ concentration of 170–180 ppm, we can plot a point representing the LGM, as shown in Figure 2.7.

Hansen and Sato (2011) estimated $\Delta T_G$ as follows. Estimates exist for deep-sea temperature over the past 70 million years, as shown in Figure 2.7. While oxygen isotope data clearly indicate a cooling trend, converting oxygen isotope data to temperature is a tricky (and uncertain) matter. Hansen and Sato (2011) relied heavily on the paper by Zachos *et al.* (2001), but Zachos *et al.* mainly presented oxygen isotope data, and only obliquely and briefly tacked on temperature to their graph. Hansen and Sato (2011) adopted their temperature scale, as shown in Figure 2.7, but no indication was provided by either Zachos *et al.* or Hansen and Sato as to how these temperatures were derived, or what the uncertainty is in the estimates. Basically, the plot in Figure 2.7 represents the isotope ratio. Zachos *et al.* interpreted the first part of the curve (prior to about 34 million years ago) as defining an equivalent deep-sea temperature. After that date, variable amounts of buildup of ice, initially in Antarctica, and most recently in Greenland, distorted the isotope ratios, and only part of the observed isotope ratio can be attributed to temperature change. Hansen and Sato pointed out that when there is heavy glacia-

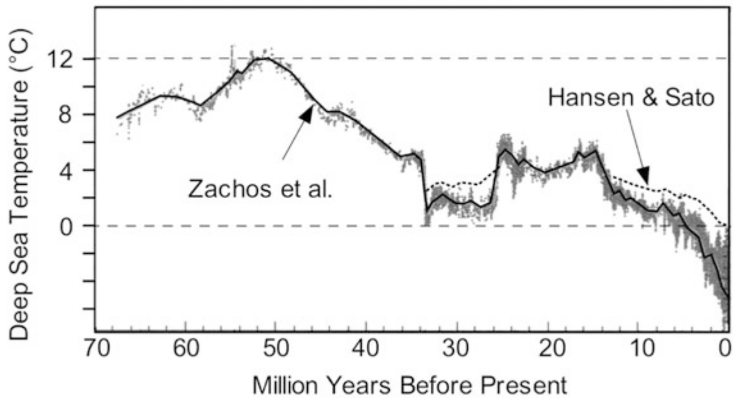



**Figure 2.7.** Estimated mean deep-sea temperature change over the past ~60 million years. The curve marked Zachos *et al.* (2001) includes the effects of ice buildup, while the curve marked Hansen and Sato is attributed only to deep-sea temperature change.

tion at Antarctica and Greenland, the isotope ratios in sediments are partly due to deep-ocean temperature change and partly due to the isotope effect in evaporation as ice sheets form. They assumed that half of the isotope ratio was due to temperature change during the last ~35 million years.

Given Hansen and Sato's rough estimate of deep-ocean temperature change over the past ~50 million years, they raised the question of the relation of deep-ocean temperature change to global mean surface temperature change. Here, they developed an argument that makes some sense, but is quite subjective and not nearly as ironclad as they implied. Their argument was:

> "Deep ocean temperature depends on sea surface temperature at high latitudes in winter, the location and season at which surface water is most dense and sinks to the deep ocean. This leads us to infer that deep ocean temperature change is a useful approximation of global mean surface temperature change on millennial time scales. This fortuitous result is a consequence of substantial offset between the two principal factors that would make temperature change at the sites of deep-water formation differ from global mean surface temperature change. First, temperature change at high latitudes is amplified relative to global mean temperature change. But, second, temperature change is smaller over ocean than over land. These two competing factors substantially offset one another. Both of these tendencies (polar temperature change amplification and ocean versus land temperature change diminution) are present in observational data and models, and are well understood."

First of all, it is not clear that the notion of a single global average temperature has much utility. Second, while it may well be true that deep-ocean temperatures are related to global average temperatures, it is by no means clear

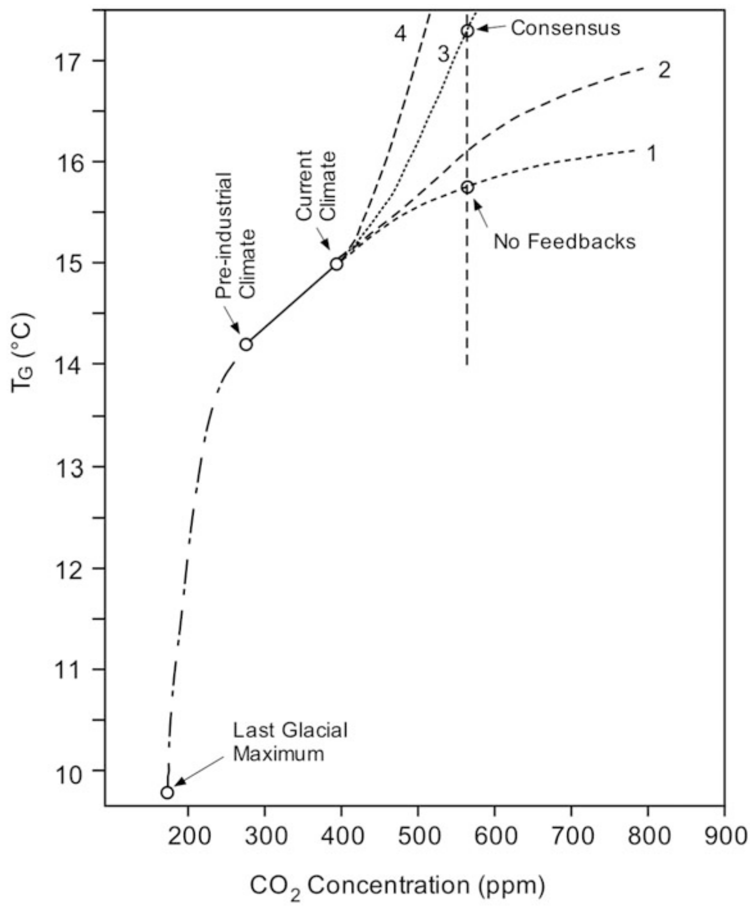



**Figure 2.8.** Inclusion of LGM point in relationship between $CO_2$ concentration and $T_G$.

that "deep ocean temperature change is a useful approximation of global mean surface temperature change on millennial time scales." Third, Hansen and Sato's claim that the amplification at high latitudes is balanced by smaller temperature rises over the ocean may not be correct quantitatively, even though these do operate in opposite directions. Hence, Hansen and Sato made assertions that are not backed up by data.

Hansen and Sato (2011) added the caveat that "deep ocean temperature change becomes less representative of global surface temperature change as the ocean temperature approaches the freezing point of water, because the deep ocean temperature is limited by the freezing point while the global mean surface can continue to cool." They then asserted without proof that over the past half million years or so, as deep-ocean temperatures approached the freezing point, "the amplitude of recent glacial–interglacial deep ocean temperature change is only about two-thirds the amplitude of global mean surface temperature change." It is not clear how they arrived at the 2/3 figure.

Hansen and Sato (2011) interpreted oxygen isotope data in deep-sea sediments to infer deep-ocean temperatures, and then asserted that these were representative of global average temperatures except when the deep-sea temperature approached the freezing point of water, whereupon the change in deep-sea temperature was assumed to represent only 2/3 of the change in global average temperature. Then, using Dwyer's estimate that bottom waters were ~4.5°C colder during the LGM, Hansen and Sato arrived at an estimate of 6.8°C for $\Delta T_G$ based on the 2/3 rule (see Figure 2.8).

The reason the LGM point lies so low is important changes took place on the surface of the Earth as the ice sheets expanded. These changes go beyond the purely spectroscopic effect of less absorption of IR by $CO_2$ in the atmosphere as the $CO_2$ concentration was lowered to below 200 ppm. The growth of large ice sheets from recent pre-industrial times to the LGM resulted in an increase in the Earth's albedo across the ice sheets, as well as for mountain glaciers. In addition, the drop in sea level moved shorelines outward, converting ocean to land, thereby further increasing the Earth's albedo. As the climate got colder, biomass and vegetation grew less abundantly, increasing the Earth's albedo still further. Undoubtedly, there were other effects as well (humidity, cloudiness, dust, etc.).

Hansen and Sato (2011) estimated the various forcings in the past, present, and future, as well as the Earth's response to a forcing. The Earth's response is expressed as climate sensitivity: °C change in average global temperature per unit change in forcing (W/m$^2$). This assumes that a single term, average global temperature, captures a description of the Earth's climate, whereas many different climate distributions across regions could conceivably lead to the same average global temperature. In some cases, direct data are available. In many cases, however, direct data are not available and Hansen and Sato (2011) utilized various models, assumptions, and inferences to derive approximate estimates of key quantities. They seems to adopt these estimates as if they were factual, which they are not. Hansen and Sato (2011) evidently believe that the long-term thermostatic regulator of the Earth's climate is the $CO_2$ concentration in the atmosphere. The balance between volcanic emissions (and, more recently, emissions due to human industrial activity) and absorption by surface carbon reservoirs (atmosphere, ocean, soil, and biosphere) determines net atmospheric composition.

Hansen and Sato (2011) carried out an analysis in which they attempted to utilize the data relating the LGM to pre-industrial times as a basis for estimating the temperature rise in going from pre-industrial times to a doubling of the $CO_2$ concentration (from 280 to 560 ppm).

According to Hansen and Sato (2011), based on Hansen *et al.* (2008), the transition between the LGM and pre-industrial times can be characterized by two major sources of forcing:

- Changes in concentration of greenhouse gases (about 75% due to $CO_2$).
- Surface changes such as ice sheet area, vegetation distribution, and shoreline movements.

Their estimates for greenhouse gas forcings were 2.25 W/m$^2$ for $CO_2$ (185 → 275 ppm), 0.43 W/m$^2$ for $CH_4$ (350 → 675 ppb) and 0.32 W/m$^2$ for $N_2O$ (200 → 270 ppb) for a total greenhouse gas forcing of 3.0 W/m$^2$. They also estimated the forcing due to surface albedo changes to be 3.5 W/m$^2$, but this estimate appears to be rather approximate. Nevertheless, they argued that a total negative forcing of 6.5 W/m$^2$ would bring about the LGM–pre-industrial transition. They assumed that the $\Delta T_G$ associated with this transition was 5°C. In that case, the Earth's scientific climate sensitivity would be:

$$\lambda = \Delta T_G/(\text{Forcing}) = 5.0/6.5 \sim 0.75^\circ\text{C}/(\text{W/m}^2).$$

There are several problems with this calculation.

One problem is that the estimate of the forcing due to greenhouse gases appears to be a bit low. According to Hansen's papers, the forcings due to various levels of $CO_2$ (without feedbacks) are as shown in Figure 2.9. In Figure 2.9, vertical lines represent:

A = typical $CO_2$ at glacial maximum in an ice age

B = typical $CO_2$ during an interglacial period between ice ages

C = current $CO_2$ level due to human impact on environment

D = $CO_2$ level after it doubles compared with pre-industrial levels.

The estimated forcings are shown as vertical double arrows:

F1 = forcing in the transition from a glacial maximum to an interglacial period (~3 W/m$^2$)

F2 = forcing due to $CO_2$ rise from before the industrial period to the present (~2 W/m$^2$). (Note that according to these calculations, the rise in $CO_2$ from pre-industrial times to the present has already produced about half the forcing that will result from doubling $CO_2$ from pre-industrial times.)

F3 = forcing due to change from pre-industrial levels to doubled $CO_2$ (~3.7 W/m$^2$).

Thus the forcing due to $CO_2$ is not 2.25 W/m$^2$ (as claimed), but 3 W/m$^2$, and the total forcing due to all greenhouse gases is not 3.0 W/m$^2$ (as claimed), but 3.7 W/m$^2$.

Another problem is that Hansen and Sato used $\Delta T_G = 5.0^\circ$C, whereas 4.5°C appears to be a better choice.

In addition, Hansen and Sato did not appear to adequately consider the forcing due to high dust levels in the atmosphere during the LGM. One estimate is that dust would produce a forcing of about 1 W/m$^2$ (Crucifix, 2006). It is also noteworthy that Bielefeld (1997) estimated that at the height of the last ice age (18,000 YBP) global radiation absorption was lower by 7–10% than it is today. That would indicate a negative forcing of 24 to 34 W/m$^2$, which is far greater than

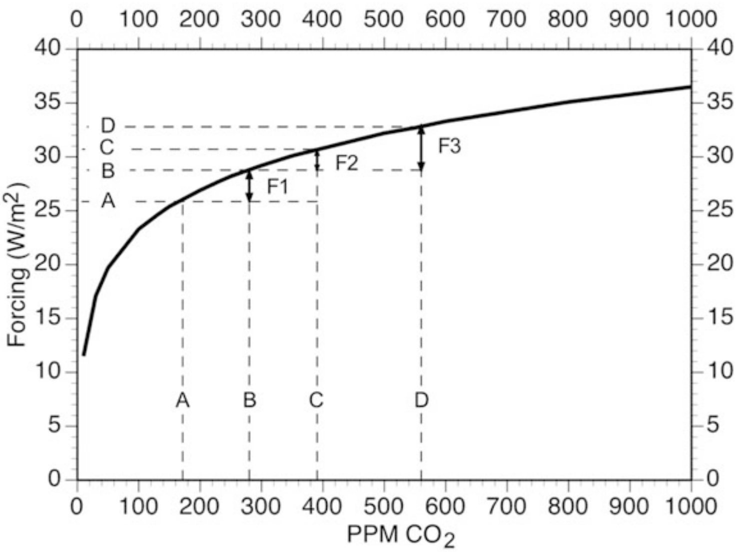



**Figure 2.9.** Forcings due to various levels of $CO_2$ concentration.

other estimates. Another concern is that no consideration was taken of possible changes in humidity or cloudiness.

If we modify Hansen and Sato's estimate by taking the forcing as $8.2\,W/m^2$ (instead of $6.5\,W/m^2$), and if we choose $\Delta T_G = 4.5°C$ instead of 5.0°C, we obtain:

$$\lambda = \Delta T/(\text{Forcing}) = 4.5/8.2 \sim 0.55°\text{C}/(\text{W/m}^2).$$

Hansen and Sato used their value for climate sensitivity ($0.75°C/(W/m^2)$) in conjunction with the forcing due to doubling of the $CO_2$ concentration (from 280 to 560 ppm): $3.7\,W/m^2$ (see Figure 2.8) to obtain $\Delta T_G \sim 3.0°C$ for a doubling of the $CO_2$ concentration. With the lower value of $\lambda$, one would obtain 2.2°C.

Crucifix (2006) provided alternate estimates of the forcings:

- Change in sea level and vegetation changes ($\sim 4\,W/m^2$)
- Reduction of greenhouse gas concentrations ($\sim 2.85\,W/m^2$)
- Other forcings, difficult to quantify, such as increased dust concentration ($\sim 1\,W/m^2$).

This sums to $7.85\,W/m^2$, but Crucifix added: "There is also a small contribution due to the surface being, on average, more elevated than today", which might bring the total close to the value $8.2\,W/m^2$ previously estimated. Crucifix felt that the value of $\lambda$ could not be pinned down well, primarily because of uncertainty in $\Delta T_G$. He attempted to use climate models to bridge this gap, but concluded: "... the ratio between LGM and $CO_2$ feedback factors cannot be accurately estimated from current state-of-the-art coupled models."

Chylek and Lohmann (2008) carried out an independent estimate of climate

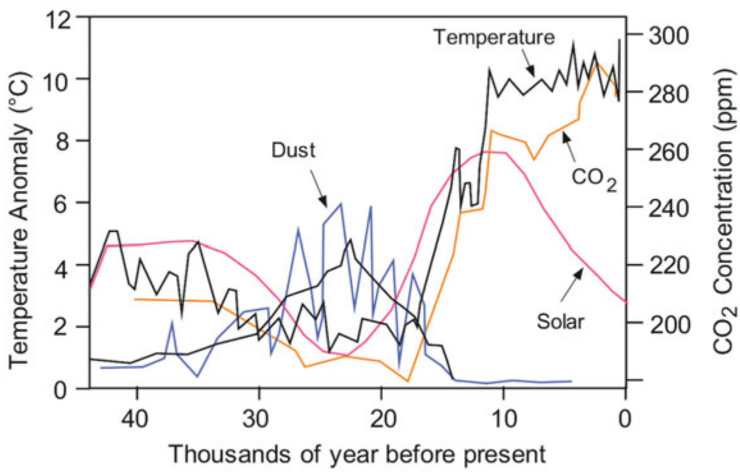



**Figure 2.10.** Smoothed data from the Vostok ice core. The dust and solar scales are arbitrary. The solar curve represents midsummer solar intensity at 65°N (adapted from C&L).

sensitivity by comparing the LGM with pre-industrial times. They asserted: "One of the uncertainties in the radiative forcing calculation during the LGM to the Holocene transition is the radiative forcing due to increased aerosol optical depth during the peak of the last ice age." In their analysis they used the LGM to pre-industrial transition and the cooling period between the warm period around 42,000 YBP and the LGM to deduce the change in aerosol radiative forcing and to estimate climate sensitivity. It was assumed that climate sensitivity was the same for both periods.

Chylek and Lohmann (2008) (C&L) utilized data from the Vostok ice core for transitions between two time periods:

(i) Warm period around 42,000 years ago ⇒ LGM (about 20,000 years ago)
(ii) LGM ⇒ pre-industrial period (about 200 years ago).

The smoothed data from the Vostok ice core used by C&L are shown in Figure 2.10.

Based on these data, C&L estimated temperature differences and forcing due to greenhouse gases as shown in Table 2.1.

The radiative forcing due to surface albedo changes (extent of ice sheets, sea ice and snow cover, exposure of new land in a low sea level state, change in surface characteristics and vegetation cover) for the LGM ⇒ pre-industrial transition was estimated to be roughly 3.5 W/m$^2$, but C&L used a range of values from 3.0 to 4.0 W/m$^2$.

C&L pointed out that the dust measurements in the Vostok ice core suggested that aerosol concentration differences from 42 KYBP to the LGM were about 53/58 as great as aerosol differences from pre-industrial time to the LGM. However,

**Table 2.1.** Parameters used by C&L.

| | $CO_2$ (ppm) | $CH_4$ (ppb) | $\Delta T$ (°C) | *Forcing via GHG* ($W/m^2$) |
|---|---|---|---|---|
| 42,000 years ago | 209 | 548 | | |
| LGM | 182 | 340 | | |
| Pre-industrial | 285 | 667 | | |
| 42,000 ⇒ LGM | | | $2.16 \pm 0.23$ | 0.93 |
| LGM ⇒ pre-industrial | | | $4.6 \pm 0.5$ | 2.67 |

they were not able to attribute forcings to these changes *a priori*. They assumed that the forcing due to aerosols were $58X$ and $53X$ for the LGM ⇒ pre-industrial, and 42,000 years ago ⇒ LGM transitions, respectively, but $X$ could not be specified *a priori*. In order to estimate the forcing due to aerosols, C&L carried out a comparison of the two transitions, assuming that the relation between $\Delta T_G$ and total forcing was the same for both transitions. Thus, they put

$$\frac{\Delta T_1}{F_{\mathrm{GHG1}} + F_{\mathrm{Alb1}} + F_{\mathrm{Aer1}}} = \frac{\Delta T_2}{F_{\mathrm{GHG2}} + F_{\mathrm{Alb2}} + F_{\mathrm{Aer2}}}$$

in which transition (1) refers to LGM ⇒ pre-industrial, and transition (2) refers to 42,000 years ago ⇒ LGM. Their estimates for $\Delta T_1$ and $\Delta T_2$ and $F_{\mathrm{GHG1}}$ and $F_{\mathrm{GHG2}}$ are given in Table 2.1. Their estimate for $F_{\mathrm{Alb1}}$ was $3.5\,\mathrm{W/m^2}$, but they did not seem to specify what they used for $F_{\mathrm{Alb2}}$. If $F_{\mathrm{Alb2}}$ is known and setting $F_{\mathrm{Aer1}} = 58X$ and $F_{\mathrm{Aer2}} = 53X$, the above equation provides a means to estimate $X$. C&L reported that their best estimate for $X$ was $0.056\,\mathrm{W/m^2}$. Working backwards, we may surmise that they must have used $F_{\mathrm{Alb2}} = 1.58\,\mathrm{W/m^2}$. Using the above value for $X$, they estimated the total forcing for the LGM ⇒ pre-industrial to be $2.67 + 3.5 + 58 \times 0.056 = 9.4\,\mathrm{W/m^2}$ and, with $\Delta T_1 = 4.6°\mathrm{C}$, climate sensitivity is $\lambda = 4.6/9.4 \sim 0.5°\mathrm{C/(W/m^2)}$. This implies that when $CO_2$ goes from ~280 to ~560 ppm, the expected temperature rise is $0.5 \times 3.7 \sim 1.8°\mathrm{C}$. C&L also examined prior glacial to interglacial transitions and, from this, estimated slightly higher values for $\lambda$. However, they pointed out:

> "At this time it is not clear whether these higher sensitivities, compared to the climate sensitivity deduced from the LGM to Holocene transition, really reflect higher climate sensitivity at the time of the considered climate transitions or whether they are artifacts due to imperfect ice core data and uncertainties in the used approximations."

The main difference between the calculations of C&L and Hansen and Sato is the much higher values of aerosol forcing used by C&L. As in the case of Hansen and Sato, C&L did not consider changes in humidity or cloudiness.

Hargreaves and Annan (2008) (H&A) wrote a commentary on the paper by C&L. They pointed out (properly) that the data in Figure 2.10 are vacillating and, depending on exactly how one chooses the data points, one can derive different results. They provided two examples. In their first example, they chose to read the temperature curves such that $\Delta T_2 \sim 0.8°C$ instead of the value 2.16°C used by C&L.[3] In this case, however, the dust forcing turns out to be negative—the implication is that it was less dusty at the LGM. Hargreaves and Annan (2008) seem to imply that this is an equally good interpretation of the Vostok data. However, there are two things wrong with this. One is that the choice of temperatures by H&A does not fit the data well in Figure 2.10. But, more importantly, the end result of a negative dust forcing at the LGM is contrary to our physical understanding and suggests that the figures chosen by H&A cannot be correct. In their second example, H&A claimed that they arrived at a dust forcing of $0.9 \pm 1.2\,W/m^2$, as compared with the estimate by C&L of $58 \times 0.056 = 3.25\,W/m^2$. This led to an estimate of $\Delta T_G \sim 2.5 \pm 0.7°C$ for a doubling of $CO_2$ from 280 to 560 ppm. However, H&A did not specify which temperatures they used in this calculation, so it is impossible to reproduce what they did. H&A then extrapolated beyond science by asserting that an estimate $\Delta T_G \sim 2.5 \pm 0.7°C$ for a doubling of $CO_2$ from 280 to 560 ppm "does not pose any significant challenge to the widely-held view that climate sensitivity is likely to lie in the range 2–4.5°C [3.25°C ± 1.25°C]." H&A evidently desired to derive as high a climate sensitivity as they could from glacial–interglacial transitions, and the best they could do was $2.5 \pm 0.7°C$—which they say does not pose a challenge to $3.25 \pm 1.25°C$. If we consider that C&L (known skeptics) derived a value of $\Delta T_G = 1.8°C$ for a doubling of $CO_2$ from 280 to 560 ppm, and H&A (defenders of orthodoxy[4]) derived 2.5°C, it seems possible that perhaps the most credible value from this type of analysis lies between these values.

None of these calculations take into account potential changes in humidity and cloudiness during these transitions, which are likely to be as large or larger than the forcings that were included.

If one were to simplistically take the result of Kohler *et al.* (2009) that a forcing of $12.43\,W/m^2$ produces a $\Delta T_G$ of 5.8°C, one might conclude that their estimate of climate sensitivity is $\lambda = 5.8/12.43 = 0.47°C/(W/m^2)$, which agrees with the result of C&L, although the data are different in both cases. It appears likely that Kohler *et al.* made the most detailed analysis of the forcings, and it is possible that their estimate of the total forcing ($12.4\,W/m^2$) is likely to be the most reliable. However, great uncertainty remains regarding $\Delta T_G$. If $\Delta T_G$ is as small as

[3] They did not actually provide the number 0.8°C but they did provide a graph and that was the value I read from their graph.

[4] One can discern the attitude of these authors toward orthodoxy regarding $\Delta T_G$ for doubling of $CO_2$ from their other publications. Furthermore, in the cited reference, H&A emphasize that estimates by the IPCC are inviolable.

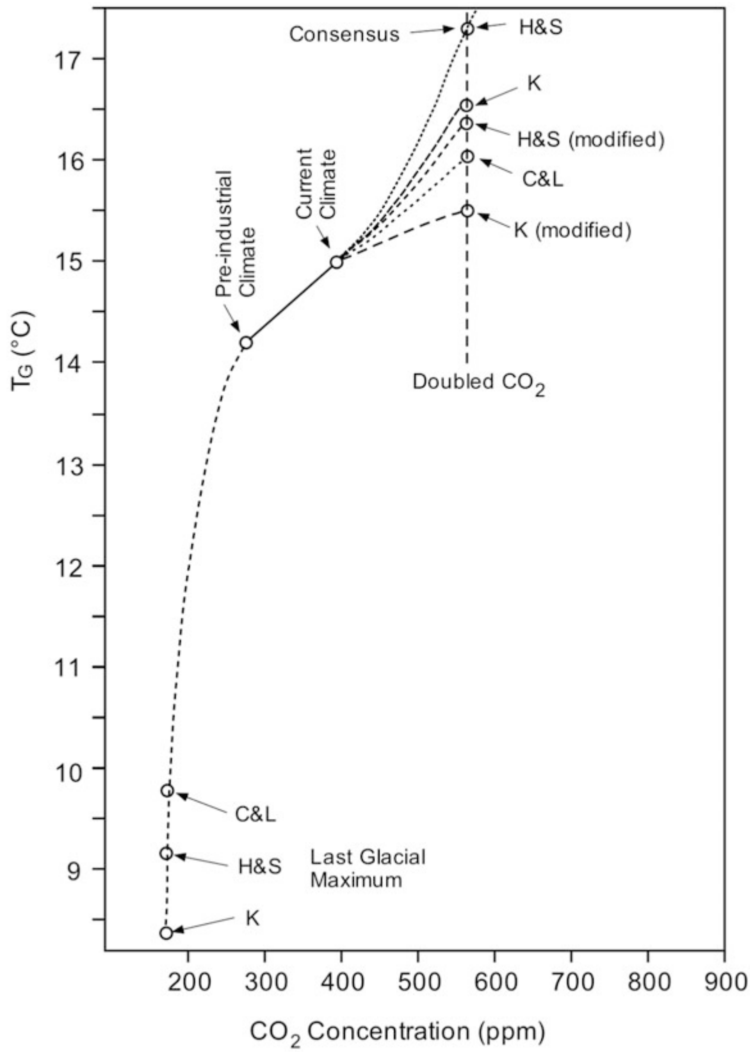



**Figure 2.11.** Summary of estimates from LGM ⇒ pre-industrial period transitions. C&L refers to Chylek and Lohmann (2008). H&S refers to Hansen and Sato (2011). K refers to Kohler *et al.* (2009). Modified values are produced herein as described in the text.

that estimated by C&L and Shakun and Carlson (2010): 4.5°C, the implied climate sensitivity would be $\lambda = 4.5/12.43 = 0.36°\text{C}/(\text{W/m}^2)$. This in turn would suggest a $\Delta T_G \sim 1.3°\text{C}$ for doubling $CO_2$. However, Kohler *et al.* somehow arrived at a figure of 2.4°C by arguments that are difficult for this writer to comprehend. In summary, we have the results shown in Figure 2.11. All of the estimates for the $\Delta T_G$ for doubling $CO_2$ are lower than the consensus value of 3.0°C based on climate models, except for the unmodified result of Hansen and Sato (2011). None of the estimates exceeds the consensus value.

All of these calculations suffer from a lack of understanding of changes in lapse rate, cloudiness, and humidity in the LGM $\Rightarrow$ pre-industrial transition.

Kohler *et al.* (2009) also performed an estimate of climate sensitivity based on glacial–interglacial cycles. They said: "Although water vapor is the most important GHG, the following compilation does not consider any changes in water vapor in the past due to missing constraints on its variability." In other words, they more or less said: *Water vapor may be the biggest factor, but since we have no data on it, we will neglect it!* Some of the data used by Kohler *et al.* (2009) are compared with data used by C&L and Hansen and Sato (2011) in Table 2.2.

It is noteworthy that Hansen and Sato (2011), which came along three years after Chylek and Lohmann (2008) and two years after Kohler *et al.* (2009), did

**Table 2.2.** Parameters for analyzing LGM–pre-industrial transitions. Forcings are in W/m$^2$. Blank elements are not available. Elements with dashes represent items that were not included.

| | *Chylek and Lohmann (2008)* | *Kohler et al. (2009)* | *Hansen and Sato (2011)* |
|---|---|---|---|
| $CO_2$ forcing | 2.4 | 2.1 | 2.25 |
| $CH_4$ forcing | 0.27 | 0.4 | 0.43 |
| $N_2O$ forcing | — | 0.3 | 0.32 |
| Total GHG forcing | 2.67 | 2.8 | 3.0 |
| Land cryosphere | | 4.54 | |
| Land ice | | 3.17 | |
| Sea ice | | 0.55 | |
| Snow cover | | 0.82 | |
| Sea ice | | 2.13 | |
| Sea ice—north | | 0.42 | |
| Sea ice—south | | 1.71 | |
| Vegetation | | 1.09 | |
| Total albedo | 3.5 | 7.76 | 3.5 |
| Dust/Aerosols | 3.2 | 1.88 | |
| Water vapor, lapse rate, and clouds | — | — | — |
| Total forcing | 9.4 | 12.43 | 6.5 |
| $\Delta T_G$ (°C) | 4.6 | 5.8[a] | 5.0 |

[a] Kohler *et al.* (2009) emphasized at considerable length that although reasonable estimates can be made for the $\Delta T$ at Antarctica, the value of $\Delta T_G$ is far more elusive. They suggested that 5.8°C was perhaps one of the better estimates but emphasized that $\Delta T_G$ is not well pinned down.

not refer to these prior papers, which essentially carried out the same calculation but with different parameters, and in the case of Kohler *et al.* with much greater detail.

Hansen and Sato (2011) then proceeded to estimate the forcings over the past ~800,000 years including about eight ice ages and interglacials using the measured $CO_2$ and $CH_4$ concentrations in ice cores, and estimates of sea level during that period. These fit the oxygen isotope data from the ice cores quite well. But this should not be a surprise. The variation of $CO_2$ and $CH_4$ over the past 800,000 years is known to have very nearly the same shape as the isotope curve. Hansen and Sato assigned temperatures to the isotope ratios both from the ice cores and from ocean sediments and claimed good agreement. According to Hansen and Sato, variation of global average temperature from glacial maxima to interglacials was estimated to be typically about 3°C about 800,000 years ago, and this slowly increased to roughly 6.8°C in the most recent ice age–interglacial transition.

By comparing ice core isotope records with deep-sea isotope records, Hansen and Sato (2011) estimated that temperature changes derived from Antarctic ice cores were roughly double the global average temperature changes in the past. This, of course, must be a very rough approximation, although Hansen and Sato (2011) seem to have adopted it as fact.

Hansen and Sato (2011) then embarked on a discussion of the temperatures reached in the past several interglacial periods as compared with our own interglacial of the past ~10,000 years. In particular, ice core data indicate that the interglacials that peaked about 125,000 and 400,000 years ago were warmer than today. Hansen and Sato (2011) concluded that the peak warm periods were "less than 1°C warmer than peak Holocene global temperature" and therefore "were also less than 1°C warmer than global temperature in year 2000." It is not clear how they reached this conclusion. It was necessary for Hansen and Sato (2011), as global-warming activists, to insist that previous interglacials were not much warmer than our own interglacial, since that would suggest that even a moderate warming compared with today's climate would result in potentially catastrophic climate changes. However, others have interpreted the data as inferring that previous interglacials were several degrees warmer than our own. Section 4.4 provides a number of references and data that show that previous interglacials were considerably warmer than the current one (e.g., Kopp *et al.*, 2009; Sime *et al.*, 2009). Another aspect of Hansen and Sato (2011)'s rhetoric regarding climate alarmism is their need to claim that today, after a global temperature rise of ~0.7°C in the past 120 years, "global temperature in year 2000 had returned, at least, to approximately the Holocene maximum." The data are not accurate enough to be certain whether this is true. Nevertheless, Hansen and Sato (2011) would like to conclude that a temperature rise of another 1°C from today's climate might raise the ocean level by 7 to 9 m. A related argument has to do with the global average temperature some 5 million years ago and the associated sea level. Hansen and Sato (2011) asserted that the global average temperature 5 million years ago was a mere 1°C to 2°C warmer than that prevailing in the 19th century prior to the industrial era, or only 1°C warmer than today. They also asserted that sea level was some 25 m higher 5 million years ago. Therefore, another global average temperature rise of ~1°C from today's climate might produce a huge rise in sea level.

However, there is considerable evidence that indicates that the global average temperature 5 million years ago was far warmer than 1°C above current temperatures. Robinson *et al.* (2008) said that about 3 million years ago, the global average temperature was 2–3°C warmer than today. However, "global warmth was distributed differently." Three million years ago, "temperatures at high northern latitudes, above 70°N, were as much as 10°–20°C higher than today, but tropical temperatures were near the same." This points out the limitation of using a single global average temperature to characterize climate.

### 2.3.4 The Early Pliocene: 3 to 5 million years ago

According to Haywood and Williams (2005):

> "Although the geography of our planet looked very similar to that of today three million years ago, the world was undergoing momentous changes everywhere, from the Americas to Tibet. At about this time, animals from South America first started to colonize North America, indicating that the Isthmus of Panama had finally risen above sea level. Along this trans-continental highway of migration, the armadillo was amongst the animals that migrated north, whilst dogs, cats, bears and many other animals headed south. In Africa, the spread of Savannah vegetation and retreat of forest habitats may have encouraged our primate ancestors to come down from the trees, colonizing the open plains of the rift valleys of east Africa and undergoing an evolutionary radiation into a number of 'graceful' and 'robust' australopithecines. Their fossil remains are found in modern Ethiopia and Tanzania. In Asia, the continued collision of India with the Eurasian land mass pushed the Himalayas still higher, intensifying the Asian monsoon. From the Americas, ancestral horses about the size of ponies migrated west along the Aleutian archipelago into Asia and Europe. In the Antarctic, the ice sheets and glaciers were not static, but fluctuated in size, influencing the global climate and sea level. In the oceans too, there were changes. The emerging Isthmus of Panama finally cut off the exit route for Atlantic water into the Pacific, and this contributed to a saltier Atlantic Ocean which may have encouraged the warm water current known as the 'Gulf Stream' in the North Atlantic to flow vigorously.
>
> For much of the past three million years our planet's global climate has been cooler than today, particularly during the ice ages of the Pleistocene. However, during the mid-Pliocene there is strong evidence for a period lasting 300,000 years, when the global climate was warmer than it is today. On Antarctica, along the Trans-Antarctic Mountains, rocks of probable mid-Pliocene age yield fossils of southern beech plants suggesting that parts of Antarctica were ice-free. The question is, what caused this globally warmer climate and what relevance does it have to our understanding of current global warming? There are two key questions. Did higher levels of greenhouse gases in the atmosphere cause Pliocene

warmth? Or was this aided and abetted by other factors such as more intense ocean circulation transporting heat from the tropics to the higher latitudes?''

Schneider and Schneider (2010) reviewed the work of several investigators regarding the relationship of $CO_2$ concentration to climate in the early Pliocene (3–5 million years ago). There is considerable evidence that about 3 million years ago, the global average temperature was several degrees warmer than it is today. Haywood and Valdes (2004) provide numerous references to previous work on ''sea surface temperatures (SSTs) reconstructed from planktonic foraminifera, ostracods, siliceous microfossil records, diatom records, terrestrial vegetation records and numerous records of higher than present sea levels.'' These investigators used ''the alkenone $CO_2$ method to reconstruct Pleistocene–Pliocene $pCO_2$ histories from six ocean localities.'' However there was a wide diversity in inferred $CO_2$ concentration at the six sites, which lends some doubt as to their accuracy. Nevertheless, there were some common features. All of the sites indicated a significant decrease in $CO_2$ concentration from 5 million years ago toward ~1 million years ago. According to Pagani *et al.* (2010), $CO_2$ concentrations were between 365 and 415 ppm about 4.5 million years ago when temperatures were 3–4°C warmer than pre-industrial values. Seki *et al.* (2010) arrived at even lower $CO_2$ concentrations. If these estimates are correct, $CO_2$ concentrations were comparable with those of today, yet the Earth was considerably warmer. Alarmists such as Pagani *et al.* (2010), who assume that $CO_2$ is the primary forcing for climate change, concluded that the longer term Earth system climate sensitivity is much higher than the fast feedback climate sensitivity (using the political definition of climate sensitivity). In fact, Pagani *et al.* (2010) suggested values as high as 9.6°C for a $CO_2$ doubling from the pre-industrial value. It is not totally clear what they meant by this, but apparently they believe that if we hold the $CO_2$ concentration at ~560 ppm and wait long enough, $T_G$ will gradually rise by up to 9.6°C. Haywood and Valdes (2004) pointed out:

> ''Numerous proposals exist within the literature to account for the relative climatic warmth of the middle Pliocene. These include increased concentrations of $CO_2$, enhanced thermohaline circulation, a more vigorous flow of surface ocean gyres, alterations in the outflow of Antarctic deep water, and changes in the elevations of mountain chains. All of these explanations have weaknesses when examined in detail and there may have been numerous contributing factors to middle Pliocene warmth. For example, it has been suggested that the warmth was generated through a combination of enhanced atmospheric $CO_2$ and an increase in thermohaline circulation.''

Their modeling led them to conclude that the main forcing that produced higher temperatures during the Pliocene was reduced land ice cover, ''but with strong positive feedbacks from clouds.'' Lunt *et al.* (2010) analyzed the Pliocene with a climate model and concluded that the Earth system climate sensitivity is 30–50% greater than the fast-feedback sensitivity, which is considerably less extreme than the result of Pagani *et al.* By contrast, Brierley *et al.* (2009) claimed that "a vast poleward expansion of the ocean tropical warm pool" was responsible for Pliocene warmth. However, Haywood and Williams (2005) concluded from their study:

> "Our results suggest that mid-Pliocene warming was caused by more carbon dioxide in the atmosphere combined with climate feedbacks associated with smaller ice sheets. Since the pattern of sea temperature change reconstructed from alkenones, and predicted by our climate model, is not consistent with that produced through changes in ocean circulation/ocean heat transport, we also conclude that there was no major change in thermohaline circulation at that time."

Those who believe that $CO_2$ is the sole arbiter of climate will attribute the warming of the Pliocene entirely to $CO_2$ and will therefore conclude that, if we wait long enough at a fixed $CO_2$ concentration of ~395 ppm, the Earth will slowly approach Pliocene conditions and that, if we hold $CO_2$ at 560 ppm and wait long enough, $T_G$ may rise by as much as 9.6°C (see Figure 2.12). Despite the many publications on the subject, what seems to be missing is this: We need a picture of the Earth under Pliocene conditions, particularly the extent of the ice sheets, but also ocean circulation, the degree of cloudiness, and the plant coverage of the Earth. Forcings need to be estimated for these factors (and more).

### 2.3.5 The past 20 million years or so

Pearson and Palmer (2000) described "the boron-isotope ($\delta^{11}B$) approach to $pCO_2$ estimation that relies on the fact that a rise in the atmospheric concentration will cause more $CO_2$ to be dissolved in the surface ocean, causing a reduction in its pH". They were able

> ". . . to estimate the pH of ancient sea water by measuring the boron-isotope composition of calcium carbonate ($\delta^{11}B_{CC}$) precipitated from it. This is because boron in aqueous solution occurs as two species, $B(OH)_3$ and $B(OH)_{4^-}$, between which the equilibrium is strongly pH-dependent over the natural acidity range of sea water. Furthermore, there is a pronounced isotopic fractionation between the species . . . , so that the ($\delta^{11}B$) of each species is highly dependent on pH. Because boron incorporation into marine carbonates is predominantly from $B(OH)_{4^-}$, ($\delta^{11}B_{CC}$) is a sensitive pH indicator. The pH of seawater is governed by the carbonate equilibria, such that for a given pH value it is possible to calculate the aqueous $CO_2$ concentration and thereby make quantitative estimates of atmospheric $pCO_2$. The pH and aqueous $CO_2$ concentration of the surface ocean vary spatially because of factors such as deep-water upwelling, local productivity regimes and freshwater inflows. To arrive at pH estimates that most closely reflect atmospheric $pCO_2$, it is necessary to measure the ($\delta^{11}B$) of carbonates that were precipitated far from coastal influences and sources of upwelling. The

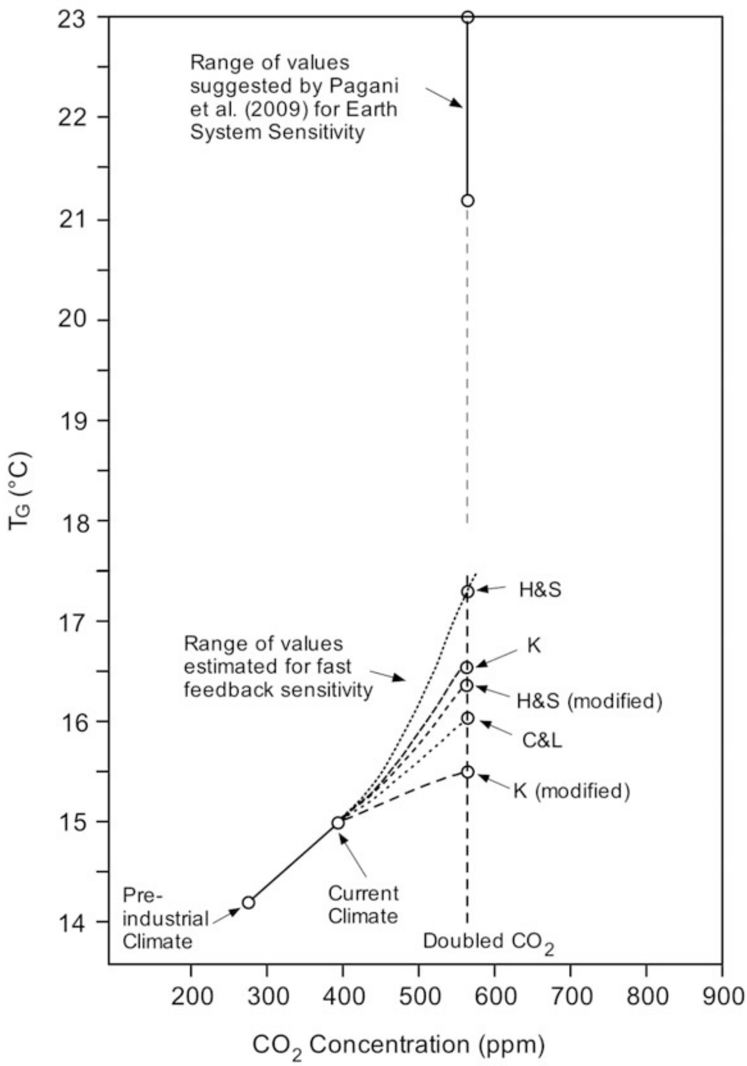



**Figure 2.12.** Range of values suggested by Pagani *et al.* (2010) for Earth system sensitivity.

ideal setting is in the low-latitude gyre systems, where a mixed layer of warm, low density, seawater in contact with the atmosphere generally overlies colder deep waters with little intermixing. Such environments support abundant planktonic foraminifera (a group of microscopic protists) that secrete calcite ($CaCO_3$) shells. The shells fall to the seafloor, from which a record of upper-ocean pH of many millions of years can be obtained.''

Pearson and Palmer (2000) ``analysed the ($\delta^{11}B$) of monospecific sample splits of surface mixed-layer dwelling foraminifera from 32 sediment samples from the

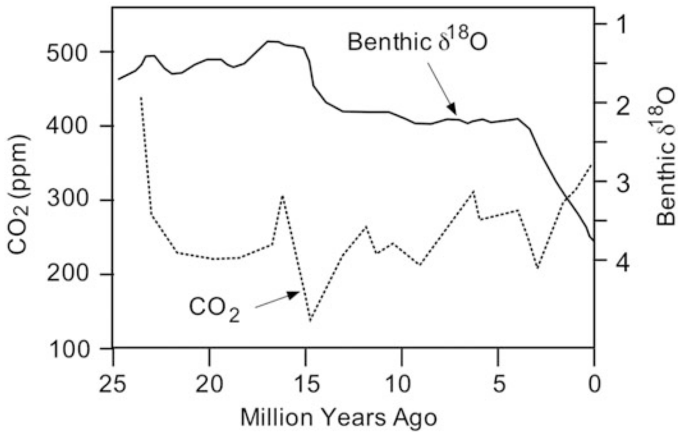



**Figure 2.13.** $CO_2$ concentration and benthic $\delta^{18}O$ (inverse measure of temperature) over the past 25 million years (adapted from Pearson and Palmer, 2000).

open tropical Pacific, spanning the past 60 Myr, augmenting data from six other previously studied samples.'' Their results for the past 25 million years are shown in Figure 2.13. Any putative relationship between $CO_2$ and climate is difficult to discern.

The use of proxies and climate models to infer relationships between climate and $CO_2$ concentration has been carried out by a number of investigators over various time scales ranging up to hundreds of millions of years. In general, the results require distant extrapolations from short recent calibration periods. Typically, there is much disagreement between different datasets, and considerable scatter within any particular set of data. In this section we consider the past 20 million years. van de Wal *et al.* (2011) provided a review article on $CO_2$ and climate over the past 20 million years. Kohler (2011) reviewed this work and carried out his own analysis partly built upon the work of van de Wal *et al.* His graph of estimates of $CO_2$ concentration over the past 20 million years is shown in Figure 2.13. The eight estimates listed in the upper-right portion were provided by van de Wal *et al.* (2011) while Kohler's estimate is shown in black with a red 400 kyr running mean. Over the most recent 2.7 million years, $CO_2$ concentrations oscillated with ice age–interglacial cycles. Note that Kohler's estimate for the early Pliocene was about 300 ppm, which is based on Seki *et al.* (2010), whereas Pagani *et al.* (2010) concluded ''$CO_2$ concentrations were between 365 and 415 ppm.''

Kohler (2011) adapted a figure from van de Wal *et al.* (2011) as shown in Figure 2.14. Unfortunately, van de Wal *et al.* (2011) were not entirely clear on the meaning of ''NH'' in regard to temperature, although they did mention incidentally: ''the reconstructed temperatures are strictly only valid in the continental areas where ice sheets develop in the NH ($\Delta T_{NH}$), being mid- to sub-polar (NH) latitudes, implying that they are therefore not necessarily representative for the

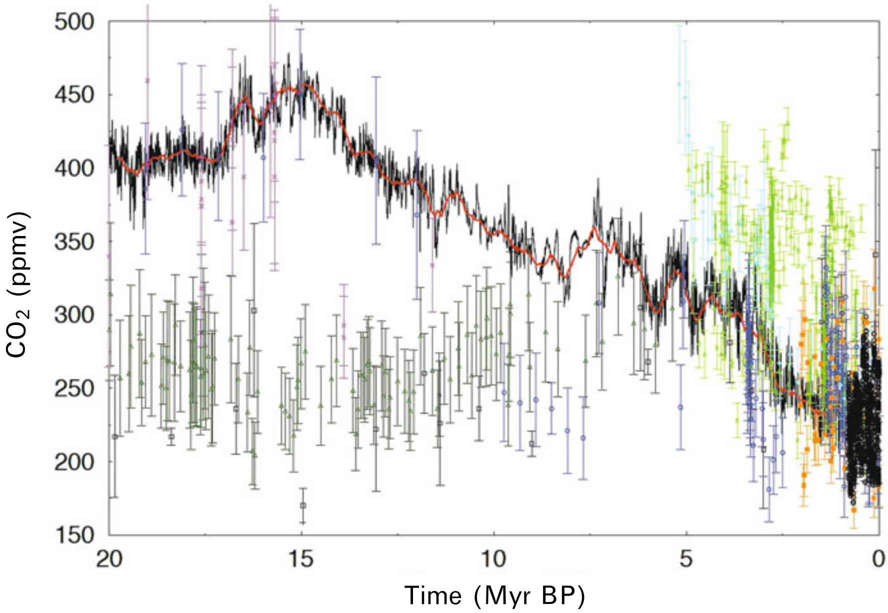



**Figure 2.14.** Estimates of $CO_2$ concentration over the past 20 million years (adapted from Kohler, 2011).

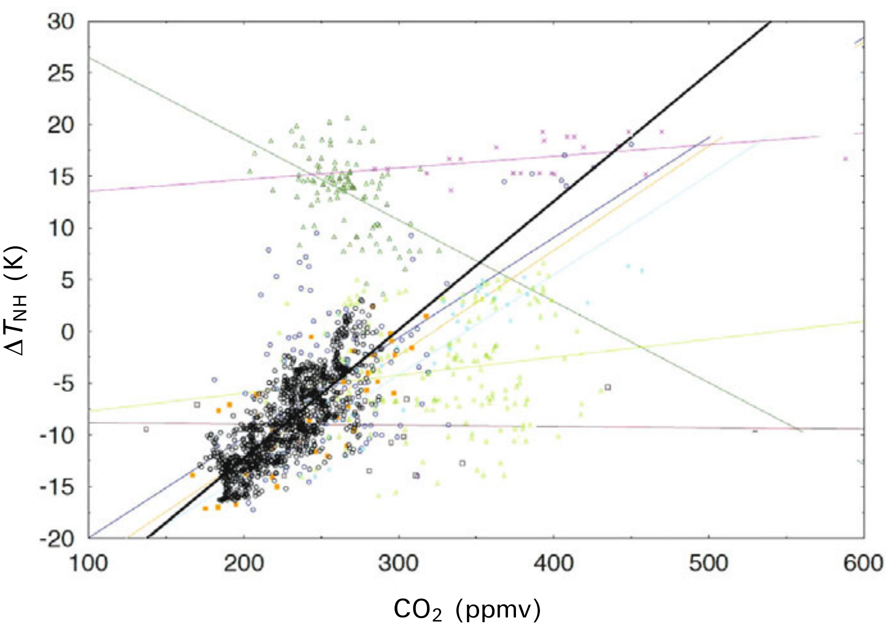



**Figure 2.15.** Dependence of $\Delta T_{NH}$ on $CO_2$ concentration as presented by Kohler (2011) based on van de Wal *et al.* (2011).

entire globe ($\Delta T_G$)." In a personal communication to this writer, van de Wal indicated that $(\Delta T_{NH}) \sim 2.5(\Delta T_G)$. Evidently, some of the data were discounted, and the very wide scatter was not considered an impediment to drawing conclusions. The final result is the black line in Figure 2.14. This line passes through $(\Delta T_{NH}) = 0$ at 300 ppm $CO_2$ and has slope 0.125°C/ppm. Thus, in going from a pre-industrial level of ~280 ppm to the present level of ~395 ppm, van de Wal *et al.* (2011) would predict that $(\Delta T_{NH}) \sim 115 \times 0.125 = 14.4°C$ and $(\Delta T_G) \sim 14.4/2.5 = 5.8°C$. There are three possibilities: (i) one possibility is that if we hold $CO_2$ at 395 ppm and wait long enough $(\Delta T_G)$ will approach 5.8°C; (ii) the second possibility is that the climate is determined by factors other than $CO_2$; (iii) the third possibility is that the results of van de Wal *et al.* (2011) are inaccurate. This writer leans to the second and third possibilities. It seems likely that the variation of $CO_2$ and $T_G$ over the past 20 million years has not been pinned down very accurately but, even if it has, the putative slope of the black line in Figure 2.14 assumes that $CO_2$ is the sole determinant of climate change. Yet, the variability of $CO_2$ over the past 20 million years was moderate, and attributing all climate changes over that period to $CO_2$ leads to a severe overestimate of the importance of $CO_2$. It seems likely that there are more things than $CO_2$ in heaven and earth than are dreamt of in the philosophy of paleoclimatologists.

Foster *et al.* (2009) showed that while the period from 25 to 5 million years ago was "a period of relative warmth" and only Antarctica was glaciated, "paradoxically" $CO_2$ concentrations were comparable with "pre-industrial values or even lower." "Records of ice rafted debris and the oxygen isotope composition of benthic foraminifera suggest that at several times over the last 25 million years substantial amounts of continental ice did build up in the Northern Hemisphere but none of these led to sustained glaciation." Foster *et al.* (2009) pointed out that the "accepted paradigm"[5] requires $CO_2$ to vary in unison with global temperature. However, they emphasized: "Reconstructing the concentration of atmospheric $CO_2$ beyond the reach of the Quaternary ice cores is, however, a notoriously difficult task. Nonetheless there is a growing consensus that $pCO_2$ did decline over the Cenozoic, but not exactly sympathetically with climate as the paradigm suggests" (see Figure 2.16). They also said: "This is likely because the $pCO_2$ records are not perfect and other phenomena such as ocean circulation, continental configuration, and surface albedo (vegetation and ice coverage) also influence climate." They suggested that other geological factors could change the threshold for NH glaciation to occur. One such factor is uplift of the North American Cordillera that "would have resulted in significant cooling of the Northern North American Continent .... This suggests uplift of the North American Cordillera in the Late Miocene may have played an important role in priming the climate for the intensification of Northern Hemisphere glaciation in the Late Pliocene."

[5] The "accepted paradigm" is an almost religious belief that only $CO_2$ concentrations control climate change, and paleoclimatologists often interpret data and models with considerable bias toward that belief.

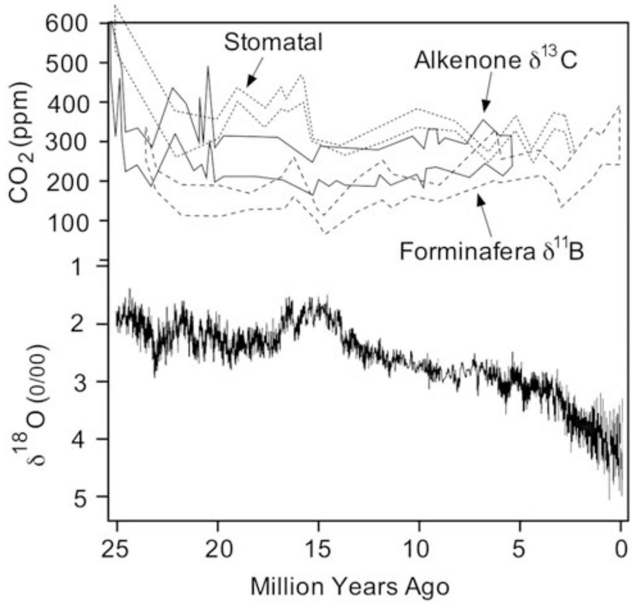



**Figure 2.16.** Comparison of $\delta^{18}O$ (an inverse measure of temperature) with $CO_2$ concentration over 25 million years (adapted from Foster *et al*., 2009).

Tripati *et al*. (2009) said:

> "Although there is speculation about the role of the carbon cycle in driving these well-studied climate changes, there is surprisingly little direct evidence to support a coupling between $pCO_2$ and climate prior to the ice core record (i.e., before 0.8 Ma). Estimates of $pCO_2$ have been generated using several methods including the difference in the carbon isotopic composition ($\delta^{13}C$) of alkenones and co-occurring foraminifera, $\delta^{13}C$ of bulk carbon and of pedogenic carbonates, boron isotope composition ($\delta^{11}B$) of foraminifera, stomatal density on fossil leaves, and carbon cycle modeling. Most reconstructions support a decoupling between $pCO_2$ and climate during the Miocene and Late Pliocene, although very little $pCO_2$ data are available and the few published proxy reconstructions yield conflicting results. In addition, few $pCO_2$ proxies have replicated the ice core data of the past 0.8 Ma."

Their goal was "to test the hypothesis that $CO_2$ and climate were closely coupled across ... major transitions." They used boron/calcium ratios in foraminifera to estimate $pCO_2$ during the major climate transitions of the past 20 million years. Their results are shown in Figure 2.17. They concluded:

> "These results show that changes in $pCO_2$ and climate have been coupled

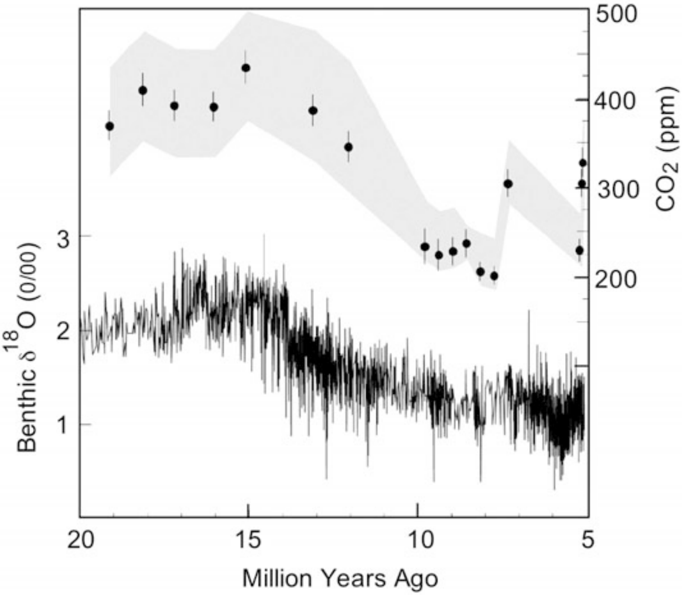



**Figure 2.17.** Estimated $CO_2$ vs. temperature over 20 million years (adapted from Tripati *et al.*, 2009).

during major glacial transitions of the past 20 myr, ... supporting the hypothesis that greenhouse gas forcing was an important modulator of climate over this interval via direct and indirect effects."

However, they also said:

"During the Middle Miocene, when temperatures were $\sim 3°$ to $6°C$ warmer and sea level was 25 to 40 meters higher than at present, $pCO_2$ appears to have been similar to modern levels."

One is left with this inference. Assuming the results of Tripati are accurate, there appears to be a general tendency for $pCO_2$ to be higher during warmer periods but, as Foster *et al.* (2009) said, the variation is "not exactly sympathetically with climate as the paradigm suggests." Nevertheless, as before, one is left with three possible interpretations similar to those reached in regard to van de Wal *et al.* (2011): (i) one possibility is that if we hold $CO_2$ at 395 ppm and wait long enough, $\Delta T_G$ will approach 3 to 6°C; (ii) the second possibility is that climate is determined by factors other than $CO_2$; (iii) the third possibility is that the results of Tripati *et al.* (2009) are inaccurate. This writer leans toward the second and third possibilities.

### 2.3.6 Initiation of Antarctic glaciation 34–33 million years ago

Liu *et al.* (2009) said:

> "About 34 million years ago, Earth's climate shifted from a relatively ice-free world to one with glacial conditions on Antarctica characterized by substantial ice sheets .... The abrupt shift to glacial conditions ... ~33.7 million years ago (Ma) is characterized by a ~+1.5 per mil (‰) change in oxygen isotopic ($\delta^{18}O$) values of benthic foraminifera (1–3) in ~300,000 years, which is indicative of continental ice accumulation and high-latitude cooling .... Proposed causes for this fundamental change in Earth's climate state include changes in ocean circulation due to the opening of Southern Ocean gateways, a decrease in atmospheric $CO_2$, and a minimum in solar insolation."

Liu *et al.* (2009) reported sea surface temperature (SST) changes, which were determined from the alkenone unsaturation index and the tetrather index from 11 globally dispersed ocean localities. They estimated benthic cooling of 3 to 5°C during the transition at 33.7 Myr.

Pearson *et al.* (2009) pointed out that the "principal geochemical fingerprint of the Eocene–Oligocene transition (EOT) is an approximately 11.5% 'shift' towards more positive values of the oxygen isotope ratio of deep-sea carbonates between 34.0 and 33.5 million years ago, the last part of which is a prominent 'step' of about 10.5% at about 33.5 Myr ago." They used "boron isotope ($\delta^{11}B$) analysis of the carbonate shells of upper-ocean planktonic foraminifera to establish palaeo-surface ocean pH" from which they inferred the dissolved $CO_2$ concentration, $[CO_2]_{aq}$ which they assumed was in approximate equilibrium with atmospheric $pCO_2$. The main uncertainties were stated to be "the value for the boron isotope ratio of seawater ($\delta^{11}B_{sw}$), sea surface temperature, and the requirement to estimate one other parameter of the carbonate system (for example, total alkalinity)." Their results are shown in Figure 2.18.

Pearson *et al.* (2009) interpreted their results to:

> "... strongly suggest that the primary cause [for the transition to Antarctic glaciation] was a diminishing greenhouse effect. Although greenhouse gases other than $CO_2$ (for which there are no proxies) may have contributed, changing $pCO_2$ atm is likely to have had the greatest forcing. Ours is the first proxy-based study to confirm a substantial $pCO_2$ decline during the climate transition. We also find a sharp $pCO_2$ increase after maximum ice growth as the global carbon cycle adjusted to the presence of a large ice cap and there was a nonlinear hysteresis effect as the ice cap withstood this transient $pCO_2$ rise. This study reaffirms the links between cryosphere development and atmospheric carbon dioxide levels at the largest and most important climatic tipping point of the last 65 million years."

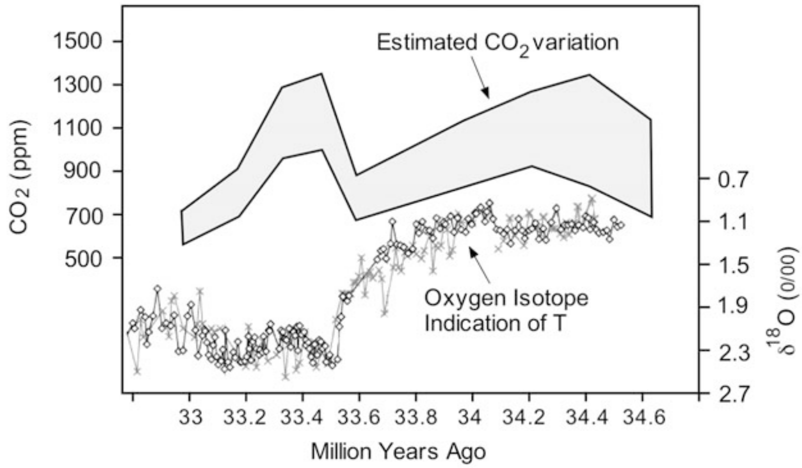



**Figure 2.18.** Comparison of $CO_2$ and a temperature proxy across the Eocene–Oligocene boundary (adapted from Pearson *et al.*, 2009).

They also suggested that the threshold for initiation of Antarctic glaciation is in the range 700–850 ppm.

These conclusions seem to be influenced by adherence to the "accepted paradigm" that $CO_2$ is the main factor in climate change. While there was indeed a moderate decrease in $CO_2$ as the Earth approached the Eocene–Oligocene boundary, the so-called "hysteresis effect" cannot be brushed away so easily. $CO_2$ levels popped up to well above the threshold while temperatures remained low. While $CO_2$ is clearly a factor in climate change, once again we must adopt the comment by Foster *et al.* (2009) that $CO_2$ variations are "not exactly sympathetically with climate as the paradigm suggests."

Peters *et al.* (2010) used "an unusually well exposed coastal incised river-valley complex in the Western Desert of Egypt to show that eustatic sea level fell and then rose by ~40 m, 2 million years prior to establishment of a permanent Antarctic Ice Sheet."

They concluded:

> "This fall in sea level is associated with a positive oxygen isotope excursion that records buildup of an Antarctic Ice Sheet with a volume ~70% of the present-day East Antarctic Ice Sheet. Both the sea-level fall and subsequent rise were coincident with a transient oscillation in atmospheric $CO_2$ concentration down to ~750 ppm, which climate models indicate may be a threshold for Southern Hemisphere glaciation. Because many of the carbon emission scenarios for the coming century predict that atmospheric $CO_2$ will rise above this same 750 ppm threshold, our results suggest that global climate could transition to a state not unlike the Late Eocene, when a large permanent Antarctic Ice Sheet was not sustainable."

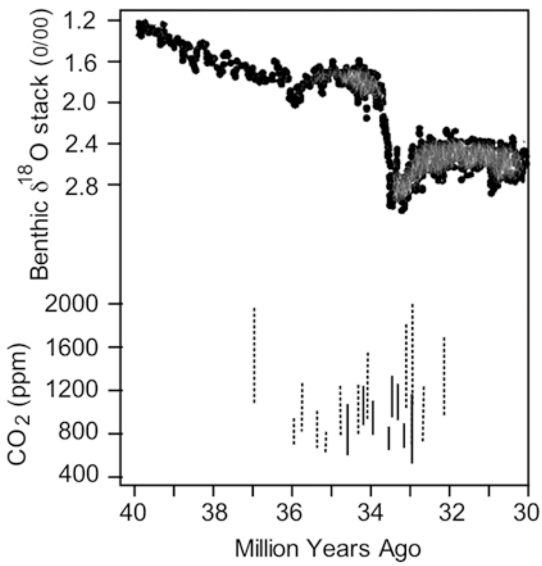



**Figure 2.19.** Comparison of $CO_2$ and a temperature proxy across the Eocene–Oligocene boundary (adapted from Peters *et al.*, 2010).

The result presented by Peters *et al.* (2010) is shown in Figure 2.19. How in the world they reached their detailed conclusions from this crude $CO_2$ data is beyond the ability of this writer to comprehend. As is the case in most paleoclimatological studies, they drew a dollar's worth of conclusions from a penny's worth of data.

### 2.3.7 Peak warming around 40 million years ago

Bohaty *et al.* (2009) described the so-called "Middle Eocene Climatic Optimum (MECO) as an enigmatic warming event that represents an abrupt reversal in long-term cooling through the Eocene." The event was centered on 40 million years ago with a duration of about half a million years. Their measurements of $\delta^{18}O$ at numerous sites "indicated that warming during the MECO event was globally ubiquitous." They found gradual warming prior to the event and rather rapid cooling after the event. They also found a significant decrease in the mass accumulation rate of deep-sea carbonates during this period at some (but not all) sites. They therefore concluded that the event was tied to an increase in $CO_2$ concentration, although they had no direct evidence of this.

Doria *et al.* (2011) "estimated the concentration of atmospheric $CO_2$ during this critical interval using stomatal indices of fossil *Metasequoia* needles from ten levels in an exceptionally well-preserved core from the Giraffe kimberlite locality in northwestern Canada." They summarized estimates of $CO_2$ concentration as shown in Figure 2.20.

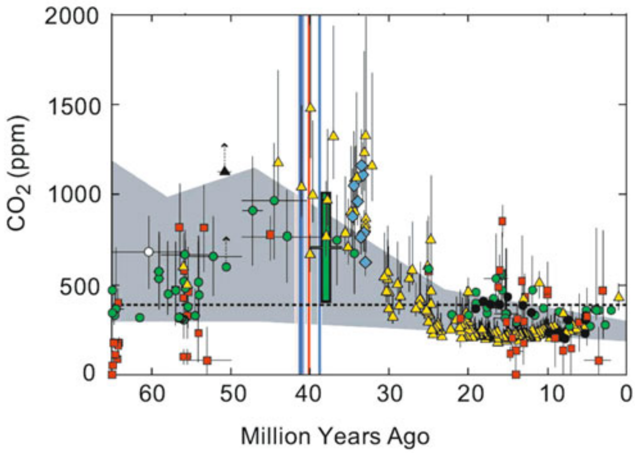



**Figure 2.20.** Estimates of $CO_2$ over the past 65 million years as provided by Doria *et al.* (2011). The gray area is modeled using GEOCARB. The colored data points are measured by various techniques referred to by Doria *et al.* (2011). Doria *et al.* measured the vertical green bar. The vertical red and blue lines are periods of relative warmth and cold.

The connection between $CO_2$ and climate remains fuzzy to this writer based on Figure 2.20.

### 2.3.8 60 to 40 million years ago

Pearson and Palmer (2000) provided the results shown in Figure 2.21. There is a general tendency for higher $CO_2$ concentrations to be associated with higher $T_G$, although a direct one-to-one correspondence is lacking.

Others have determined that $CO_2$ concentrations were relatively high about 50 million years ago. For example, Lowenstein and Demicco (2006) estimated that $CO_2 \sim$ 1,000–3,000 ppm about 50 million years ago. Pagani *et al.* (2005) pointed out that "the relation between the partial pressure of atmospheric carbon dioxide ($pCO_2$) and Paleogene climate is poorly resolved." They "used stable carbon isotopic values of di-unsaturated alkenones extracted from deep-sea cores to reconstruct $pCO_2$ from the middle Eocene to the late Oligocene (~45 to 25 million years ago)." Their results indicated that $pCO_2$ ranged between 1,000 to 1,500 ppm in the Middle to Late Eocene, then decreased in several steps during the Oligocene, and reached modern levels by the latest Oligocene.

Edwards *et al.* (2010) provided the result shown in Figure 2.22, which is similar in some ways to that of Pearson and Palmer (2000) in that the warm period from 60 to 40 million years ago is associated with generally higher values of the $CO_2$ concentration. However, Figure 2.21 shows considerable scatter, and furthermore, there isn't much variation in $CO_2$ while temperatures changed considerably over the past 20 million years. These results seem to suggest that on balance the warmest climates are associated with higher $CO_2$ concentrations, but

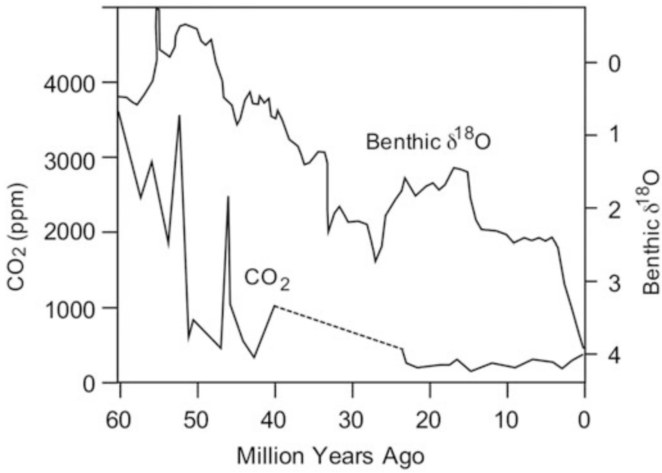



**Figure 2.21.** $CO_2$ concentration and benthic $\delta^{18}O$ (inverse measure of temperature) over the past 60 million years (adapted from Pearson and Palmer, 2000).

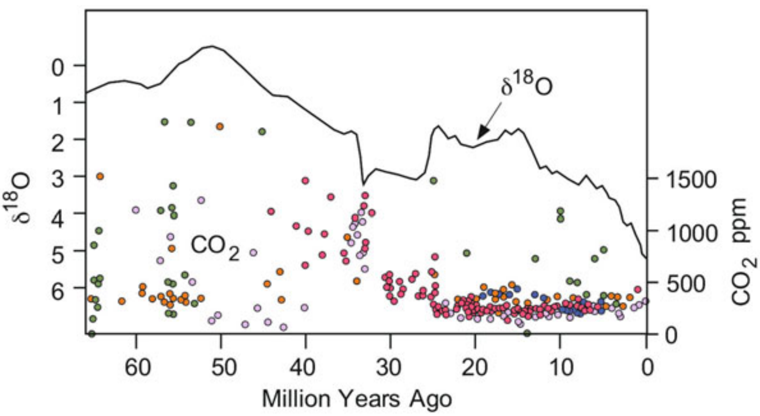



**Figure 2.22.** $CO_2$ concentration and benthic $\delta^{18}O$ (inverse measure of temperature) over the past 60 million years (adapted from Edwards *et al.*, 2010).

the wide scatter in estimates of $CO_2$ concentration preclude detailed comparisons between $CO_2$ and climate.

Kent and Muttoni (2008) suggested:

> "... India's northward flight and collision with Asia was a major driver of atmospheric $CO_2$ concentration ($pCO_2$) and thus global climate in the late Cretaceous and Cenozoic. Subduction of Tethyan oceanic crust with a carpet of carbonate-rich pelagic sediments deposited during transit beneath the high productivity equatorial belt resulted in a component flux of $CO_2$ delivery to the

> atmosphere that maintained high $pCO_2$ levels and warm climate until the decarbonation factory waned with the collision of Greater India with Asia at $\sim$50 Ma, closely coinciding with the Early Eocene climatic optimum. At about this time, the India continent and the highly weatherable Deccan Traps drifted into the equatorial humid belt where uptake of $CO_2$ by silicate weathering further perturbed the equilibrium towards progressively lower $pCO_2$ levels and a cooling trend that eventually triggered the expansion of Antarctic ice sheets in the earliest Oligocene, even if global seafloor production rates remained steady.''

This conclusion appears to be based on the supposition that climate is controlled by $CO_2$ and, for any time period in which climate changed, a geological model for a change in $CO_2$ must be developed to explain why the climate changed. The arguments in this study seem plausible, but it does not appear to this writer as clear-cut as Kent and Muttoni (2008) seem to think.

Cui *et al.* (2011) discussed the transient global-warming event known as the Paleocene–Eocene Thermal Maximum that occurred about 55.9 million years ago. ''The warming was accompanied by a rapid shift in the isotopic signature of sedimentary carbonates, suggesting that the event was triggered by a massive release of carbon to the ocean–atmosphere system.'' They said that ''the source, rate of emission and total amount of carbon involved remain poorly constrained.'' They used ''an expanded marine sedimentary section from Spitsbergen to reconstruct the carbon isotope excursion as recorded in marine organic matter [and found that] the total magnitude of the carbon isotope excursion in the ocean–atmosphere system was about 4‰.'' They used a climate model to infer that the peak rate of carbon addition was slower than the present rate of carbon emissions, although emissions were extended over a longer period.

Ruddiman (2010) wrote a ''Perspective'' article in *Science* entitled ''A paleoclimatic enigma''. In this paper, he emphasized that the Earth's climate had been cooling from pole to pole for 50 million years prior to the onset of alternating ice ages and interglacials about 2.7 million years ago. During this 50-million-year period:

> ''Arctic forests changed from frost-intolerant evergreens to temperate deciduous trees to cold-adapted spruce and larch and eventually to tundra. Antarctica was mostly ice-free until 34 million years ago; glaciers of varying size then existed on the continent until 14 million years ago, after which a large and relatively stable ice sheet formed. The gradual shift toward heavier $\delta^{18}O$ values in $CaCO_3$ shells of sea-floor foraminifera since 50 million years ago documents a combined deep-ocean cooling and increase in Antarctic ice.'' [See Figure 2.23].

Ruddiman (2010) went on to say:

> ''Until a decade ago, most paleoclimate modelers attributed this ongoing bipolar cooling to a gradual reduction in the $CO_2$ concentration in the atmosphere. This inferred $CO_2$ decrease was ascribed to a combination of reduced

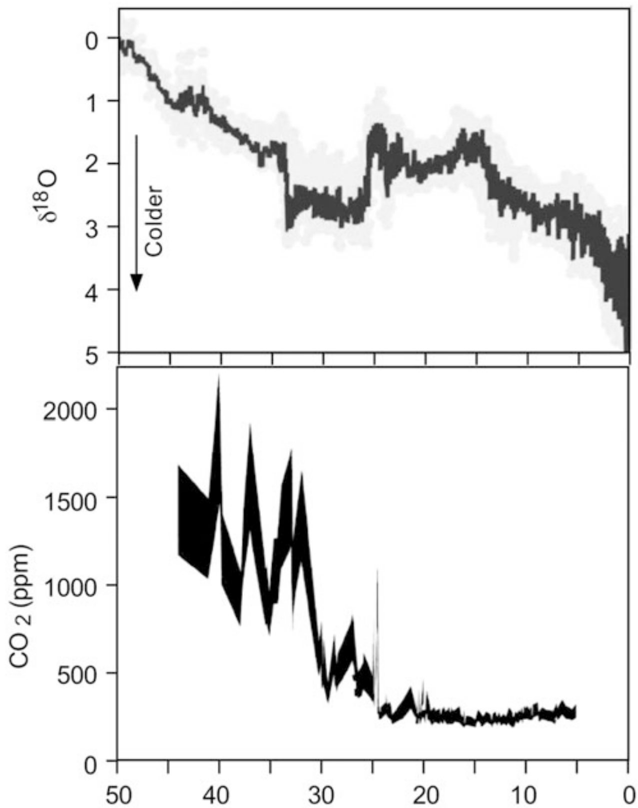



**Figure 2.23.** $CO_2$ concentration and benthic $\delta^{18}O$ (inverse measure of temperature) over the past 60 million years (adapted from Ruddiman, 2010).

volcanic $CO_2$ input to the ocean and atmosphere because of a slowing rate of sea-floor spreading and increased $CO_2$ removal by enhanced chemical weathering in tectonically uplifting regions like Tibet.

In a broad sense, this long-term $CO_2$ decrease provided some support for the idea that $CO_2$ has been the long-term driver of global cooling, but a closer look revealed major problems. By 22 million years ago, the alkenone and boron isotope data both showed that estimated $CO_2$ concentrations were already within the range typical of the glacial cycles of the past 800,000 years. If $CO_2$ concentrations of 180 to 300 ppm have played an integral role in allowing glacial cycles in the past 800,000 years, why did comparably low $CO_2$ values 22 million years ago not initiate glacial cycles? And if the average $CO_2$ trend has not fallen in the past 22 million years, what caused the substantial bipolar cooling during that time? Other proposed causes seem insufficient to explain large-scale cooling. Gradual plate motions and falling sea level have extended the northern margins of circum-Arctic continents into cooler near-polar latitudes, but models suggested that these factors were not enough to explain the major cooling observed."

The problem as Ruddiman explained is "persistently low $CO_2$ concentrations estimated for the past 22 million years" during which the climate cooled substantially. Although Ruddiman did not consider this, it appears that there are inconsistencies between $CO_2$ and climate prior to 22 million years ago as well, although, to some extent, higher $CO_2$ was roughly associated with warmer climates. Ruddiman said: "Paleoclimatologists were left with three possibilities." These were:

(1) They "might have overlooked something crucial."
(2) Effects other than $CO_2$ "could have had a much stronger effect than thought."
(3) "The proxy methods used to reconstruct $CO_2$ concentrations prior to ice-core records could be invalid."

Ruddiman discounted the first possibility and leaned toward the third. The argument seems to come down to this. Ruddiman doubts that there is a missing factor, but known factors do not seem to explain the variability of climate. Therefore, the only thing that he can think of that could be the cause of long-term climate change is variable $CO_2$. Since the data on $CO_2$ do not agree with this precept, the data must be wrong. This type of argument has been used a number of times recently in climatology. If the data do not agree with theory, throw the data out! However, that seems antithetical to the scientific method.

One interesting event during this era was the so-called Paleocene–Eocene Thermal Maximum (PETM) that occurred about 55 million years ago. There is good evidence that $T_G$ rose by at least several degrees (some estimates range from 4 to 9°C) in as little as 10,000 to 30,000 years. It is widely believed that this could only result from a sudden massive input of greenhouse gases. However, Zeebe (2011):

> "... estimated the size of the PETM carbon input based on sediment records of deep-sea carbonate dissolution and showed that the subsequent rise in atmospheric $CO_2$ alone was insufficient to explain the full amplitude of global warming. We concluded that in addition to direct $CO_2$ forcing, other processes must have caused a portion of the PETM warming .... Our study showed that there were processes in addition to $CO_2$ forcing that caused part of the warming, not that $CO_2$ was irrelevant. The processes are as yet unidentified—some may have operated independently, others as a response or feedback to the $CO_2$ release."

In contrast to Zeebe's indication of uncertainty regarding the PETM, Kump (2011) asserted that he understands the whole process. The initial release of $CO_2$ provided warming that added $CH_4$ to amplify the effects of $CO_2$. In fact, Kump (2011) provided a detailed description of the Earth during the PETM. Most of this seems to be subjective cloth woven from invisible thread. The methane hydrate hypothesis was discussed by Higgins and Schrag (2006) who concluded that analysis of the PETM leads to "a high climate sensitivity". Pagani *et al.* (2006) concluded: "... the PETM either resulted from an enormous input of $CO_2$ that currently defies a mechanistic explanation, or climate sensitivity to $CO_2$ was extremely high.''

As Royer *et al.* (2011) pointed out, ''the PETM is considered a paleo-analog of present day climate change in terms of rate and magnitude of carbon release'' although, as Kump (2011) emphasized, the annual release of carbon during the PETM was far less than today's, but it was sustained over a much longer time.

### 2.3.9 100 to 300 million years ago

Royer *et al.* (2011) compared crude estimates of $CO_2$ concentration with estimates of benthic $\delta^{18}O$ and tropical sea surface temperatures (SST) over the time range from 125 million years ago to 50 million years ago. The $CO_2$ and SST data show considerable scatter. There was a warm period at around 55 million years ago but it does not seem to have been accompanied by higher $CO_2$. In this regard, Royer *et al.* (2011) chose to ignore multiple $CO_2$ measurements near 55 million years ago that were low and, instead, accepted one outlier measurement that was four times higher. From this, they derived a high sensitivity of $\Delta T_G$ to $CO_2$ concentration. This result does not seem credible to this writer.

### 2.3.10 Estimates of climate sensitivity based on $CO_2$ and climate in the Phanerozoic

#### *2.3.10.1 Introduction*

During the Phanerozoic (the past 540 million years or so), the Earth experienced significant changes. These included redistribution of continents via continental drift, the emergence of vascular plants driving up oxygen content in the atmosphere, changing $CO_2$ concentrations (as high as 20 times current levels in some periods), and many other changes, as discussed by Berner (2004). One particular time period, the so-called Permo-Carboniferous between about 330 and 280 million years ago, was marked by extensive world glaciation, low $CO_2$ levels, and high oxygen content (30–35%). In addition, the brightness of the Sun increased with time across this eon.

As with almost every area of climatology, data on the Phanerozoic climate and $CO_2$ concentrations are sparse and noisy, and the interpretation of the data in terms of climatological parameters requires complex models and a number of assumptions. Various investigators have arrived at different interpretations regarding the connection between $CO_2$ concentrations and climate change during the Phanerozoic. Most have concluded that changing $CO_2$ concentrations was the main factor producing long-term climate change. Others claim that the effect of $CO_2$ was secondary and galactic cosmic ray variability was the important factor.

#### *2.3.10.2 Climate during the Phanerozoic*

Veizer (2005) pointed out: ''in the Phanerozoic, some organisms secreted their shells as the mineral calcite ($CaCO_3$), which often preserves the original oxygen

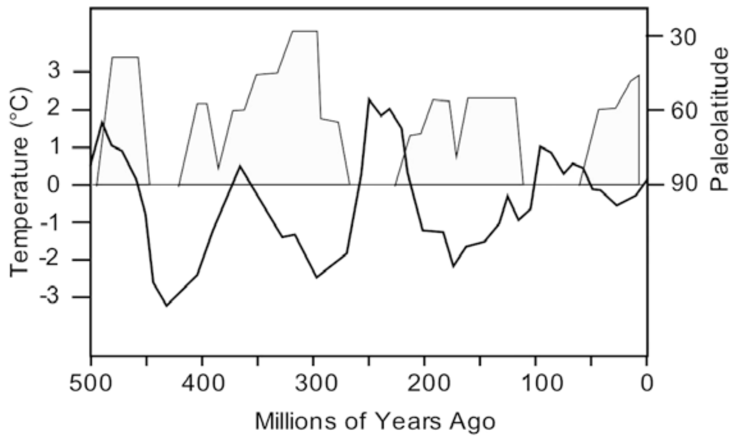



**Figure 2.24.** Estimated variations of tropical seawater temperatures during the Phanerozoic (heavy line). The extent of glaciation (paleolatitude) is shown as shaded areas (adapted from Veizer *et al.*, 2000; Veizer, 2005).

isotope ratio, and this, in turn, reflects the ambient seawater temperature.'' In earlier work, Veizer and co-workers ''generated a large database of several thousand well-preserved calcitic shells that cover this entire 545 million years timespan. Such detrended isotope data correlate well with the climatic history of the planet, with tropical sea surface temperatures fluctuating by perhaps 5 to 9°C between the apexes of icehouse and greenhouse times, respectively.''

Veizer (2005) indicated: ''the record of climate variations during the Phanerozoic shows intervals of tens of millions of years duration characterized by predominantly colder or predominantly warmer episodes, called icehouses and greenhouses, respectively. Superimposed on these are higher order climate oscillations, such as the episodic waning and waxing of ice sheets.'' Veizer's estimates for Phanerozoic climates are shown in Figure 2.24.

Royer *et al.* (2004) corrected estimates of sea surface temperature during the Phanerozoic due to changes in pH of the oceans induced by changes in the $CO_2$ level of the atmosphere and changes in Ca concentrations and the calcium carbonate saturation state in seawater. Their result is shown in Figure 2.25, in which paleo sea surface temperatures are greatly increased when $CO_2$ concentrations are higher.

Subsequently, Shaviv and Veizer commented on the paper by Royer *et al.* (2004) and Royer *et al.* replied to their comment. According to Shaviv and Veizer:

> ''The analysis of Royer *et al.* (2004) assumes an unrealistically high pH correction. First, it neglects the ice-volume effect, which changes the relation between $\delta^{18}O$ and $\Delta T$. Second, this large pH correction implies high temperatures for seawater even during times of extensive glaciations. Moreover, the analysis of Royer *et al.* (2004) consists of bootstrapping, by introducing a

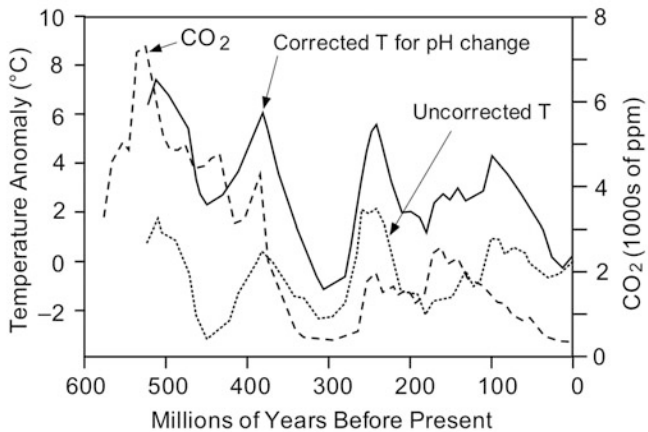



**Figure 2.25.** Corrected changes in tropical sea temperatures due to change in pH from changing $CO_2$ concentration (adapted from Royer *et al*., 2004).

correction to $\Delta T$ that is an implicit function of R($CO_2$). It is then not surprising that a correlation between $\Delta T$ and R($CO_2$) is obtained. This would be the case irrespective of the R($CO_2$) model utilized. A proper analysis, which avoids this bootstrapping and considers a more realistic pH correction, shows that the global temperature sensitivity to $CO_2$ is still relatively small. In summary, while we acknowledge that the proposition of Royer *et al*. (2004) has some merit and likely will result in some modification of the $\delta^{18}$O signal, the cosmic ray flux still remains the primary climate driver for any realistic pH correction. Even for the scenario that entirely disregards the ice-volume effect, the impact of cosmic ray flux would still be at par with that of $CO_2$."

R($CO_2$) is the ratio of $CO_2$ concentration to that prevailing in the pre-industrial period (280 ppm) [R($CO_2$) = $CO_2$/280]. Royer *et al*. disputed these conclusions. They claimed that prolonged cold intervals during the periods 460–400 Myr and 220–120 Myr, while R($CO_2$) was high, are unjustified. They also disputed the validity of the ice volume effect, particularly during periods with no glaciation. They concluded:

"The correspondence between the Phanerozoic records of atmospheric $CO_2$ and glacial sediments, and the revision of the $\delta^{18}$O paleo-temperature record toward values better matching the glacial sediment record, strongly implicate $CO_2$ as a primary driver of climate over these timescales. Cosmic ray flux is likely only of second-order significance."

Over roughly the same time period of the Shaviv/Veizer–Royer *et al*. controversy, Wallmann (2004) developed a box model that included pH corrections. He began with this introduction:

"Proxy data and box modeling demonstrate that $pCO_2$ has oscillated over the Phanerozoic due to changing rates of mantle degassing, weathering, organic carbon burial and carbonate turnover. The simulated changes in $pCO_2$ correspond roughly to paleoclimatic reconstructions supporting the view that Phanerozoic climate change has been driven mainly by changes in atmospheric $pCO_2$. A different picture emerges from the evaluation of $\delta^{18}O$ values in marine carbonate fossils. These data show regular oscillations with a shorter period indicating changes in surface temperatures at low latitudes that are consistent with some paleoclimatic reconstructions but not with surface temperatures derived from $pCO_2$ modeling. This difference may be regarded as evidence for the decoupling of $pCO_2$ and climate evolution. The latter view is supported by recent modeling of galactic cosmic radiation over the last billion years. These new data show a surprisingly strong correlation with $\delta^{18}O$-based temperature reconstructions suggesting that climate change has been driven mainly by cosmic radiation. Nevertheless, temperatures calculated from the marine $\delta^{18}O$ record are met with skepticism because the extremely low Jurassic surface temperatures derived from this proxy are not consistent with other observations."

Wallmann (2004) provided the estimate of the average global surface temperature shown in Figure 2.26.

Several Internet sites claim that Veizer *et al.* (2000) updated their global average Phanerozoic temperatures based on oxygen isotope data online in 2004 at:

*http://www.science.uottawa.ca/geology/isotope_data/*

However, that website is defunct. Nevertheless, Ziegler presented a graph that is claimed to be this update at:

*http://climaterealists.com/index.php?id=6680*

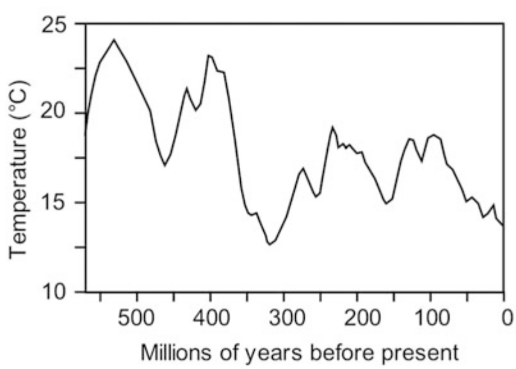



**Figure 2.26.** Estimate of average global temperature during the Phanerozoic (adapted from Wallmann, 2004).

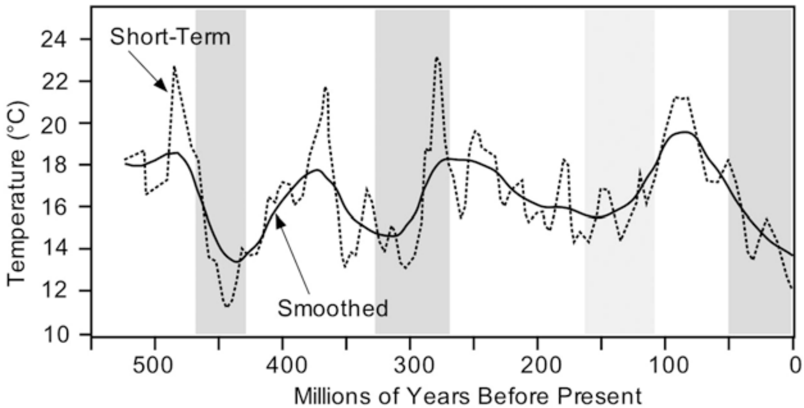



**Figure 2.27.** Temperatures derived from $\delta^{18}O$ values of calcitic shells for the Phanerozoic (adapted from Ziegler). Darker shading represents very cold glacial periods. Light shading represents a cool period.

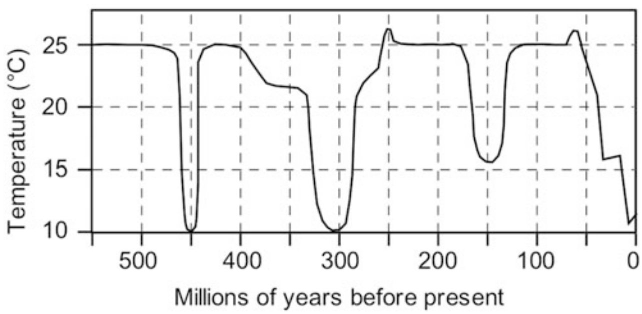



**Figure 2.28.** Estimate of global average temperature for the Phanerozoic (adapted from Scotese, 2002).

See Figure 2.27. This figure has been used by a number of websites and encyclopedias but it is not clear what the original source is.

There is some considerable variance between various rough estimates of the Phanerozoic climate (see Figure 2.28). Nevertheless, the following salient points seem to be generally agreed upon:

(1) For much of the Phanerozoic, global average temperatures were perhaps as high as 25°C as compared with present day temperatures of about 14°C, showing that for much of the Proterozoic the Earth was a veritable hothouse of warmth.
(2) There were two deep glacial cold periods embedded in the Phanerozoic, during which evidence exists that glaciation may have reached latitudes down to 30°, and global temperatures dropped to perhaps as low as 10°C. The ranges over which these occurred were roughly 470–440 and 330–280 million years ago. The

glacial period from 330 to 280 million years ago was the deepest and is referred to as the "Permo-Carboniferous period".

(3) There was an additional cold period centered on 150 million years ago when global average temperatures dropped by about 10°C to perhaps 15°C.

(4) Starting around 50 million years ago, the Earth entered into a period that was mainly a cooling trend.

#### *2.3.10.3 $CO_2$ variability during the Phanerozoic*

In this section, we discuss the evidence from the Phanerozoic (the past 540 million years) regarding $CO_2$ concentrations. We begin with a brief summary of results provided by Berner (2004), which provides a good overview and introduction, and follow that with data from other sources. The "short-term carbon cycle" is described by Berner (2004) as shown in Figure 2.29. The word "short-term" is used for characteristic times for transferring carbon between reservoirs that range from days to tens of thousands of years:

> "Carbon dioxide is taken up via photosynthesis by green plants on the continents or phytoplankton in the ocean. On land carbon is transferred to soils by the dropping of leaves, root growth, and respiration, the death of plants, and the development of soil biota. Land herbivores eat the plants, and carnivores eat the herbivores. In the oceans the phytoplankton are eaten by zooplankton that are in turn eaten by larger and larger organisms. The plants, plankton, and animals respire $CO_2$. Upon death the plants and animals are decomposed by microorganisms with the ultimate production of $CO_2$. Carbon dioxide is

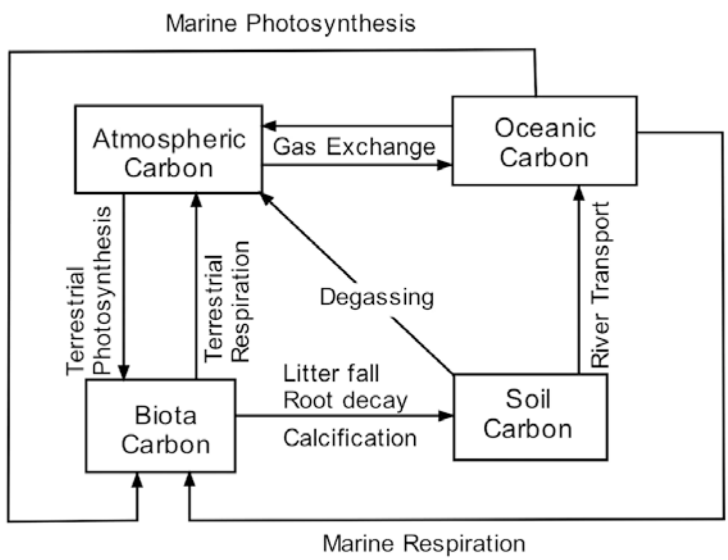



**Figure 2.29.** The short-term carbon cycle (adapted from Berner, 2004).

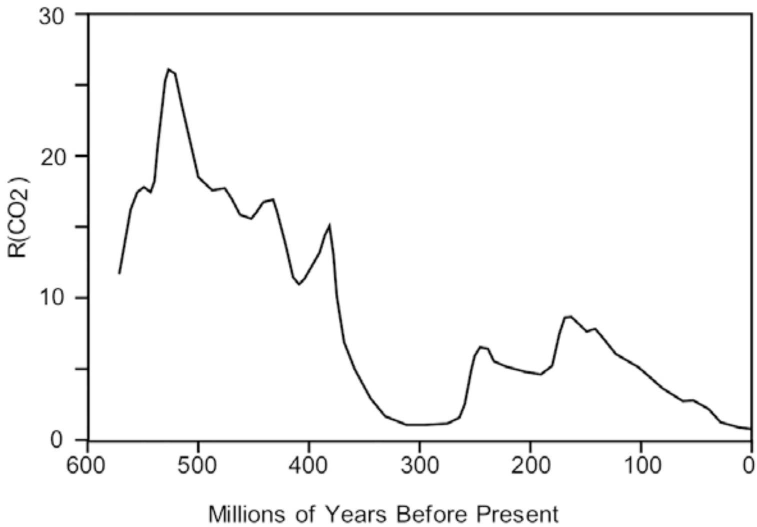



**Figure 2.30.** Plot of R($CO_2$) vs. time based on geological models (adapted from Berner, 2004).

exchanged between the oceans and atmosphere, and dissolved organic matter is carried in solution by rivers from soils to the sea."

As the short-term cycle proceeds, concentrations of the two principal greenhouse gases, $CO_2$ and $CH_4$, can change as a result of perturbations of the cycle, resulting in global warming and cooling over centuries and many millennia.

Over longer periods of time (millions of years) additional processes can add or remove $CO_2$. Because there is more than a thousand times more carbon in rocks than there is in the oceans, atmosphere, biosphere, and soils combined, carbon transfers to and from rocks can result in significant changes in atmospheric $CO_2$ over long time periods. Berner (2004) discussed the processes whereby carbon is exchanged with rocks. Two opposing processes are involved. $CO_2$ is stored in rocks as calcium carbonate. Decarbonization via volcanism, metamorphism, and diagenesis, releasing $CO_2$ to the atmosphere while producing calcium silicate. Berner (2004) described how these cycles operated over the past 550 million years. The details are extensive and well beyond the scope of this review.

Using geological models, estimates have been made of the concentration of $CO_2$ during the Phanerozoic as shown, for example, in Figure 2.30. According to Berner (2004):

"The most dramatic feature of the curve is the large drop in $CO_2$ occurring in the mid-Paleozoic (400–300 Ma). This drop is due mainly to a combination of changes brought about by the rise of large vascular land plants. The plants both accelerated weathering and provided biologically resistant organic remains for burial in sediments, causing a drop in $CO_2$."

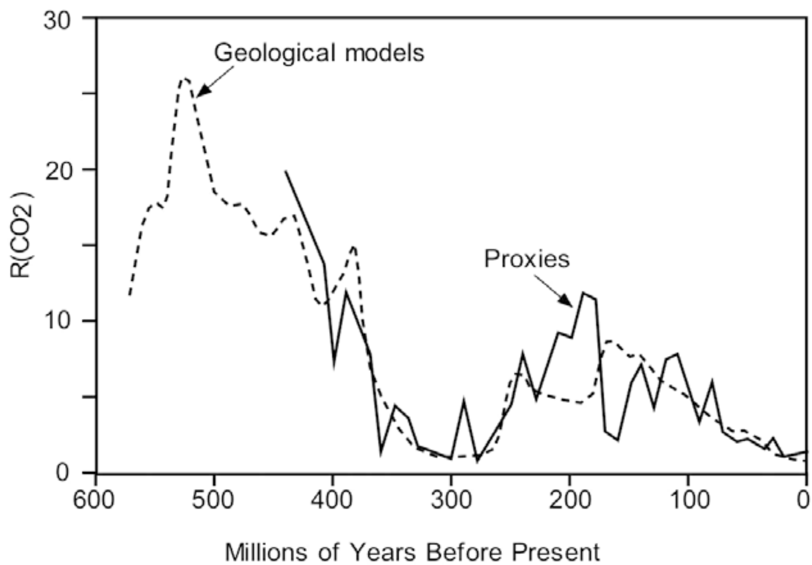



**Figure 2.31.** Plot of $R(CO_2)$ vs. time based on proxies, compared with geological models (adapted from Berner, 2004).

Proxies have been used to estimate $CO_2$ levels during the Phanerozoic. According to Berner (2004),

> "Methods include determining (1) the $\delta^{13}C$ of carbonates in paleosols; (2) the stomatal density of fossil leaves; (3) the degree of fractionation of carbon isotopes of specific compounds secreted by phytoplankton and preserved in sedimentary rocks; and (4) the boron isotopic composition of marine carbonate fossils. Each of the methods has its own problems, but if certain precautions are taken, they provide reasonable estimates of ancient $CO_2$ levels."

In addition, various proxies have yielded the curve of $R(CO_2)$ vs. time as shown in Figure 2.31.

According to Berner (2004),

> "There are problems with all of the methods of $CO_2$ estimation, and the [$R(CO_2)$] curves are not intended to be used as an accurate $CO_2$ measure (as is sometimes mistakenly done), but rather as a suggestion of how $CO_2$ has changed over the Phanerozoic. New advances . . . will undoubtedly cause modifications . . . ."

Rothman (2002) used the difference between the $\delta^{13}C$ of bulk organic matter and calcium carbonate ($\delta^{13}C$) to calculate the value of atmospheric $CO_2$ concentration during the Phanerozoic as shown in Figure 2.32. Rothman's estimates for $R(CO_2)$ are much smaller than those of Berner (2004). Rothman acknowledged this difference but felt that his estimates were justified. However, Berner (2004)

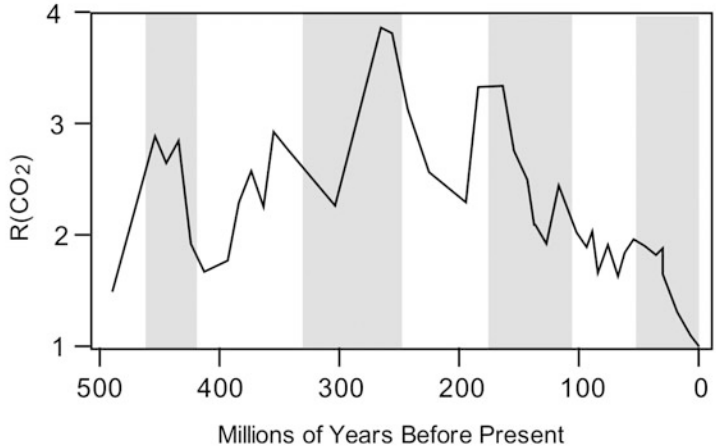



**Figure 2.32.** $R(CO_2)$ estimated by Rothman (2002). Gray areas are periods attributed to "relatively cool climates".

criticized Rothman's approach, pointing out: "the calibrations based on the study of marine plankton do not apply generally to bulk material. Also, it has been shown that fractionation of carbon isotopes by plant-derived organic matter is not a simple function of $CO_2$, but rather a strong function of atmospheric $O_2$ that varies with time .... These considerations indicate that the simple use of $\delta^{13}C$ to derive $CO_2$ values over the Phanerozoic is an inappropriate approach to the problem of deducing paleo-$CO_2$."

#### *2.3.10.4 Comparison of Phanerozoic climate with $CO_2$ concentrations*

Crowley and Berner (2001) said:

> "Geologists have long known that on time scales of tens of millions of years, intervals of continental glaciation were interspersed with times of little or no ice. The magnitude of warmth during these warm intervals is impressive. [About] 65 to 145 million years ago (Ma)], duck-billed dinosaurs roamed the northern slope of Alaska. Deep and bottom waters of the ocean, now near freezing, could reach a balmy 15°C. In the 1980s, a convergence of results from paleoclimatic data and geochemical and climate models suggested that such long-term variations in climate were strongly influenced by natural variations in the carbon dioxide ($CO_2$) content of the atmosphere. Lately, some geochemical results have raised concerns about the validity of this conclusion. $CO_2$ concentrations over the past 65 million years appear to have reached low levels well before the most recent phase (the past 3 million years) of Northern Hemisphere glaciation. This is especially true for times of elevated temperatures at about 50 to 60 Ma and 16 Ma, when $CO_2$ was apparently low. A study spanning the Phanerozoic also suggests some decoupling between times of predicted high $CO_2$ and some climate

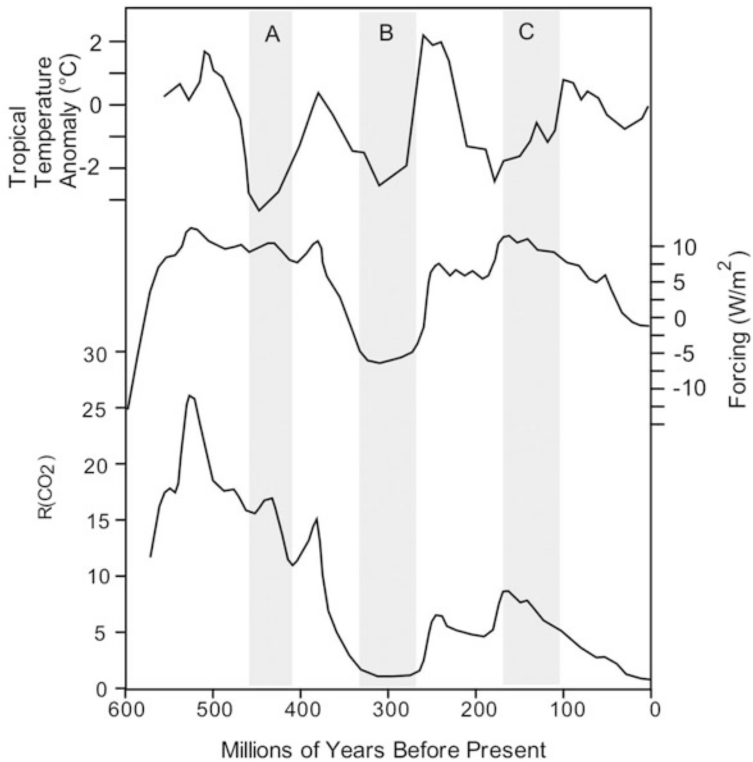



**Figure 2.33.** Comparison of R($CO_2$) with temperature changes during the Phanerozoic. The upper curve is tropical sea temperature anomaly. The middle curve is estimated forcing due to changing $CO_2$, taking into account the gradually strengthening Sun. The lower curve is estimated R($CO_2$). Gray areas A and C are time periods when $CO_2$ is disjoint with temperature, while gray area B has $CO_2$ and temperature in good agreement (adapted from Crowley and Berner, 2001).

indices. In light of these results, it is important to reevaluate the validity of the assumed $CO_2$–climate link. Here we address this issue by comparing estimates of Phanerozoic $CO_2$ variations and net radiative forcing with the continental glaciation record and low-latitude temperature estimates.''

Crowley and Berner (2001) then went on to compare the best available data on Phanerozoic temperatures from oxygen isotopic composition of fossils with levels of $CO_2$ based on geological modeling and proxy data (see Figure 2.33). The forcing represents a combination of two things. One is the effect of variable $CO_2$ due to the greenhouse effect. The other is the fact that solar intensity increased by about 6% during the Phanerozoic. Early in the Phanerozoic, with solar intensity 6% lower than at present, the solar forcing would have been about $-14\,W/m^2$.

This was counteracted by greenhouse forcing from $CO_2$ with $R(CO_2)$ reaching values higher than 20. On balance, the forcing due to these two factors is shown as the middle curve in Figure 2.33. If $CO_2$ was the main driver of climate change, then tropical sea temperature should follow the forcing curve. For gray area B in Figure 2.33, there is a perfect consonance between low $CO_2$ concentration and low forcing. However, for gray areas A and C, the forcings were strongly positive but temperatures were low.

Crowley and Berner (2001) pointed out:

> "There is a major discrepancy during the period 120 to 220 Ma between cold low-latitude temperatures and high levels of $CO_2$ .... The overall low correspondence between low-latitude $\delta^{18}O$ and net [$CO_2$ levels] begs for an explanation, especially because of the striking correspondence between low net [$CO_2$ levels] and major continental glaciation from 256 to 338 Ma".

They suggested that in the case of the relatively short-lived glaciation of about 440 Myr, which occurred at a time of high $R(CO_2)$, "climate models suggest that the unusual continental configuration of ... a large landmass tangent to the South Pole could result in conditions where high $CO_2$ and glaciation can co-exist." Nevertheless, they insisted that "the persistent Phanerozoic de-correlation between tropical $\delta^{18}O$ and $R(CO_2)$ demands a more comprehensive explanation." They suggested that one possibility is that the temperature estimates are erroneous. Another is that "climate change in the tropics can be largely decoupled from mid–high-latitude ice volume changes." While they insisted that "the first-order agreement between the $CO_2$ record and continental glaciation continues to support the conclusion that $CO_2$ has played an important role in long-term climate change," they nevertheless concluded:

> "Given the need for better confidence in some of the paleoclimate data and unanticipated complications arising from altered tectonic boundary conditions, it may be hazardous to infer that existing discrepancies between models and data cloud interpretations of future anthropogenic greenhouse gas projections."

Royer (2006) compared 490 published proxy records of $CO_2$ over the Phanerozoic with records of global cool events to evaluate the strength of $CO_2$–temperature coupling over the Phanerozoic. Figure 2.34 shows Royer's result in comparison with that of Crowley and Berner (2001). Royer found that the predominant glacial periods were between 350 and 290 million years ago, and the past 30 million years when $CO_2$ concentrations were lower. The glacial period at 445 million years ago seems to be a contradiction of the $CO_2$–climate connection, but Royer (2006) argued that the glacial period was brief and the $CO_2$ level at that time is uncertain.

Royer (2006) concluded:

> "For periods with sufficient $CO_2$ coverage, all cool events are associated with

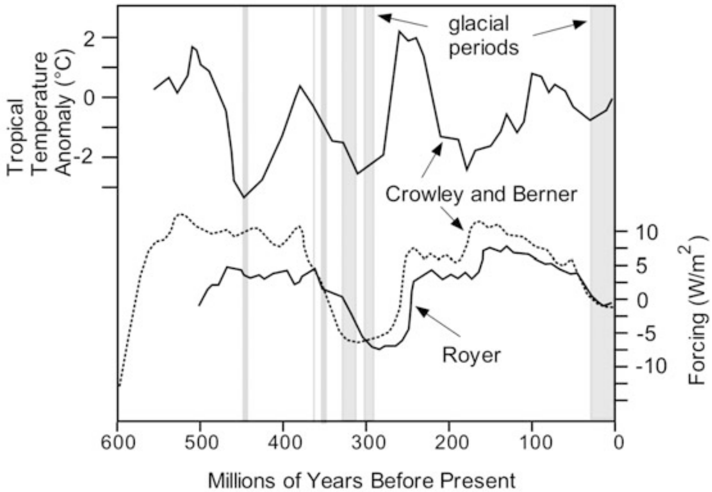



**Figure 2.34.** Royer (2006)'s estimate of the net forcing due to $CO_2$ variability and a gradually strengthening Sun compared with that of Crowley and Berner (2001). The vertical gray bars are Royer's estimates of glacial periods, as compared with the curve of temperature given by Crowley and Berner (2001).

$CO_2$ levels below 1000 ppm. A $CO_2$ threshold of below ~500 ppm is suggested for the initiation of widespread, continental glaciations, although this threshold was likely higher during the Paleozoic due to a lower solar luminosity at that time. Also, ... a $CO_2$ threshold of below ~1000 ppm is proposed for the initiation of cool non-glacial conditions. A pervasive, tight correlation between $CO_2$ and temperature is found both at coarse (10 million-year timescales) and fine resolutions up to the temporal limits of the data set (million-year timescales), indicating that $CO_2$, operating in combination with many other factors such as solar luminosity and paleogeography, has imparted strong control over global temperatures for much of the Phanerozoic."

With the passage of time since about 2004, the belief that $CO_2$ controls global temperature has become more widespread. Vaughn (2007) reviewed the field and concluded that $CO_2$ concentration is an important factor in major long-term changes in climate.

Came *et al.* (2007) claimed that they had developed an improved method for estimating paleotemperatures. They claimed that their results show a much better correlation of $CO_2$ variability and temperature change. However, they only estimated the temperature at two specific times during the Phanerozoic, and their results are not very convincing to this writer.

Fletcher *et al.* (2008) contributed new estimates of $CO_2$ concentrations from 200 million years ago to 60 million years ago. They concluded that there is a coupling of $CO_2$ and temperature.

Breeker *et al.* (2010) developed yet another estimate of paleo-$CO_2$ concentrations over the past 400 million years. They also concluded that there is a coupling of $CO_2$ and temperature.

It is interesting that since 2004 each successive published paper purports to find a tighter relationship between $CO_2$ and temperature in the Phanerozoic, yet the data have not changed much. One possibility is that there really is such a correlation and better analyses have uncovered this. An alternate hypothesis is that only by emphasizing the role of $CO_2$ in climate change can one obtain research funding in the 21st century. As a result, increasingly more bias creeps into published papers as investigators seek to ingratiate themselves with orthodoxy. In all cases, the data are sparse, noisy, and difficult to interpret. It remains difficult to resolve the degree to which these two alternatives are involved.

#### *2.3.10.5 Climate sensitivity assuming "The Force" is with $CO_2$*

Perhaps the most pervasive issue in modern climatology is the question of how much global warming ($\Delta T$) in the 21st century would result from a doubling of the $CO_2$ concentration from the pre-industrial level of 280 ppm. While many estimates have been made, the canonical value often used is $\sim$3°C. Like the porridge in *The Three Bears*, this value is just right—not so great as to lack credibility and not so small as to seem benign. Unfortunately, all of the estimates made to date by various procedures lack adequate data and involve considerable speculation.

Assuming that variations in $CO_2$ concentration were the major cause of all historical climate change (which seems to be a widespread belief amongst paleoclimatologists) one can attempt to quantitatively estimate the relationship between changing $CO_2$ and global average temperature from the data. Unfortunately, most of the data are noisy and uncertain. According to Figures 2.25 to 2.27, the global average temperature dropped by roughly 11°C prior to the great glaciation around 300 million years ago, while R($CO_2$) dropped from roughly 16 to 1. A factor of 16 represents four doublings. Hence, one might conclude that going backward in time from 300 million years ago, each doubling of $CO_2$ produced a temperature rise of $11/4 = 2.8$°C. However, the glacial period at 445 million years ago would involve infinite climate sensitivity since $CO_2$ did not appear to vary much during that glacial period.

Royer *et al.* (2007) provided another estimate of climate sensitivity by fitting proxy data to a geological model for $CO_2$ during the Phanerozoic. Unfortunately, the data are sparse, noisy, and somewhat unreliable. Nevertheless, Royer *et al.* (2007) concluded that $\Delta T_G$ is greater than 1.5°C and the best fit for the effect of doubling $CO_2$ is $\Delta T_G \sim 2.8$°C.

#### *2.3.10.6 Correlation with galactic cosmic rays*

Veizer *et al.* (2000) presented

> "... a reconstruction of tropical sea surface temperatures throughout the

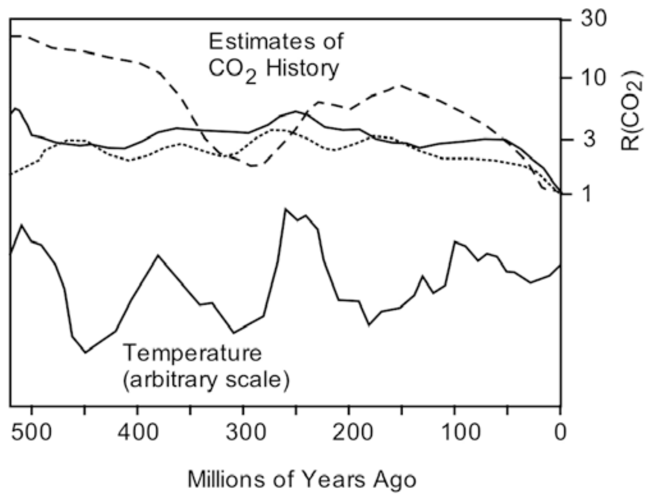



**Figure 2.35.** Comparison of estimates of $CO_2$ history with tropical sea temperature in the Phanerozoic (adapted from Veizer *et al.*, 2000).

> Phanerozoic eon from [their] database of oxygen isotopes in calcite and aragonite shells. The data indicated large oscillations of tropical sea surface temperatures in phase with the cold and warm cycles, thus favoring the idea of climate variability as a global phenomenon.''

But their data were not in consonance with reconstructed atmospheric carbon dioxide concentrations. They concluded: ''The results can be reconciled if atmospheric carbon dioxide concentrations were not the principal driver of climate variability on geological timescales for at least one-third of the Phanerozoic eon, or if the reconstructed carbon dioxide concentrations are not reliable'' (see Figure 2.35).

Shaviv and Veizer (2003) analyzed the ''reconstructed seawater paleotemperature record for the Phanerozoic and compared it with the variable cosmic ray flux (CRF) reaching Earth'' as well as ''the reconstructed partial pressure of atmospheric $CO_2$ ($pCO_2$).'' They found ''that at least 66% of the variance in the paleotemperature trend could be attributed to CRF variations, likely due to solar system passages through the spiral arms of the galaxy. Assuming that the entire residual variance in temperature is due solely to the $CO_2$ greenhouse effect, [they proposed] a tentative upper limit to the long-term 'equilibrium' warming effect of $CO_2$, one which is potentially lower than that based on general circulation models.'' They used Berner's estimates for $p(CO_2)$, and $\delta^{18}O$ values of calcitic shells to estimate proxy-based paleo tropical sea surface temperatures. Cosmic ray activity indicators were based on $^{10}Be$ and $^{14}C$ isotopes. The results of Shaviv and Veizer (2003) are shown in Figure 2.35. Paleo sea surface temperature anomalies were taken from estimates based on oxygen isotope proxies. The process by which Shaviv and Veizer arrived at temperature anomalies from variations in cosmic ray

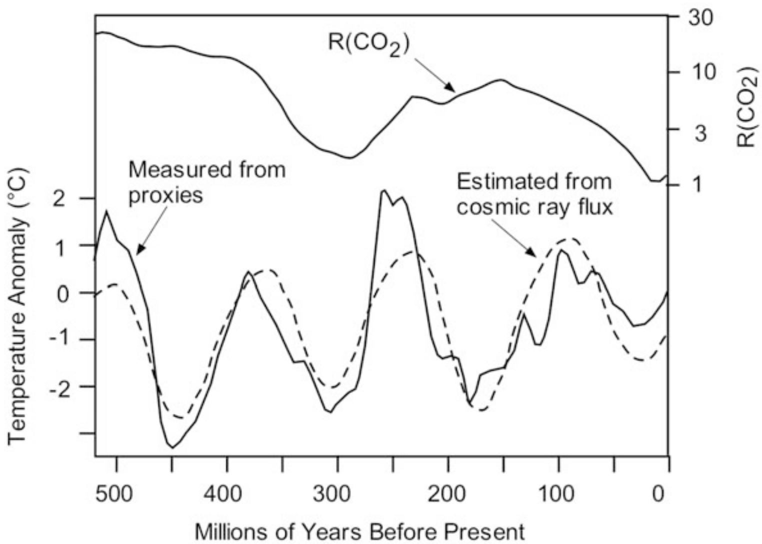



**Figure 2.36.** Comparison of R($CO_2$) and climatic effect of cosmic rays with estimated tropical sea surface temperature anomalies from proxies during the Phanerozoic (adapted from Shaviv and Veizer, 2003).

flux remains unclear to this writer. While Figure 2.36 is very supportive of the argument made by Shaviv and Veizer that cosmic rays are more important than $CO_2$ in determining long-term climate change, the basis for this figure seems murky.

However, as we discussed previously, Royer *et al.* (2004) presented corrected estimates of sea surface temperature during the Phanerozoic, due to changes in pH of the oceans induced by changes in the $CO_2$ level of the atmosphere and changes in Ca concentrations and the calcium carbonate saturation state in seawater. With these changes, the variability of $CO_2$ was claimed to conform better to paleo-temperatures, while the cosmic ray record does not. Shaviv and Veizer rebutted Royer's arguments, and the matter does not seem to be fully resolved.

### *2.3.10.7 Oxygen in the Phanerozoic atmosphere*

It would be overly simplistic to treat the Phanerozoic as if it were an extension of our current climate, but with variable $CO_2$ concentration. Continental drift produced significant changes in the distribution of landmasses on Earth, producing variable feedback effects in response to changing $CO_2$. The Earth's atmosphere was quite different. Atmospheric $O_2$ concentration varied considerably over the Phanerozoic. Oxygen levels reached as high as 30–35% in the so-called Permo-Carboniferous between about 330 and 270 million years ago. During that period, "giant insects, including dragonflies reached wing spans up to 80 cm. Along with dragonflies, there are unusually large amphibians, mayflies, millipedes, hexapods, and arachnids confined to this same time span, and these organisms also metabolize by passive diffusion. Thus, animal fossils provide further evidence for the hypothesized high $O_2$ concentrations during the Permo-Carboniferous" (Berner, 2004). The principal cause of the high $O_2$ values was the rise of large vascular land plants that brought about increased $O_2$ production due to the increased global burial of microbially resistant lignin-rich organic matter in sediments.

#### *2.3.10.8 Phanerozoic summary*

As with almost every area of climatology, data on the Phanerozoic climate and $CO_2$ concentrations are sparse and noisy, and the interpretation of the data in terms of climatological parameters requires complex models and various assumptions. Various investigators have arrived at different interpretations regarding the connection between $CO_2$ concentrations and climate change during the Phanerozoic. As Figure 2.35 shows, Shaviv and Veizer (2003) found a periodic variation in the climate that seemed to match variations in cosmic ray flux, and $CO_2$ variations that did not seem to be highly relevant to climate change. However, a different interpretation of the data suggests that $CO_2$ variability was associated with climate change and cosmic rays play at most a secondary role.

The evidence suggests that the Earth was relatively warm from about 550 to 400 million years ago, although the temperature may have varied considerably within that time frame. Around 400 million years ago, the Earth began to cool, and the cooling bottomed out with extensive glaciation for about 40 to 50 million years approximately 330 million years ago. Subsequently, the Earth warmed again, and finally cooled again during the most recent 100 million years. Variations of the climate on shorter time scales within that general scope are subject to considerable uncertainty. The data and models for $CO_2$ suggest that R($CO_2$) was very large prior to about 300 million years ago, peaking about 550 million years ago. R($CO_2$) declined slowly from 550 million years ago and very rapidly from 400 to 350 million years ago. The cold period centered around 300 million years ago was associated with very low values of R($CO_2$). Temperature rose significantly after about 280 million years ago but $CO_2$ rose only very moderately. Over the last 100 million years, temperatures and R($CO_2$) both declined. There seems to be very little doubt that major changes in the Earth's climate are at least sometimes associated with large changes in R($CO_2$).

Boucota and Gray (2001) provided a very lengthy detailed review of Phanerozoic climatic models and the relationship to the $CO_2$ content of the atmosphere. They concluded:

> "... considerable disparity exists between the curves generated by the varied models .... The wide disparities between the various published curves suggest that the presently published models are inadequate. Considerable disparity also exists between all the models and the geological climatic evidence indicating changing climatic gradients through the Phanerozoic. This indicates, based on

> present knowledge of climates of the geological past, that there is no simple straightforward relation between levels of atmospheric $CO_2$, as estimated by the various modelers and changes in the global climatic gradient.''

Although the review by Boucota and Gray (2001) was written prior to several of the papers cited herein, the conclusions seem to remain valid.

#### *2.3.10.9 Concluding remarks*

The widely held view amongst geologists and climatologists alike is that the primary cause of long-term climate changes is variability of $CO_2$ concentration due to long-term imbalances between $CO_2$ degassing at spreading centers and the conversion of atmospheric $CO_2$ to mineral carbon through long-term silicate weathering and oceanic carbonate formation. The argument goes (more or less): ''If it wasn't $CO_2$, what else could it have been?'' Foster *et al.* (2009) described this as the ''accepted paradigm'' that requires $CO_2$ to vary in unison with global temperature. Thus, paleoclimatologists have been trying for decades to establish a relationship between climate and $CO_2$ concentration over many millions of years. There is some evidence that over many millions of years, higher $CO_2$ concentrations are often, but not always, associated with warmer climates. However, there is a great deal of scatter in the $CO_2$ proxy data, and this relationship is difficult to pin down quantitatively. Royer (2010) began his commentary with the statement:

> ''Global temperatures have covaried with atmospheric carbon dioxide ($CO_2$) over the last 450 million years of Earth's history. Critically, ancient greenhouse periods provide some of the most pertinent information for anticipating how the Earth will respond to the current anthropogenic loading of greenhouse gases. Paleo-$CO_2$ can be inferred either by proxy or by the modeling of the long-term carbon cycle. For much of the geologic past, estimates of $CO_2$ are consistent across methods.''

This seems to be a rather optimistic view, considering the data from his paper (see Figure 2.37). This figure compares various estimates of tropical sea surface temperature (SST) with estimates of $CO_2$ concentration over the time period 120 million years ago to 40 million years ago. Royer's point (I think) is that throughout this period SST was at least several degrees warmer than today and, even though there is much scatter in the $CO_2$ estimates, the general level of $CO_2$ concentration was much higher than today. This argument seems to make some sense from 120 million years ago to $\sim$90 million years ago. Yet, there are difficulties from 70 million years ago to 50 million years ago when SST remained high, yet the $CO_2$ concentration appears to have been much lower. In any event, the extreme scatter in the data in Figure 2.37 does not convey confidence that any valid conclusions can be drawn.

The best chance to use paleoclimatic data to infer climate sensitivity is probably the Last Glacial Maximum (LGM) some 20,000 years ago, when the

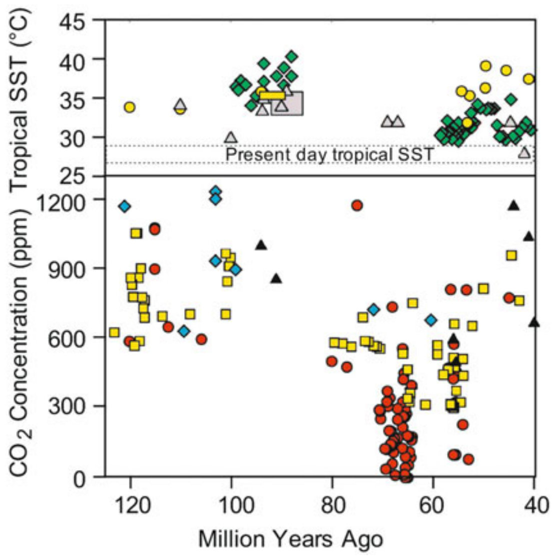



**Figure 2.37.** $CO_2$ and tropical sea surface temperatures (adapted from Royer, 2010).

total negative forcing produced a global average temperature decrease of roughly 4.5°C. Hansen and Sato (2011), Chylek and Lohmann (2008), and Kohler *et al.* (2009) all independently estimated the forcing at the LGM (see Table 2.2). The contribution of the diminution of $CO_2$ at the LGM to total cooling was estimated by these studies to be in the range 16 to 33%. While it seems likely that solar input to higher latitudes triggered the cycles, the variability of $CO_2$ concentration played a part in determining the extremity of the temperature cycle that resulted from this trigger. The changes in $CO_2$ concentration between glacial maxima and interglacials ($\sim$180 to $\sim$280 ppm) are well documented in ice core records, although no one seems to have a satisfactory explanation for the $CO_2$ concentration changing this much (simple solubility in the oceans does not suffice). However, the estimates of forcings, particularly due to dust, vary considerably from investigator to investigator and it is difficult to pin down climate sensitivity to $CO_2$ change. However, changes in humidity and cloudiness are unknown and may be very large factors. There are good estimates available of global average temperature and the $CO_2$ concentration at the Last Glacial Maximum (LGM) 20,000 years ago, and if these data are compared with values in the pre-industrial era (a few hundred years ago) one can thereby estimate the sensitivity of the climate to $CO_2$ concentration over the range $\sim$180 to $\sim$280 ppm. Using this estimated climate sensitivity, one can then estimate the global average temperature rise in going from 280 to 560 ppm. The various investigators have come up with a range of projections. It is noteworthy that this range of estimates for the real world $\Delta T_G$ due to doubling $CO_2$ from 280 to 560 ppm is from $\sim$1 to $\sim$3°C. However, as we stated above, these estimates do not take into account possible differences in humidity and cloudiness.

The data on temperature and $CO_2$ over hundreds of millions of years are far less reliable, and conclusions drawn from these time periods are dubious at best.

Our conclusion here is that $CO_2$ is probably one of several major factors in long-term climate change, but other factors such as the placement of the continents on Earth, the functionality of ocean currents, the past history of the climate, the orientation of the Earth's orbit relative to the Sun, the luminosity of the Sun, the presence of aerosols in the atmosphere, volcanic action, land clearing, biological evolution, etc. are also important. Hence, there is probably no single curve relating global average temperature to $CO_2$ concentration but, rather, a set of curves that depend on the above factors.

## 2.4 CONTINENTAL DRIFT AND CONTINENTAL GEOMETRY AS A FACTOR IN PALEOCLIMATE CHANGE

### 2.4.1 Effects of continental geometry

Since the general acceptance of the continental drift theory, it has been widely surmised that changing continental geometries likely contributed to long-term climate change. However, it is not exactly clear how this occurred. "Continents are important to climate for three main reasons: they are a platform upon which polar glaciers can form; they are the primary sites of the silicate weathering reaction that governs atmospheric $CO_2$ (the amount of weathering is strongly affected by the continental configuration); they affect the geometry of ocean basins and, hence, the ability of oceans to transport heat from one latitude to another" (Pierrehumbert, 2009). Dietz and Holden (1970) provided a good description of the continental drift process. Campbell pointed out:

> "... at certain times in the past, the equatorial ocean currents were able to circulate the Earth. This allowed more warming because of a much higher rate of ocean re-circulation and currents diverging from the equator to the north and south would be warmer. Equatorial flows at other times have been blocked resulting in higher latitude currents forming circumpolar currents. This isolates the polar continents and causes polar temperatures to drop."

Frakes and Kemp (1972), Sellers and Meadows (1975), Kennett (1977), Ravelo *et al.* (2004), and many others have discussed the effects of continental drift on climate.

Several studies have been carried out using climate models to estimate the effect of hypothetical landmass distributions on global climate. However, none of these is entirely convincing. Nevertheless, without using climate models, we can draw a few conclusions in this regard.

The albedo of snow/ice cover may be as high as 0.9. The albedo of land depends upon the nature of the land (forest, desert, plains, etc.) but on average it is probably something like 0.35. The albedo of the oceans is probably about 0.1. The net albedo of the Earth depends on a global average of all land and ocean areas, but clouds add significantly to the global average albedo. The present day global average albedo is estimated to be roughly 0.3. During epochs when there are landmasses at high latitudes or at the poles, the potential for glaciation of polar areas increases significantly since snow falling on land can accumulate. This can increase the overall average albedo, leading to further cooling. Thus, landmasses at high latitudes are widely believed to be conducive to colder climates. Conversely, when most of the continents are at tropical or mid-latitudes, the accumulation of snow and ice will be constrained and the albedo of the Earth will be smaller. This will induce warming, and the lack of polar ice indicates that the oceans will be higher. Thus, continental margins will be flooded and the area of exposed continents will decrease (i.e., land area is converted to water area). This will decrease the global albedo further, producing more warming. Hence the occurrence of landmasses at polar or moderate latitudes promotes global cooling or warming, respectively.

While landmasses in polar areas are ideal sites for ice sheet formation, the total heat balance of the Earth is determined by how much solar energy gets absorbed. Since the preponderance of solar energy input to the Earth is in the tropics (where solar energy per unit area is a maximum, and land area per unit latitude is also a maximum) absorption of solar energy in the tropics is of paramount importance. Since land has a much higher albedo than water, an unusual preponderance of landmasses within middle to low latitudes will be conducive to global glaciation. Indeed, such a continental distribution occurred some 600 MYBP, and may have contributed to formation of a snowball Earth. This situation has not been encountered at any time subsequent to that period. Any resultant glaciation would further increase the Earth's albedo by lowering sea level, exposing continental shelves. Additional continents in the tropics would also increase the silicate weathering rate, thus reducing the atmospheric $CO_2$ concentration. It was suggested that these combined effects might lead to the growth of large ice caps, nucleated on islands or continents bordering the polar seas (Kirschvink, 2002).

Burrett (1982) carried out paleocontinental reconstructions for the period 570 to 200 MYBP and made rough estimates of land distribution amongst deserts, forests, etc. in order to estimate the albedo of the Earth. His goal was to test how geographical placement of land and overall global albedo affected paleoclimates. He did not find any obvious correlations of land placement and albedo with the onset of glaciation and suggested that the issues are more complex. It seems likely that merely having a landmass at one pole without major barriers to overall ocean flow, may not lead to glaciation.

Another important factor in determining the global climate is the network of pathways for ocean currents to transport heat. When the polar areas are openly exposed to ocean currents from equatorial zones, heat is efficiently transported to polar areas, thus reducing glaciation, raising the oceans, and warming the planet. When the polar areas are thermally isolated from equatorial zones, they are more likely to freeze over, thus cooling the planet. The presence of a wide network of mid-latitude landmasses can obstruct transport of heat to polar areas.

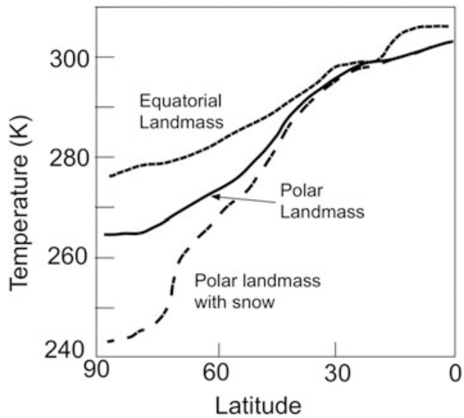



**Figure 2.38.** Dependence of temperature on latitude for three hypothetical distributions of landmass.

Warm wet landmasses located in the tropics enhance the uptake of $CO_2$ by silicate rock weathering. An additional factor is the placement of the landmasses. If they are conjoined, the humidity in the interior is likely to be low, thus reducing $CO_2$ uptake by the land. Conversely, if the land is distributed as separate bodies with close access to moisture from nearby oceans, $CO_2$ uptake by tropical landmasses is enhanced. Thus, the $CO_2$ concentration in the atmosphere can undergo wide variations over geologic time as continental drift rearranges the continents. This will affect global climate via the greenhouse effect.

In one study of note, two idealized continental geometries based on present day total land area were analyzed with a climate model: (1) a tropical land belt 17°N to 17°S and (2) polar land caps from 90° to 45°N and S (Barron, 1984). The polar land cap model was subdivided into two subordinate cases, one of which was unconstrained, and the other had imposed a thin permanent snow cover from 70° to 90°N and S. The resultant temperature profiles vs. latitude are shown in Figure 2.38. Note that the modeled profile for polar landmass with snow is similar to that which exists today.

Smith and Pickering (2003) proposed what they called a "unifying explanation for the four major icehouses during the past ~620 million years." All four icehouses developed when a large continent lay within or less than 1,000 km from one or both geographic poles but there have been periods when a polar continent such as Antarctica has not been glaciated. Thus a polar or sub-polar position for a continent appears to be a necessary (but not sufficient) condition for widespread glaciation. High topography has also been invoked as an important factor. Other important factors for establishment of continent-wide ice sheets are the opening of high-latitude gateways and the closing of subtropical gateways. However, whether the changes in circulation lead to increased snow and ice accumulation in high-latitude regions depends in part on the strength of the contemporaneous circumpolar circulation. The problem is complex and requires numerical modeling.

The authors believed that astronomical factors and other processes became significant in driving glacial–interglacial events only after continental configurations, gateways, and associated ocean gyres were established.

Gerhard and Harrison (2001) suggested:

> "The primary driving force behind [long-term] climate cycling is tectonic, specifically by controlling distribution of landmasses on the Earth's surface, which in turn controls the geometry of ocean currents and thus the transfer of heat around the Earth. When equatorial ocean currents exist, the Earth tends to be in a greenhouse state. In contrast, when continents exist in positions that impede or block significant equatorial currents, the Earth tends to be in the icehouse condition. Transitions between the two states are slow but may be punctuated by rapid shifts."

The present distribution of land as a function of latitude is shown in Figure 2.39. Two thirds of the land area occurs in the Northern Hemisphere. This undoubtedly is the reason ice sheets form primarily in the NH during ice ages. The presence of land is necessary to allow the accumulation of ice. In addition, land responds more readily to seasonal changes than do the oceans. This might suggest that the level of summer insolation would control the ability of ice fields to expand or contract.

As M&M said:

> "The fundamental reason for this is lack of convection. In the oceans, heat can convect between depths as well as horizontally, but on land, heat must

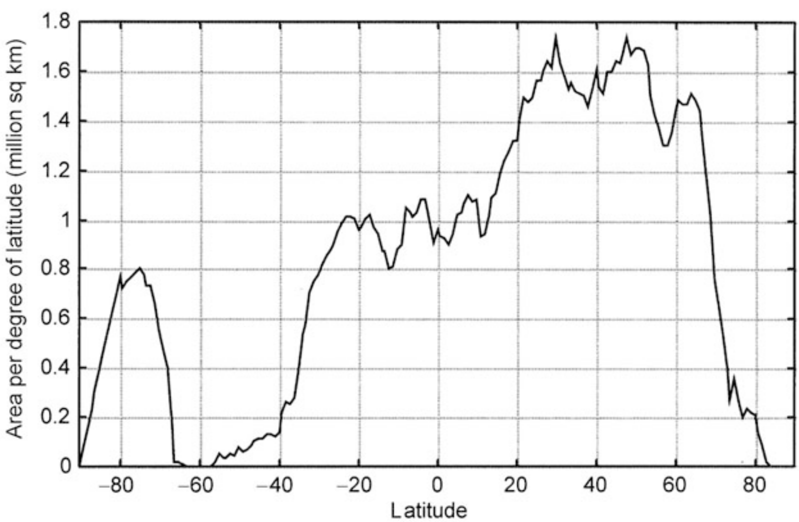



**Figure 2.39.** Land area vs. latitude on the Earth. Two thirds of the landmass is north of the equator (M&M, p. 189, by permission of Praxis Publishing).

diffuse, and that is a much slower process. Seasonal changes rarely penetrate more than about two meters. Ocean water mixes readily; cooling water contracts and sinks to the bottom until the temperature of the entire depth of water drops to 4°C. The uppermost 50 meters or so of the ocean, called the *mixed layer*, is thoroughly mixed by wind and waves. The importance of land in the formation of large glaciers is illustrated by the presence of glaciers in Greenland and Antarctica. These are the only landmasses that extend close to the poles, and they are the only ones with extensive glaciers remaining from the Ice Ages. In Greenland, the glaciers extend southward almost 30 degrees from the North Pole; in Antarctica, they extend about 20 degrees from the South Pole. Large areas in Canada and Russia that are closer to the North Pole than southern Greenland, but don't reach as close as northern Greenland, have no glaciation. This suggests that *polar roots* on land are necessary and, if they exist, then the glaciers can extend much further from the polar regions. Although sea ice covers the Arctic Ocean, it does not appear able to provide the same kind of roots that are provided by land."

Once glaciers begin to form, the increased albedo from their surfaces may provide a positive feedback to enhance their formation, although precipitation is also needed. It is not obvious that increased cold alone will lead to increased ice.

The modeled history of the Earth's climate and its relationship to the arrangement of landmasses is described in considerable detail by Christopher R. Scotese at his website (*http://www.scotese.com*). He provides maps of the landmasses roughly every 20 to 40 million years, starting around 540 million years ago, with brief descriptions of the prevailing climates. However, it is not always apparent why climates changed dramatically while the continents hardly changed over the same interval. For example, Scotese's maps for 480 million years ago and 440 million years ago are quite similar; yet he says that mild climates covered most of the globe 480 million years ago while a "South Polar Ice Cap covered much of Africa and South America" 440 million years ago.

### 2.4.2 Evolution of glaciation near the South Pole ~34 MYBP

Antarctica has been located over southern polar latitudes since about 150 MYBP, yet it is believed to have remained mostly ice free, vegetated, and with mean annual temperatures well above freezing until about 34 MYBP. About 34 million years ago, the Earth underwent a significant climate change. Evidence for cooling and the sudden growth of an East Antarctic ice sheet (EAIS) comes from marine records and other geological data (DeConto and Pollard, 2003).

"Fifty million years ago our planet was on average 6°C warmer, and atmospheric greenhouse gases, such as carbon dioxide ($CO_2$), were four times that of current levels.[6] Temperature changes at the poles were probably twice the

[6] It should be noted that Zachos *et al.* estimated that 50 million years ago the Earth was about 12°C warmer than today.

global average. Antarctica did not have an ice sheet, but may have had small regions of alpine glaciation and a temperate climate that supported large areas of forest-like vegetation including palms, ferns, and rainforest trees .... About 34 million years ago, at the end of the Eocene Period, a 'sudden' (in just 200,000 years) fall in global temperature of 3–4°C occurred. This cooling led to the expansion of ice on Antarctica by up to 10 million km$^3$, and a corresponding fall in global sea level of up to 40 m as ocean water was incorporated into the continental ice sheet. The development of an ice sheet on Antarctica is one of the most significant changes to Earth's climate known in the geological record. It marks the abrupt end of the so-called 'greenhouse' world, and the beginning of the 'icehouse' world'' (Naish).

The main evidence for cooling and sudden growth of ice on Antarctica comes from isotope measurements on ocean sediments containing matter that was ice-rafted from icebergs calving off the edges of the Antarctic ice sheet. Deep-sea cores prior to 34 MYBP contain plant pollen originating from the nearby Antarctic continent indicating that lush temperate forests prevailed, whereas at later dates they were replaced by colder climate tundra.

Kennett (1977) pointed out that the Antarctic continent had been in a high-latitude position long before glaciation commenced there. However, continental glaciation developed only when the present day Southern Ocean circulation system became established, as obstructing landmasses moved aside. He described the historical evolution of continental drift:

| | |
|---|---|
| 65–55 MYBP | Australia and Antarctica were joined. |
| 55 MYBP | Australia began to drift northward from Antarctica, forming an ocean, although circum-Antarctic flow was blocked by the continental South Tasman Rise and Tasmania. |
| 55–38 MYBP | The Southern Ocean was relatively warm and Antarctica largely non-glaciated. |
| 38 MYBP | A shallow-water connection had developed between the southern Indian and Pacific Oceans. Substantial Antarctic sea ice began to form. This resulted in a rapid temperature drop in bottom waters of about 5°C. Thermohaline oceanic circulation was initiated at this time much like that of the present day. |
| 39–22 MYBP | Gradual isolation of Antarctica from Australia and perhaps the opening of the Drake Passage. Widespread glaciation probably occurred throughout Antarctica, although no ice cap existed. |
| 14–11 MYBP | The Antarctic ice cap formed. This occurred at about the time of closure of the Australian–Indonesian deep-sea passage. |

One theory is that the freezing of Antarctica was caused by a series of movements in Earth's major tectonic plates, because the timing of ice sheet growth in Antarctica coincided with sea-floor spreading that pushed Antarctica away from Australia and South America. The opening of these ocean gateways produced a strong circumpolar current in the Southern Ocean that is thought to have thermally isolated the Antarctic continent, cooling it to a level where an ice sheet could rapidly grow (Naish). This belief is supported by ocean general circulation model simulations, which indicate that these changes would have reduced southward oceanic heat transport, thus cooling Southern Ocean sea surface temperatures (DeConto and Pollard, 2003).

However, an alternative explanation has been offered in which declining $CO_2$ (from 1,200 ppm at 50 MYBP to 600 ppm at 34 MYBP) initiates ice sheet height/mass balance feedbacks that cause the ice caps to expand rapidly with large orbital variations, eventually coalescing into a continental-scale East Antarctic Ice Sheet. According to this model, the opening of Southern Ocean gateways plays a secondary role in this transition, relative to $CO_2$ concentration. This model for the glacial inception and early growth of the East Antarctic Ice Sheet used a general circulation model with coupled components for atmosphere, ocean, ice sheet, and sediment that incorporated palaeogeography, greenhouse gases, changing orbital parameters, and varying ocean heat transport (DeConto and Pollard, 2003). However, assumptions regarding past changes in $CO_2$ concentration seem somewhat contrived and, furthermore, it seems very unlikely that a $CO_2$ level of 1,200 ppm could drive global average temperature up by 12°C.

There is some uncertainty as to how stable the Antarctic ice sheets have been over the past 34 million years. According to Naish, "geological evidence shows that global sea level has risen and fallen by 10 to 40 m many times during the last 34 million years, with each cycle of sea level change lasting 40,000 or 100,000 years." The sea level changes imply that Antarctica had extensive periods when its ice sheets were highly unstable, fluctuating in volume by up to 80%. This is thought to be particularly true between 34 and 15 million years ago when atmospheric $CO_2$ levels may have been twice as high as today and global average temperatures may have been 2°C warmer than today. Naish claims: "a second major cooling step occurred about 15 million years ago when the Antarctic ice sheets are thought to have expanded to their present size."

### 2.4.3 Effect of the Isthmus of Panama on NH glaciation in the past 2,700,000 years

Haug (2004) raised some vital questions:

> "Why did Antarctica become covered by massive ice sheets 34 million years ago, while the Arctic Ocean acquired its ice cap only about 3 million years ago? Since the end of the extremely warm, dinosaur-dominated Cretaceous Era 65 million years ago, heat-trapping greenhouse gases in the atmosphere have ... declined ... and the planet as a whole has steadily cooled. So why didn't both poles freeze at the same time?"

According to Haug (2004), the explanation for glaciation of Antarctica is straightforward:

> "The supercontinent of Gondwana broke apart, separating into subsections that became Africa, India, Australia, South America, and Antarctica, and passageways opened between these new continents, allowing oceans to flow between them. When Antarctica was finally severed from the southern tip of South America to create the Drake Passage, Antarctica became completely surrounded by the Southern Ocean. The powerful Antarctic Circumpolar Current began to sweep all the way around the continent, effectively isolating Antarctica from most of the warmth from the global oceans and provoking large-scale cooling."

However, the explanation for the delay in glaciation of the Northern Hemisphere is more problematic. Haug (2004) emphasized the "huge gap" in Central America that allowed tropical water to flow between the Atlantic and Pacific Oceans. When the Isthmus of Panama formed about 3 MYBP, it partitioned the Atlantic and Pacific Oceans and may have fundamentally changed global ocean circulation. According to Haug (2004), before the Isthmus of Panama formed, Pacific surface waters mixed with Atlantic waters, roughly balancing the two oceans' salinity. However, the North American, South American, and Caribbean Plates began to converge about 5 MYBP slowly forming the Isthmus of Panama. This gradually restricted the exchange of water between the Pacific and Atlantic, and their salinities diverged. Evaporation in the tropical Atlantic and Caribbean left those ocean waters saltier and put fresh water vapor into the atmosphere. The Trade Winds carried the water vapor from east to west across the low-lying Isthmus of Panama and deposited fresh water in the Pacific through rainfall. As a result, the Pacific became relatively fresher, while salinity steadily increased in the Atlantic. As this salinity increased after closing of the Pacific–Atlantic connection—also known as the "Central American Seaway" (CAS)—the water transported northward in the Atlantic became warmer and saltier. As Haug (2004) explained:

> "As this water reaches high North Atlantic latitudes, it transfers heat and moisture to the atmosphere, leaving behind cold, salty, dense water that sinks toward the ocean floor. This water flows at depths, southward and beneath the Gulf Stream, to the Southern Ocean, then through the Indian and Pacific Oceans. Eventually, the water mixes with warmer water and returns to the Atlantic to complete the circulation. The principal engine of this global circulation, often called the Ocean Conveyor, is the difference in salt content between the Atlantic and Pacific Oceans."

According to Haug (2004), the Gulf Stream intensified as a result of the closure of the Pacific–Atlantic connection, and this transported more warm salty watermasses to high northern latitudes, amplifying the Ocean Conveyor. In 1968, Peter Weyl hypothesized that this would have brought a critical ingredient for ice sheet growth to the Northern Hemisphere—moisture—leading to a buildup of ice sheets in the north (Keigwin, 1982). However, evidence later developed that the salinity contrast between the Atlantic and Pacific had already started to develop by 4.2 MYBP. Thus, Haug raised the question: "If the salinity had already changed by 4.2 million year ago, why didn't glaciation start until 2.7 million years ago? On the contrary, the Earth experienced a warm spell between 4.5 million and 2.7 million years ago." And in a similar way, we could ask why did glaciation begin about 2.7 MYBP? Haug (2004) provided a possible answer but it seems rather contrived.

A more recent study (Bartoli *et al.* 2005) emphasized that the Pleistocene climate has been characterized by a persistent succession of glacial–interglacial cycles that they believe were driven by orbital forcing. However, these Northern Hemisphere glaciations (NHGs) and large-scale Arctic sea ice did not begin until about 3 MYBP, which they argued was an epoch when a major reorganization of the ocean–climate system took place. This event appears to be connected to the final closure of the CAS, ending the introduction of Pacific surface water into the Atlantic Ocean. They raised two questions in regard to this event:

(1) What was the precise timing of the final closure of the CAS?
(2) Was there a causal relationship between the CAS closure and the onset of NHGs?

Bartoli *et al.* (2005) studied high-resolution data from planktic and benthic foraminifers in the northern North Atlantic, a region crucial for the understanding of NHGs. They examined evidence of continental-scale ice sheets, especially on Greenland, recorded as ice-rafted detritus released from drifting icebergs into sediments of the mid- and high-latitude ocean. After a transient precursor event at 3.2 MYBP, signals of large-scale glaciations suddenly started in the North Atlantic in two steps, at 2.92–2.82 MYBP and 2.74–2.64 MYBP. They also noted that the time period around 2.7 MYBP was the onset of ice-rafted detritus in the Pacific. Thus they described an irreversible "climate crash" that began from 2.74–2.64 MYBP. This climate crash is reflected in the sudden change in benthic and planktic species that took place over a small time interval. They also found evidence for a "major expansion of global ice volume" and the consequent drop in sea level from 2.92 to 2.64 MYBP was estimated at 45 m.

Bartoli *et al.* (2005) established the time scale for the onset of glaciation in the NH. However, it is not clear that they established the connection between closure of the CAS and the onset of glaciation except to point out that glaciation followed soon after the closure. The two questions raised by them remain answered only in vague terms. The cause–effect relationship between closing of the CAS and the onset of glaciation in the NH remains difficult to prove.

Several studies have employed climate models to investigate the matter. Murdock *et al.* (1997) employed a coupled ocean–atmosphere climate model to study two cases: the CAS fully open and the CAS fully closed. They found that

CAS closure "was more conductive to North Atlantic deep water formation," and that the North Atlantic warmed "significantly" after CAS closure, resulting in "increased evaporation and precipitation along its borders." They concluded that their results were "consistent with the hypothesis [that CAS closure led to glaciation in the NH] although it is not possible to completely refute or verify it on the basis of model output."

Lunt *et al.* (2008) tested the hypothesis that closure of the CAS led to NH glaciation by using a fully coupled fully dynamic ocean–atmosphere general circulation model with boundary conditions specific to the Pliocene, and a high-resolution dynamic ice sheet model. They carried out two GCM simulations with closed and open Panama seaways, and used the simulated climatologies to force the ice sheet model. They found that the models support the Panama Hypothesis to a modest extent, in that the closure of the seaway results in a more intense Atlantic thermohaline circulation, enhanced precipitation over Greenland and North America, and ultimately larger ice sheets. However, the volume difference between the ice sheets in the closed and open configurations was found to be small, equivalent to about 5 cm of sea level. They therefore concluded that although the closure of the Panama seaway may have slightly enhanced or advanced the onset of NH glaciation, it does not appear to be a major forcing mechanism.

Nisancioglu *et al.* (2003) also performed interesting studies but did not resolve the issue.

Prange and Schulz (2005) used a climate model to investigate the effect of closure of the CAS on the climate of the NH. The model results indicate an increase in annual mean sea surface temperatures of about 1°C in the North Atlantic and North Pacific oceans as a result of the Panama closure.

Driscoll and Haug (1998) offered an alternative hypothesis for the onset of NH glaciation due to closing of the CAS. They argued that closing the Panamanian isthmus would increase thermohaline circulation and bring enhanced moisture supply to high latitudes, promoting ice and snow formation at high latitudes, but the accompanying heat release would have inhibited ice growth. Instead, they proposed a possible solution whereby enhanced moisture transported to Eurasia would enhance freshwater delivery to the Arctic via Siberian rivers. Freshwater input to the Arctic would facilitate sea ice formation, increase the albedo, and isolate the high heat capacity of the ocean from the atmosphere. It would also act as a negative feedback on the efficiency of the "ocean conveyor belt heat pump".

Molnar (2008) provided a critical review of the relationship between closing of the CAS and the onset of ice ages in the NH. He concluded that the relevant evidence can be interpreted to permit a causal relationship between them but can also be interpreted to show no such relationship. The approximate simultaneity of the closing of the CAS with the onset of global cooling and the first major ice advance is highly suggestive. However, he concluded that the timing of the actual closure has not been pinpointed. The hypothetical connection between a closed CAS and the onset of glaciation requires profoundly different North Atlantic

Ocean circulation, but simulations using general circulation models provide a range of differences in circulation for open and closed seaways.

Steph *et al*. (2010) wrote a lengthy paper dealing with changes in the Pacific between about 4.8 and 3.6 MYBP but its relevance to the onset of glaciation after that time is somewhat nebulous to this writer.

In an interesting related study, Cane and Molnar (2001) pointed out that global climate change around 3–4 MYBP is thought to have influenced the evolution of hominids, via the aridification of Africa, and may have been the precursor to Pleistocene glaciation about 2.75 MYBP. Whereas most explanations of these climatic events involve changes in circulation of the North Atlantic Ocean due to the closing of the Isthmus of Panama, they suggested that closure of the Indonesian seaway 3–4 MYBP ago could be responsible for the aridification of Africa and other climate changes. Their model indicated that northward displacement of New Guinea, about 5 MYBP, might have switched the source of flow through Indonesia from warm South Pacific waters to relatively cold North Pacific waters. This would have decreased sea surface temperatures in the Indian Ocean, leading to reduced rainfall over eastern Africa. They further suggested that changes in the equatorial Pacific might have reduced atmospheric heat transport from the tropics to higher latitudes, stimulating global cooling and the eventual growth of ice sheets.

Uriarte (2009) provided a revealing discussion of the relation between the formation of the Isthmus of Panama and the freezing of the Arctic. He described "a somewhat paradoxical theory" in which the closure of the isthmus reduced leakage of warm Caribbean water to the Pacific, and thus increased the flow of warm water transported by the Gulf Stream to the North Atlantic. This increased evaporation, and "as a result, rainfall levels rose in Siberia, thus increasing the amount of water discharged by the Siberian rivers into the Arctic, facilitating its winter freezing, since fresh water freezes at a higher temperature than salty water. In a positive feedback process, the freezing of the surface waters in the Arctic increased the albedo over a vast region and furthermore isolated the ocean from the atmosphere, thus decreasing the transfer of heat from the water to the air." Uriarte illustrated this theory with a figure as shown in Figure 2.38a.

Uriarte also described a second theory that

> "... postulates that before the formation of the isthmus, the Gulf Stream penetrated much further into the Arctic than afterwards. Thus, before the change in ocean currents, the Arctic remained unfrozen, at least in summer. When the Panama isthmus was still open, part of the flow of very salty water from the Atlantic equatorial current escaped out into the Pacific instead of turning north. This meant that the salinity and density of the surface current of both the Gulf Stream and the North Atlantic Drift was lower, which facilitated its penetration into the Arctic Ocean. However, when the isthmus finally closed off the passage between the Atlantic and the Pacific, the proportion of tropical waters in the upward flow increased, as did its salinity. The water mass transported by the

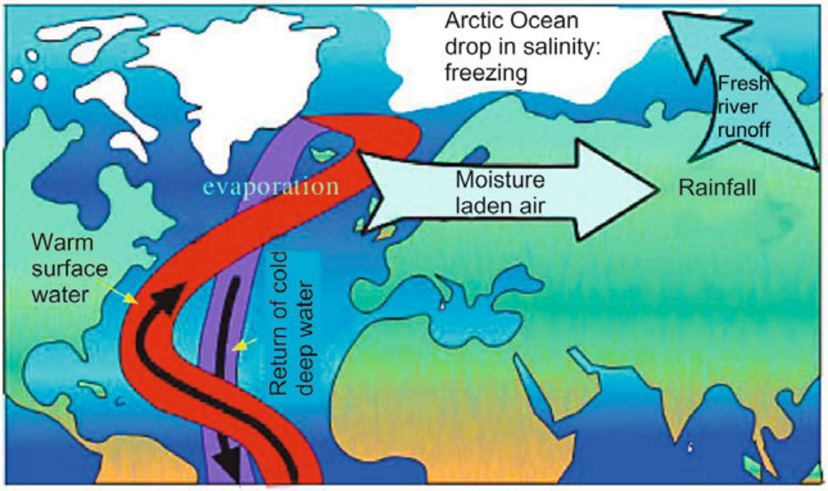



**Figure 2.40.** Arctic freezing induced by increased flow of tropical waters to the north (adapted from Uriarte, 2009).

> current, already fairly dense and salty, became even denser as it cooled on its way north, and so sunk before reaching the Arctic Ocean."

The decreased penetration of tropical waters to the north resulted in cooling and eventual glaciation of the north. Uriarte prepared a diagram of this theory as shown in Figure 2.38b.

## 2.5 ICE AGES IN THE RECENT GEOLOGICAL PAST

As we shall demonstrate in the sections of this book that follow, there is evidence that the climate of the Earth has undergone significant sharp oscillations over the past 3 million years, superimposed on a downward long-term trend (Zachos *et al.*, 2001). The Earth has vacillated between two end points.

At one end point the climate of the Earth is not unlike that prevailing today, give or take a few degrees. Under these conditions, there are residual ice sheets covering Antarctica and Greenland, and the poles are covered with snow and ice the year around. However, the climate of the Earth at moderate latitudes is quite benign. This is commonly called an interglacial period, and the current interglacial period is known as the "Holocene". There is evidence that there may have been significant temperature fluctuations during past interglacials, and the Holocene appears to be unique in its duration and stability. Furthermore, there is some evidence that the previous two interglacials reached higher temperatures than we have experienced in the Holocene.

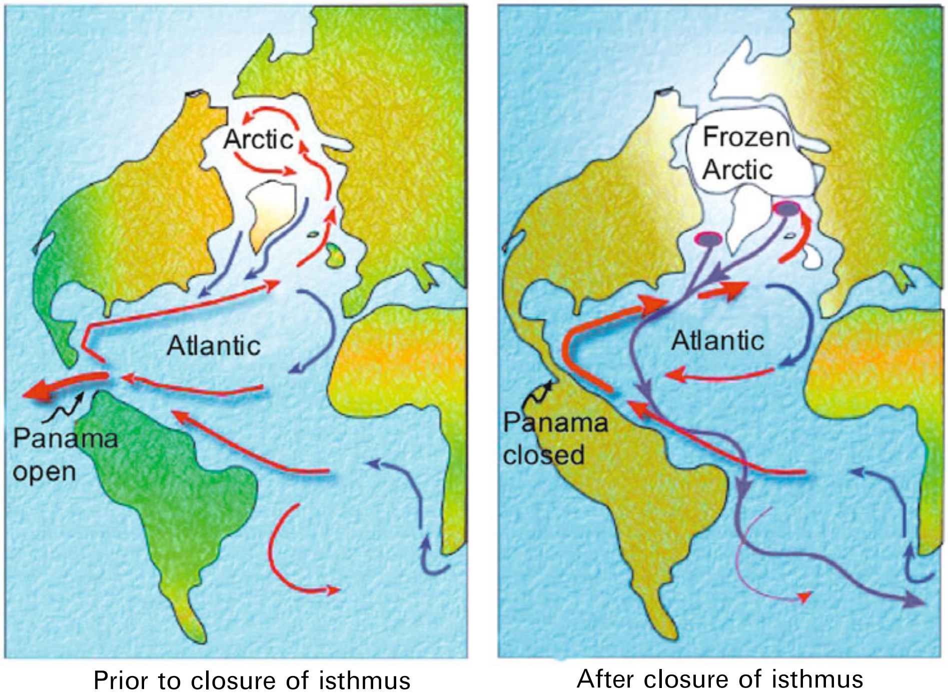



**Figure 2.41.** Arctic freezing induced by decreased flow of tropical waters to the north (adapted from Uriarte, 2009).

At the other end point, a gigantic ice sheet forms over much of Canada and Scandinavia which, in combination with Antarctica, sequesters so much of the Earth's water as ice that the ocean level drops by more than 100 meters,[7] global average temperatures drop significantly, and temperatures at high latitudes drop even more. Figure 2.42 shows an estimate of global average temperature over the past 3 million years. The data in this figure indicate that there have been oscillations about a continuing downward trend, and over the past few hundred thousand years the duration and depth of the cold periods has increased. We refer to these cold periods as ice ages. Clearly, these temperature variations were not nearly as extreme as the climate extremes described in previous sections (hothouse or snowball Earth). Nevertheless, the occurrence of an ice age has a major world-wide impact on the geography, weather, flora, and fauna of the planet. In the ensuing chapters we will describe what is known from experimental data about past ice ages and we will review the theories that have been offered to explain their occurrence.

[7] The removal of water from the oceans was actually about 50 m greater than this because the crust below the ocean rebounded about 50 m when water was removed at the LGM.

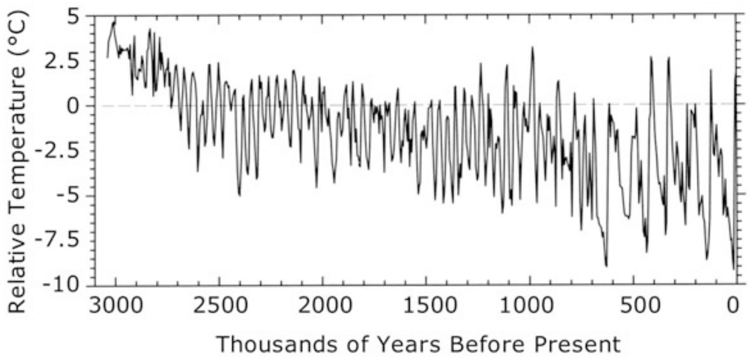



**Figure 2.42.** Global average temperature over the past 3 million years (adapted from Raymo, 1992).

## 2.6 GEOLOGICAL EVIDENCE OF ICE AGES

A few geologists of the 19th century noted the presence of large boulders with characteristic scratch marks in the Swiss Alps and scratch marks on the walls of rock in mountains; they suggested that these may have been generated by huge ancient glaciers that covered the mountains. The three main sources of evidence were: (1) grooves and scratches on rocks in place and on boulders shoved along under the ice, (2) extensive unstratified deposits known as "till" traceable to glacier action, and (3) transported material that could only have been delivered by ice (not water).

Louis Agassiz was the principal proponent of the ice age theory, but it took many years to gain acceptance. Imbrie and Imbrie (1979) described this history in their classic book. Prior to the implementation of ice core drilling and use of sediments to infer historical temperatures tens or hundreds of thousands of years ago, geologists had to rely on their observations of rocks and strata for guidance. Three books written around the turn of the end of the 19th century provide good insights into what was known prior to modern techniques for estimating historical temperatures. Geike (1894) provided Figures 2.43 and 2.44.

Bubble Rock in Maine is a favorite subject for photographers (see Figure 2.45).

According to Wright (1920), rocks with scratches and striations longitudinally along their longest diameters are evidence of glacial action:

> "It is easy to see that the stones of all sizes, while being dragged along underneath the ice, would be held in a comparatively firm grasp as to be polished and striated and scratched in a peculiar manner. On the shores of bays and lakes and in bottoms of streams we find that the stones are polished and rounded in a symmetrical manner, but are never scratched. The mobility of water is such that the edges and corners of the stones are rubbed together by forces acting successively in every possible direction. But in and under the ice the firm grasp of the

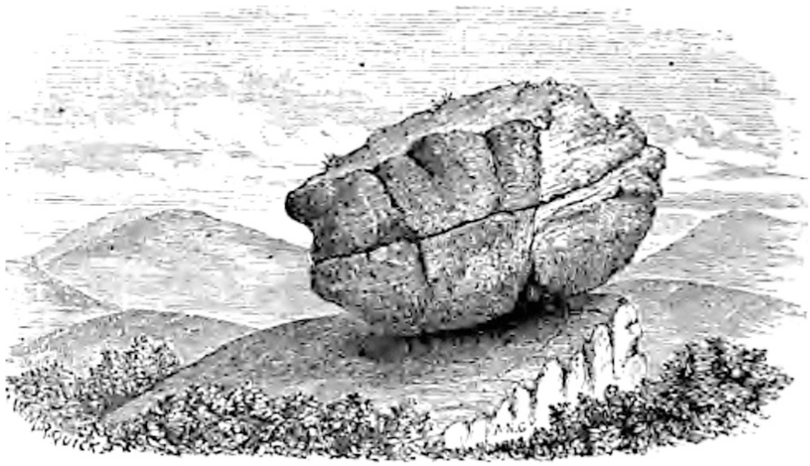


**Figure 2.43.** Erratic stone (Geike, 1894).

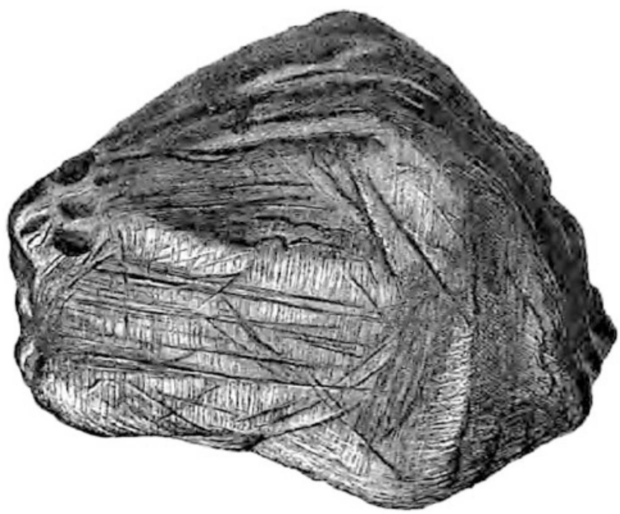


**Figure 2.44.** Scratched stone (Geike, 1894).

stiff semi-fluid causes the stony fragments to move in a nearly uniform direction, so that they grate over the underlying rocks like a rasp .... From the stability of the motion of such a substance as ice there would ... result grooves and striation both on the rocks beneath and on the boulders and pebbles that, like iron plowshares, are forced over them. Scratched surfaces of rock and scratched stones are therefore, in ordinary cases, most trustworthy indications of glacial

**Figure 2.45.** Bubble Rock, Acadia, Maine (*http://flickr.com/photos/iamtonyang/29259194/*).

action. The direction of the scratches upon these glaciated boulders and pebbles is also worthy of notice. The scratches upon the loose pebbles are mainly in the direction of their longest diameter—a result that follows from a mechanical principle that bodies forced to move through a resisting medium most swing around so as to proceed in the line of least resistance. Hence the longest diameter of such moving bodies will tend to come in line with the direction of the motion.''

However, Wright (1920) cautioned:

> ''A scratched surface is, however, not an infallible proof of the former presence of a glacier where such a surface is found, or, indeed, of glacial action at all. A stone scratched by glacial forces may float away upon an iceberg and be deposited at a great distance from its home. Indeed, icebergs and shore-ice may produce, in limited degree, the phenomena of striation that we have just described.''

Wright (1920) went on to say that although longitudinal striations can be caused by factors other than moving ice, these can by identified by the informed observer:

> ''Stones are also striated by other agencies than moving ice. Extensive avalanches and landslides furnish conditions analogous to those of a glacier, and might in limited and favorable localities simulate its results. In those larger

> geological movements, also, where the crust of the earth is broken and the edges of successive strata are shoved over each other, a species of striation is produced. Occasionally this deceives the inexperienced or incautious observer. But by due pains all these resemblances may be detected and eliminated from the problem, leaving a sufficient number of unquestionable phenomena due to true glacial action."

Wright (1920) also made the point that deposits left by moving water are always stratified:

> "A second indubitable mark of glacial motion is found in the character of the deposit left after the retreat of the ice. Ice and water differ so much from each other in the extent of their fluidity, that there is ordinarily little danger of confusing the deposits made by them. A simple water deposit is inevitably stratified. The coarse and fine material cannot be deposited simultaneously in the same place by water alone. Along the shores of large bodies of water the deposits of solid material are arranged in successive parallel lines, the material growing finer and finer as the lines recede from the shore. The force of the waves is such in shallow water that they move pebbles of considerable size. Indeed, where the waves strike against the shore itself, vast masses of rock are often moved by the surf. But, as deeper water is reached, the force of the waves becomes less and less at the bottom, and so the transported material is correspondingly fine, until, at the depth of about seventy feet, the force of the waves is entirely lost; and beyond that line nothing will be deposited but fine mud, the particles of which are for a long while held in suspension before they settle.
>
> In the deltas of rivers, also, the sifting power of water may be observed. Where a mountain-stream first debouches upon a plain, the force of its current is such as to move large pebbles, or boulders even, two or three feet in diameter. But, as the current is checked, the particles moved by it become smaller and smaller until in the head of the bay, or in the broad current of the river which it enters, only the finest sediment is transported. The difference between the size of material transported by the same stream when in flood and when at low water is very great, and is the main agent in producing the familiar phenomena of stratification. During the time of a flood vast bodies of pebbles, gravel, and sand are pushed out by the torrent over the head of the bay or delta into which it pours; while during the lower stages of water only fine material is transported to the same distance; and this is deposited as a thin film over the previous coarse deposit. Upon the repetition of the flood another layer of coarser material is spread over the surface; And so, in successive stages, is built up in 'all the deltas of our great rivers a series of stratified deposits'. In ordinary circumstances it is impossible that coarse and fine material should be intermingled in a water deposit without stratification. Water moving with various degrees of velocity is the most perfect sieve imaginable; so that a water deposit is of necessity stratified."

By contrast, deposits left by moving ice are not stratified:

> "It is evident that ice is so nearly solid that the earthy material deposited by it must be unassorted. The mud, sand, gravel, pebbles, and boulders, dragged along underneath a moving stream of ice, must be left in an unstratified condition—the coarse and the fine being indiscriminately mingled together. This is the character of the extensive deposits of loose material that cover what we designate as a glaciated region .... [In such an] unstratified deposit, a variety of materials is mingled that were derived from rocks both of the locality and from far-distant regions. Moreover, the pebbles in this deposit are the most of them polished and scratched after the manner of those which we know to have been subjected to glacial action."

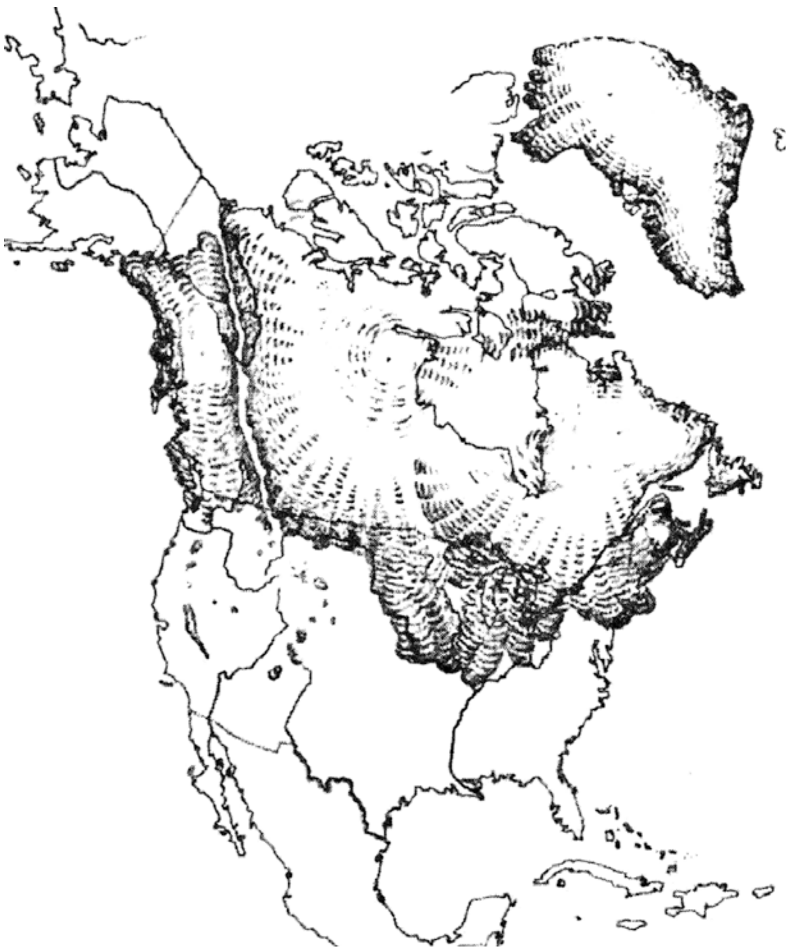


**Figure 2.46.** Extent of the most recent ice age in North America (Chamberlain in Geike, 1894).

Finally, Wright (1920) discussed the fact that the southern margin of the region where unstratified deposits containing striated stones and transported material was exceedingly irregular in two respects. The southern edge of these deposits does not follow a straight east–west line, but in places withdraws to the north (crenate character), and in other places extends lobe-shaped projections far to the south (serrate character). According to Wright, it was the crenate character of its southern border that was of most significance. Wright emphasized that the southern border, with its indentation and projections, was not determined by any natural barrier based on the geography of the region, but instead was determined by "the irregular losses in momentum such as would take place in a semi-fluid moving in the line of least resistance from various central points of accumulation."

Thomas C. Chamberlain (Geike, 1894) reviewed the geological evidence for glacial phenomena on the Earth's surface prior to acquisition of ice core and benthic data on past ice ages. In North America it was found that a tract of about 4,000,000 square miles had been overspread by glaciers and nearly one half of North America was covered with drift deposits. He mentioned the concerns of doubters but concluded: "the uncompromising evidence of the deposits themselves and by the ice-grooved rock floor on which these rest, seems to compel acceptance of the glacial theory." Chamberlain concluded that the extent of the ice sheet was roughly as shown in Figure 2.46.

These descriptions represent only a fraction of the ample evidence available to late 19th century geologists that there was a previous ice age, although the existence of multiple historical ice ages could only be conjectured.

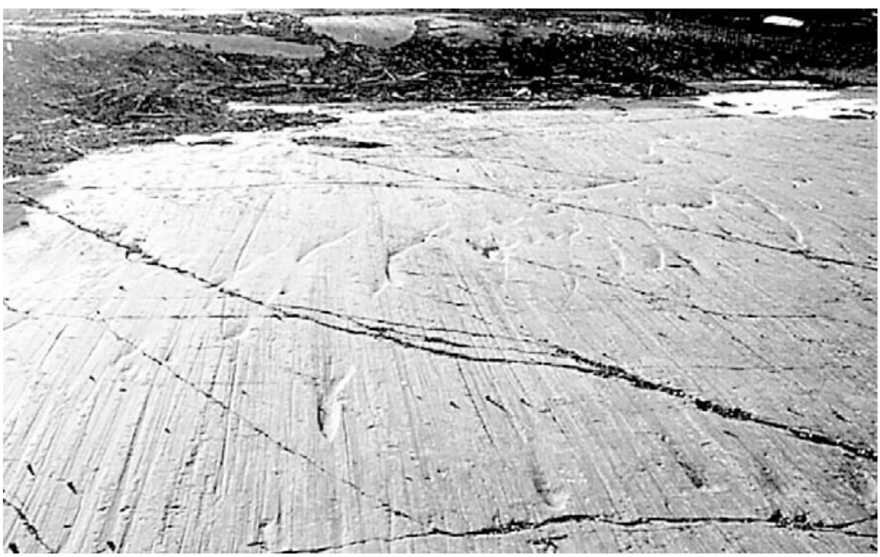


**Figure 2.47.** Glacial striations (UWESS).

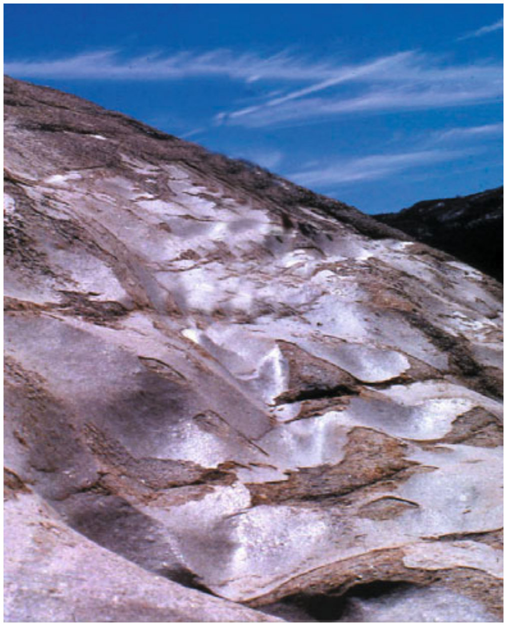


**Figure 2.48.** Example of polishing of bedrock by glacial silt (UWESS).

More recently, the University of Washington Earth and Space Sciences Department (UWESS) has produced a number of excellent presentations on ice ages that are very descriptive and instructive. The entire structure of the great valley in Yosemite National Park is presented as an example of a classic alpine glaciated landscape.

Glacial erosion occurs by abrasion, crushing and fracturing, and quarrying of joint blocks. Ice is not hard enough to abrade rocks, but rock fragments imbedded in the base of the glacier can abrade rocky terrain below, leaving characteristic striations (see Figure 2.47).

The UWESS described how glacier action can pluck large blocks leaving characteristic scalloped terrain. Fine silts suspended in glacial melt water can polish underlying bedrock (see Figure 2.48).

In addition, the UWESS provided many more examples and illustrations of past glacial action.

# 3

# Ice core methodology

## 3.1 HISTORY OF ICE CORE RESEARCH

Willi Dansgaard is a Danish scientist who is credited with the original idea of using ice cores to probe temperature changes over the past thousands of years. His book provides a very interesting history of the early evolution of this technique (Dansgaard, 2005).

There are different isotopic forms of water (hydrogen can either be H or D, and oxygen can either be $^{16}$O, $^{17}$O, or $^{18}$O). While 99.99% of water is $H_2{}^{16}O$, other forms (particularly $H_2{}^{18}O$ and the $HD^{16}O$) occur in concentrations of about 2,000 and 320 ppm (parts per million), respectively. When water evaporates a higher concentration of the lighter form of water appears in water vapor and, conversely, when water vapor condenses there is an increase in the concentration of the heavier form in the product liquid compared with the original vapor.

The concentrations of the heavy water components $H_2{}^{18}O$ and $HD^{16}O$ in water samples were originally expressed in parts per million. However, the isotopic composition of water is now presented as deviations of the concentrations of its heavy components from the composition of an international standard reference called SMOW (standard mean ocean water) and is designated by the symbol delta ($\delta$). In common use, $\delta^{18}O$ indicates $\delta(H_2{}^{18}O)$, whereas $\delta(D)$ indicates $\delta(HD^{16}O)$. The definition of $\delta^{18}O$ is:

$$\delta^{18}O \equiv \left( \frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{Sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{Reference}}} - 1 \right) \times 1{,}000$$


DOI 10.1007/978-3-642-30029-5_3, 

For δ(D), D replaces $^{18}O$ and H replaces $^{16}O$ in the above equation. Both of the δ values of SMOW are thus zero by definition. The units of δ are typically given in parts per thousand and assigned the symbol ‰ (with two zeros in the denominator as opposed to the percent sign, %, which would indicate parts per hundred). The SMOW reference contains 997,680 ppm of $H_2{}^{16}O$, 320 ppm of $HD^{16}O$, and 2,000 ppm of $H_2{}^{18}O$.

In 1952, Dansgaard pondered whether the isotopic composition of rainwater changed from one rain shower to the next. On a lark, he decided to carry out a series of simple studies by collecting rainwater in bottles in his yard. He was able to attribute the various phases of a two-day rainstorm to a descending pattern of cloudiness. As time went on, the rain was formed at steadily decreasing altitudes and therefore at steadily increasing temperatures. Dansgaard was able to show that the δ-value of the rain increased steadily (became less negative) as the temperature at which the rain formed increased. When a cloud produces rain, it loses more $H_2{}^{18}O$ than the corresponding concentration in vapor. This effect is greater the lower the temperature at which the rain forms. Dansgaard built upon this early experiment with much more sophisticated and extensive studies, including airplane flights into rain clouds to gather samples *in situ*. Eventually, he developed the model shown in Figure 3.1 for northern climes. Water evaporates from the sea with depleted $^{18}O$. As the clouds move toward shore they cool, and as rain continues to fall the remaining water vapor in the clouds is further depleted in $^{18}O$. Thus, as water-bearing clouds move inland, they cool ever more and the depletion of $^{18}O$ continues. The snow that accumulates on ice sheets above land is depleted in $^{18}O$ in proportion to the general climatic temperatures prevailing.

After that, Dansgaard carried out expeditions to large glaciers in northern Norway. Samples as old as 700 years were taken (based on carbon dating of $CO_2$ entrapped in air bubbles). However, analyses of the bubble air showed reduced

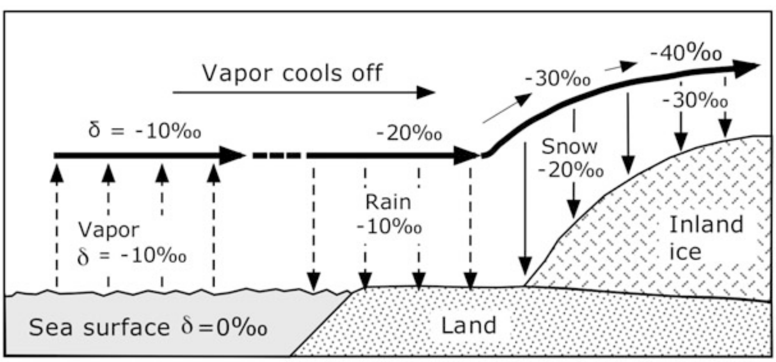



**Figure 3.1.** δ-changes (isotopic fractionation) in vapor and precipitation by evaporation from the sea, and precipitation from a cooling air mass as it moves towards higher latitudes and/or higher altitude (adapted from Dansgaard, 2005).

contents of the most soluble gases that were more or less washed out by melt water. It was concluded that old atmospheric air had to be sought in the deep cold glacier ice of Greenland or Antarctica.

The Greenland ice cap contains 50% of the fresh water on Earth outside Antarctica. The ice cap covers 85% of the area of Greenland. It measures 2,500 km from north to south and about 750 km from west to east in mid-Greenland. The surface reaches an elevation of 3,250 m above sea level at the highest point. Unlike the American and Scandinavian ice sheets built up during each ice age in the past, most of the Greenland ice cap survived the intervening warm periods for two reasons: (1) the high surface elevation (at present 2/3 of its area lies above 2,000 m) and (2) the ample supply of precipitation from the nearby Atlantic Ocean to replenish melt-off.

Accumulated past snowfall in the polar caps and ice sheets provides a basis for paleoclimate reconstruction. These are referred to as ice cores even though strictly speaking there is typically a combination of snow and ice. Somewhat compressed old snow is called "firn". The transition from snow to firn to ice occurs as the weight of overlying material causes the snow crystals to compress, deform, and recrystallize in more compact form. When firn is buried beneath subsequent snowfalls, the density is increased as air spaces are compressed due to mechanical packing as well as plastic deformation. Interconnected air passages may then be sealed and appear as individual air bubbles (see Figure 3.2). At this point the firn becomes ice. Paleoclimatic information derived from ice cores is obtained from four principal mechanisms: (1) analysis of the stable isotopes of hydrogen and atmospheric oxygen; (2) analysis of other gases in the air bubbles in the ice; (3) analysis of dissolved and particulate matter in the firn and ice; and (4) analysis of other physical properties such as thickness of the firn and ice. The firn–ice transition usually occurs at a depth of around 70 to 100 m, typically deeper in Antarctica than in Greenland.

The mechanism by which stable isotopes of oxygen and hydrogen carry a temperature signal is as follows. The vapor pressure of normal water is higher than the heavier forms of water (containing either $^{18}O$ or D or both) because the lighter molecules have higher average velocities at the same temperature. When liquid water evaporates, the vapor that is formed is relatively speaking poorer in the heavier forms of water. Conversely, the remaining liquid water will be enriched in water containing the heavier isotopes. In the inverse process, when condensation occurs, the lower vapor pressure of water containing the heavier isotopes will cause that water to condense more rapidly than lighter isotopes of water. The magnitude of this enrichment is temperature dependent. Thus, the relative isotope concentrations in the condensate will be a direct indicator of the temperature at which condensation occurred. The ice presently buried at depth in polar caps and ice sheets was once water vapor that condensed out and became incorporated into the firn and, ultimately, the ice core of the ice sheet. The isotope ratios contained in this buried ice contain an implicit historical record of the temperatures prevailing when precipitation occurred, perhaps many thousands of years ago. In addition to the relative heavy/light isotope ratios, the trapped

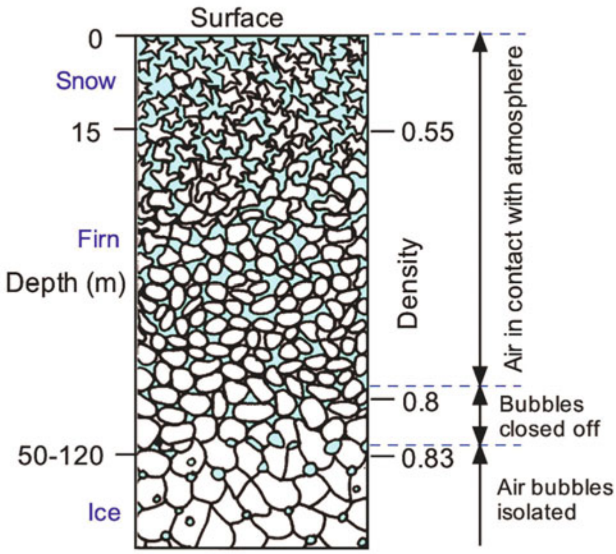



**Figure 3.2.** The sintering process as snow is converted to firn and then on to ice with bubbles of air entrapped (adapted from *http://www.csa.com/discoveryguides/icecore/review.php*).

bubbles in ice cores provide a record of atmospheric concentrations of trace gases including greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Furthermore, the ice cores contain records of aerosols and dust content resulting from volcanic eruptions and other changes in particulate content in the atmosphere. The relative atmospheric concentrations of greenhouse gases as well as aerosol and particulate content coupled with other climate information can provide insight into both the importance of these as causes or effects of temperature change, as well as how they might couple in either a positive or negative feedback sense.

According to Soon and Baliunas (2003a, b):

> "The ice sheets that cover Antarctica, Greenland, the islands north of Canada and Russia, and the tops of some mountainous areas, represent the accumulation of as much as several hundred thousand years of snowfall. In very cold, dry areas, such as the interior of Greenland and Antarctica, the record is particularly good because there is little year-to-year evaporation or melt, and snow compresses into annual layers of ice. The thickness of these layers is an indication of the amount of precipitation that fell at that location during the year the layer was deposited, and the isotopic make-up of the water in the ice can provide a proxy for temperature .... Heavier HDO and $H_2{}^{18}O$ molecules will condense more quickly than $H_2{}^{16}O$. The concentration of D and $^{18}O$ in the ice sample is a measure of the temperature at which the snow that formed that ice fell. However, as more precipitation falls, the water vapor in the atmosphere

becomes depleted in D and $^{18}O$, so the last snow to fall will have a different D and $^{18}O$ concentration than the first snow that fell. In areas of heavy snowfall this can cause significant differences in proxy temperature estimates."

However, the process by which precipitated snow is gradually compressed into firn and then ice, entrapping gas bubbles and preserving isotope concentrations, may take hundreds of years or longer. As a result, ice core data typically represent averages smeared over several hundred (or more) years.

Oard (2005) provided a good description of ice cores. Ice cores longer than 3,000 m have been recovered. In Greenland these represent deposition for up to 150,000 years, and in Antarctica they have reached up to about 800,000 years.

In the late 1950s, Dansgaard led several expeditions to Greenland to acquire ice from icebergs and, although these did not provide historical temperature data of any significance, the results provided further validation of the dating approach. The first ice core was taken at Camp Century in 1964. This core was dated back to about 100,000 years before the present (YBP). The results indicated an ice age from about 100,000 YBP to about 10,000 YBP, permeated by many fluctuations. Temperature fluctuations during the most recent 10,000 years were much smaller, but there was evidence of a post-glacial optimum around 5,000 YBP, a Medieval Warm Period around 1,000 YBP, and a Little Ice Age from around 500 YBP to 100 YBP.

Since then, a series of ice core studies at Greenland have provided a wealth of information on historical temperatures. Ice cores from Greenland have the advantage that annual layers are relatively thick, due to relatively high precipitation, and can be visually observed in many cases. However, the Greenland ice cores only cover a maximum time range of up to about 150,000 YBP.

One of the early ice core sites was the so-called *Dye 3* site which was previously part of the U. S. Army DEW line, located at 65°N in Greenland. Coring was conducted at the Dye 3 site and bedrock was reached at a depth of 2,037 m. This site was physically accessible but a site higher on the ice with smooth bedrock below would have been better.

The *Greenland Ice Core Project (GRIP)* was a multinational European research project, which involved eight nations (Belgium, Denmark, France, Germany, Iceland, Italy, Switzerland, and the United Kingdom). GRIP successfully drilled a 3,028 m ice core into the bed of the Greenland Ice Sheet at Summit in central Greenland between 1989 to 1992 at 72°N.

The *Greenland Ice Sheet Project (GISP)* was a decade-long project to drill ice cores in Greenland and involved scientists and funding agencies from Denmark, Switzerland, and the United States.

There was also a follow-up U. S. *GISP2* project, which drilled at a geologically better location on the summit. This hit bedrock in 1993 after five years of drilling, producing an ice core 3,053 m in depth.

The *North Greenland Ice Core Project (NGRIP)* site was near the center of Greenland (75°N). The core reached the depth of 2,917 m. The cores were cylinders of ice four inches in diameter brought to the surface in 3.5 m lengths.

The site chosen had a flat basal topography to avoid the flow distortions that rendered the bottoms of the GRIP and GISP cores unreliable. Thus, the NGRIP data extended back further in time, reaching the Eemian interglacial period prior to the most recent ice age, which indicated that temperatures during that interglacial period were comparable with those existing today.

A number of ice cores have also been drilled at Antarctica. They provide longer term records than Greenland and have recently been extended to about 800,000 YBP. However, the annual layers are very narrow and dating is therefore more difficult.

The *Vostok* ice core at Antarctica provided data for 420,000 years and revealed four past glacial cycles. Drilling stopped just above Lake Vostok. However, the Vostok core was not drilled at a summit, hence ice from deeper down had flowed from upslope, complicating dating and interpretation.

The *EPICA Dome C* core in Antarctica was drilled at 75°S (560 km from Vostok) at an altitude of 3,233 m, near Dome C. The ice thickness there is 3,309 m and the core was drilled to 3,190 m. Present day annual average air temperature is $-54.5^{\circ}$C and snow accumulation is 25 mm/year. The core went back 800,000 years and revealed eight previous glacial cycles.

Two deep ice cores were drilled near the *Dome F* summit (77°S) at an altitude of 3,810 m. The first core (1995–1996) covered a period back to 320,000 years. The second core (2003–2007) extended the climatic record of the first core to about 720,000 years.

The *West Antarctica Ice Sheet Divide (WAIS Divide)* is a U. S. deep-ice coring project in West Antarctica. The purpose of the WAIS Divide project is to collect a deep ice core from the flow divide in central West Antarctica in order to develop a unique series of interrelated climate, ice dynamics, and biologic records focused on understanding interactions among global Earth systems. The WAIS Divide ice core will provide Antarctic records of environmental change with the highest possible time resolution for the last ~100,000 years and will be the Southern Hemisphere equivalent of the Greenland GISP2, GRIP, and North GRIP ice cores. The most significant and unique characteristic of the WAIS Divide project will be the development of climate records with an absolute annual-layer-counted chronology for the most recent ~40,000 years. It is believed that the WAIS Divide record will have only a small offset between the ages of the ice and the air trapped in the ice. The combination of high time resolution and this small age offset will allow interactions between climate variations and atmospheric composition to be studied at a level of detail previously not possible in deep long Antarctic ice core records. As such, it is intended that the WAIS Divide ice core will enable detailed comparison of environmental conditions between the Northern and Southern hemispheres, and the study of greenhouse gas concentrations in the paleo-atmosphere, at a greater level of detail than previously possible. It is hoped thereby to determine (a) the role of greenhouse gases in ice ages and (b) whether initiation of climate changes occurs preferentially in the south or the north. Drilling was completed in 2011 to a depth of 3,405 m.

## 3.2 DATING ICE CORE DATA

### 3.2.1 Introduction

There are two major issues in deriving historical data from ice cores:

(1) Developing a date–depth relationship that provides a chronology of ice core measurements at any depth.
(2) Developing algorithms for proxies contained in the cores (typically based on isotope ratios) that reveal temperature, ice accumulation, or other historical climatological data.

The actual procedures used in dating ice cores typically involve a number of intricately woven factors. Dating of Greenland ice cores is greatly enhanced by the ability in many cases to visually discern annual layers, although these tend to blur below a moderate depth. But, Greenland cores typically only go back a bit over 100,000 years.

According to Alley and Bender (1998), visual counting of annual strata for Greenland ice is accurate to about 1% for the most recent 11,500 years. Although accuracy is reduced in older ice from colder times, it appears to be as good as that of other dating techniques to perhaps 50,000 years ago. Arguably, annual layers from Greenland remain visible past 100,000 years, but they often appear distorted because ice sheets spread and thin under the influence of gravity, and the bottom layers of ice become extremely chaotic.

However, visual resolution of annual layers is not feasible in Antarctica where annual precipitation is much less and the layers are more closely packed. Uncertainty in the Vostok (Antarctica) time scale as of 2001 was estimated to be as high as $\pm$15,000 years (Parrenin *et al.*, 2001) In fact, the procedures used for Antarctica ice cores are so complex and arcane that it is usually difficult to clarify what has been done, what assumptions have been made, and how reliable these assumptions are. Many investigators have relied on a comparison of key transition points in the isotope ratio vs. depth curve with oscillations in the curve of time dependence of solar input to high latitudes. One thereby uses the astronomical theory to assign ages to key points in the isotope ratio vs. depth and interpolates between these key points. Such processes are referred to as "orbital tuning" (or just "tuning"). However, the assignment of these key dates is a subjective process. More importantly, once orbital tuning is employed, the value of the results for testing the astronomical theory is greatly diminished because the astronomical theory was used to define the chronology and one ends up with circular reasoning. Since one of the main reasons to obtain and analyze ice cores is to test the astronomical theory, such circular reasoning can be counterproductive. But there seems to be widespread bias in the community of paleoclimatologists to defend the astronomical theory at all costs, using all manner of tinkering with the data to seek agreement. When disagreements are found between the data and the theory, it is amazing that some paleoclimatologists almost seem to imply that the data must contain errors!

### 3.2.2 Age markers

Most methodologies for deriving an age–depth relationship in ice cores are problematic in estimating absolute age, but provide better renditions of relative age over segments of the core. Independent absolute age markers based on independent data may provide a basis for assigning absolute ages to some key points along the core. One may then use relative ages derived from the core to interpolate between these fixed points. However, such markers are usually relatively recent, while chronology errors accumulate down the core and increase with age.

***Volcanic materials*** The occurrence of a major volcanic eruption with worldwide deposition of ash and sulfate chemicals will leave its imprint on the ice in a core. Since volcanic materials typically settle out of the atmosphere within about one to three years, a marker is established in the ice core by noting the position in the core where ash occurs. There is good independent evidence on the ages of major volcanic eruptions that date back to about 1,000 YBP. Zielinski *et al.* (1994) identified evidence of volcanic activity in a Greenland core that go as far back as 9,000 YBP. However, it is not clear whether the ice layers determined the age of the volcanoes or vice versa. Volcanic evidence is only useful over a small recent part of the core.

***Matching to dates from layer counting in Greenland cores*** Absolute ages can be inferred from the upper parts of most Greenland cores by visual counting of annual layers. For Antarctic cores, this method is not available. However, in some cases, it is possible to find patterns of isotope variability that seem to indicate the same phenomena in both Greenland and Antarctic cores. One may then assume that the Greenland age can be assigned to the Antarctic core at the depth where the corroborating evidence occurs.

The production rates of the cosmogenic radionuclides $^{10}Be$ and $^{14}C$ in the atmosphere are modulated by solar activity and by the strength of the Earth's magnetic field. By matching the wiggles in these curves vs. depth in Antarctic cores to wiggles in the curves for Greenland cores (which are dated by visual counting of layers), age markers can be derived from these chronologies at periods of large $^{10}Be$ and $^{14}C$ variations (when synchronization is robust). This provided time markers at 2,716 YBP and 5,279 YBP for an Antarctic core (Parrenin *et al.*, 2007).

Another basis for transfer of Greenland chronologies to Antarctica is to compare the $CH_4$ content of air trapped in the core at both sites at dates where sharp transitions in $CH_4$ content occur. It is believed that variations in $CH_4$ concentrations equilibrate across the globe in less than a year. However, because of the slow accumulation of ice at Antarctic sites, there is a much larger difference in Antarctic cores between the age of entrapped gas and the ice in which it is embedded. Models have been used to estimate $\delta$(depth) = depth difference between gas bubbles and ice with the same age.

The so-called *Laschamp geomagnetic excursion* produced a reversal of the Earth's geomagnetic field that is evidenced by a structured peak in $^{10}$Be records in ice cores. The Greenland ice cores yield an age of about 41.2 KYBP for this occurrence, and this age was assigned to the position in the Antarctic core where a similar peak occurred (Parrenin *et al*., 2007b). Independent measurements of the age of this event from sources other than ice cores suggest an age in the range 40.0 to 41.4 KYBP.

***Antarctic volcanic eruption*** There is independent evidence of a large volcanic eruption from volcanic Mt. Berlin in Antarctica that occurred about 92.5 KYBP. If ash is located in the core, it can be attributed to that date.

***Speleothems in caves*** Speleothems are mineral deposits formed from groundwater within underground caverns. Stalagmites, stalactites, and other forms may be annually banded or contain compounds that can be radiometrically dated. From $^{18}O/^{16}O$ ratios in the deposits, it has been estimated that a very abrupt sharp warming from a previous deep ice age occurred around 130 KYBP (Yuan *et al*., 2004). If this sudden rise in temperature can be properly identified in an ice core, it can be attributed to this age estimate. The sharp warming would have produced a sudden rise in $CH_4$ concentration in trapped gases, and the occurrence of such a sharp rise in $CH_4$ can also be dated around 130 KYBP.

### 3.2.3 Counting layers visually

The simplest method (though very tedious) is based upon the fact that in most Greenland locations, layers can be visually distinguished down to moderate depths. This method is somewhat analogous to dating by counting tree rings. These layers are due to annual changes in local conditions (precipitation, solar irradiance, temperature, dust deposits, etc.) that produce an annual cycle in the way snow is deposited on the surface (Shuman *et al*., 2001). In a location on the summit of an ice sheet where there is relatively little flow, accumulation tends to move down and away, creating layers with minimal disturbance. However, in a location where underlying ice is flowing, deeper layers may be highly distorted and display increasingly variable characteristics.

The layering in glacial ice is often noticeable with the naked eye because crystals from summer snow are larger than those of winter snow. At the Greenland Ice Sheet Project 2 (GISP2) site, where accumulation is high (approximately 0.24 m ice/yr), missing years due to deflation by wind or sublimation are claimed to be unlikely (Meese *et al*., 1997).

Svensson *et al*. (2005) reported on the NorthGRIP VS profile covering the depth interval 1,330–3,085 m, which corresponds to the time interval 9–123 KYBP. They provided Figures 3.3 and 3.4. Figure 3.3 shows the results of line scan photography on a number of sections of the ice core. In these images, transparent ice appears black while any opaque layers or compacted bubbles appear white. Recent Holocene ice was mainly transparent and regular annual layers are not readily discerned (Figure 3.3a). However, ice core stratigraphy is clearly visible throughout the previous glacial period. During the coldest climatic events the

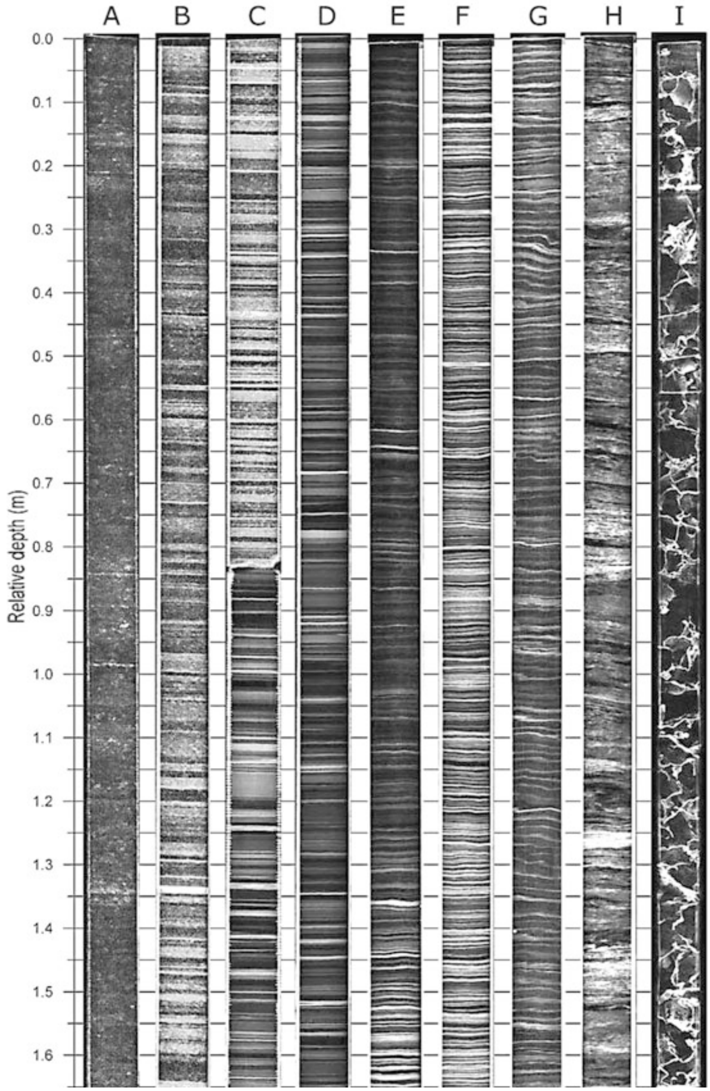



**Figure 3.3.** Examples of line scan images of ice cores from various depths. Each ice section is 1.65 m long, 3 cm thick, and 8–9 cm wide. (a) Holocene ice, 1,354.65–1,356.30 m depth. White patches are most likely ice crystal interfaces within the ice. (b) Ice from the Younger Dryas, 1,504.80–1,506.45 m depth. The bright layer at 1.33 m relative depth is a volcanic ash layer. (c) 1,750.65–1,752.30 m depth. (d) Ice from around the Last Glacial Maximum, 1,836.45–1,838.10 m depth. (e) Ice from a sharp climatic transition (IS19) at 2,534.40–2,536.05 m depth. (f) Ice from the cold period preceding IS19 at 2,537.70–2,539.35 m depth. (g) Microfolding starts to appear below 2,600 m, 2,651.55–2,653.20 m depth. (h) 2,899.05–2,900.70 m depth, overall horizontal layering is still obvious, but individual cloudy bands are not distinguishable. (i) 3,017.30–3,018.95 m depth, the grain boundaries of large crystals are visible (Svensson *et al.*, 2005).

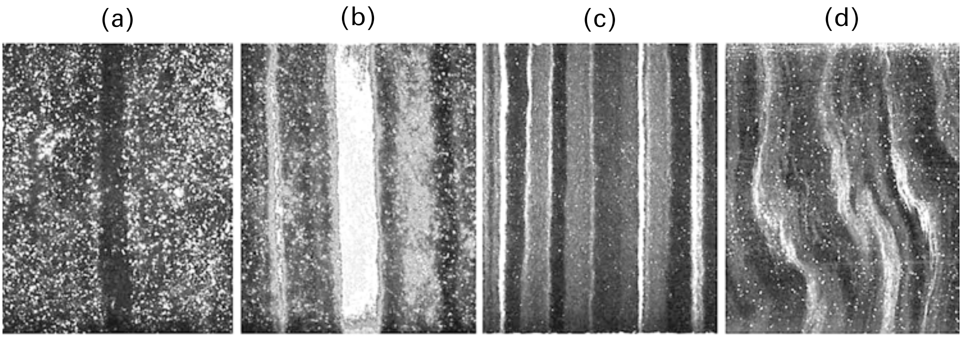



**Figure 3.4.** Close-up examples of line scan images (rotate 90° to compare with previous figure). The sections shown are 6 cm high and 7.5 cm wide. (a) 1412.1 m depth, Holocene ice with visible air bubbles. The band of clear (dark) ice indicates a possible melt layer or ice where the air bubbles are converted into clathrate hydrates. (b) 1,506.1 m depth, the visible Vedde volcanic ash layer in the Younger Dryas. (c) 1,836.9 m depth, detailed layering around the Last Glacial Maximum. (d) Example of microfolding at 2,675.0 m depth. At greater depths the layering is again more regular (Svensson *et al*., 2005).

intensity and the frequency of visible layers or cloudy bands were highest (Figures 3.3b–d).

A very distinct transition between ice drilled during the 1999 season and ice recovered in the 2000 season is found at the 1,751.5 m depth (Figure 3.3c). It is also noteworthy that ice that was stored for one year at NorthGRIP showed much more pronounced cloudy bands than freshly drilled ice. Also the density of white patches and bubbles are much higher in the stored ice. This clearly demonstrates that the internal structure of the ice core relaxes after recovery, even when the ice is stored under optimal cold conditions.

Down to a depth of about 2,600 m, horizontal layering of the ice is very regular (Figure 3.3f). Below this depth small disturbances in the layering such as microfolds start to appear (Figures 3.3g and 3.4d). Below 2,800 m, the visual stratigraphy becomes more uncertain with more diffuse and inclined layering, and in some depth intervals it is impossible to distinguish individual layers (Figure 3.3h). The ice crystals in the deepest ice are large, of the order of 1–10 cm diameter, and in the lowest 100 m of the ice core ice crystal boundaries are visible in the line scan images (Figure 3.3i).

Unfortunately, layer counting is not feasible in central Antarctica where annual cycles are barely distinguishable due to low annual accumulation (Parrenin *et al*., 2007a). However, layers can be discerned in the upper part of the core at Law Dome (on the coast), which receives a great deal more snow than the inland domes.

Over the most recent 110,000 YBP, annual dust or cloudy bands were the most prominent annual layer markers of the GISP2 core:

> "During the late spring and summer in Greenland, there is an influx of dust. This dust peak is in part a result of dust storms that occur in both hemispheres

during the spring/summer period and atmospheric circulation changes that enable the stratospheric load to reach the troposphere. Dust particles in solid ice and ice melt-water scatter incident light, and the intensity of light scattered at 90° to the incident light direction is proportional to the mass of suspended particulates" (Meese *et al.*, 1997).

Many of these bands can be seen visually. However, a more sensitive method for observing the bands utilizes laser light scattering (LLS). LLS allows extension of visual stratigraphy further down in the core. The LLS method is based on the fact that dust particles in the water or ice will scatter the light from a laser beam, and the amount of scattered light orthogonal to the beam is proportional to the amount of dust. However, the system works better if the ice has melted, because bubbles in the ice also scatter the light in the upper portion of the core. The bubbles disappear about 1,400 m down the core as they change into air/ice clathrates. However, the LLS method applied to water is time consuming and destroys the ice, so the method is not as widely used as solid LLS (Oard, 2005).

According to Meese *et al.* (1997) the LLS method can be used as an annual layer indicator even though the signal changes from one of depth hoar to layers of increased dust concentration as one goes from the Holocene to the Ice Age (hoar layers are porous low-density snow layers). It was also claimed that the LLS measurements were consistent with visible stratigraphy down to considerable depths. LLS is a very valuable dating tool throughout almost the entire length of the core, particularly in the deeper ice at GISP2 where the other techniques either fail or become increasingly unreliable. However, an increased particulate concentration may not be restricted to the spring or summer and additional influxes of dust may occur during any part of the year, creating additional peaks of a non-annual nature. The LLS signal can also be used as an indicator of major climate changes and of some volcanic events. Meese *et al.* (1997) claimed that 110,000 annual layers have been detected down to 2,800 m. In fact, they believe they were able to count 50,600 more annual layers at an accuracy of 24% from 2,800 to 3,000 m. The age at 3,000 m was about 161,000 YBP. However, this lower layer was probably distorted by ice flow, and the extension to 3,000 m is likely to be invalid.

### 3.2.4 Layers determined by measurement

Layers may also be counted by making physical measurements on the core (rather than by visual observation). Seasonal $\delta^{18}O$ cycles make exact dating possible by counting layered variations in this quantity downward from the surface. Figure 3.7a shows $\delta^{18}O$ for a core increment that was deposited from AD 1210 to 1240. When corrected for thinning, the distance between two minima is a measure of precipitation in the year of deposition. The decade from AD 1225 to 1235 was drier than the preceding decade and, since the $\delta^{18}O$ mean values were lower, it was apparently cooler (assuming an unchanged summer to winter precipitation ratio) (Dansgaard, 2005). However Oard (2005) has argued that this procedure is not

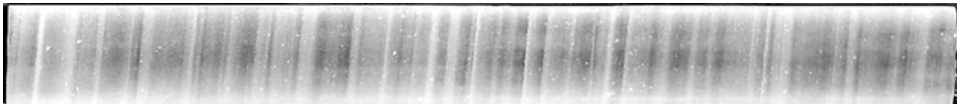


**Figure 3.5.** Section of the GISP2 ice core from 1,837–1,838 m deep in which annual layers are clearly visible. The appearance of layers results from differences in the size of snow crystals deposited in winter vs. summer and resulting variations in the abundance and size of air bubbles trapped in the ice. The age range of this section was about 16,250 ± 20 years (*http://en.wikipedia.org/wiki/Image:GISP2D1837.jpg*).

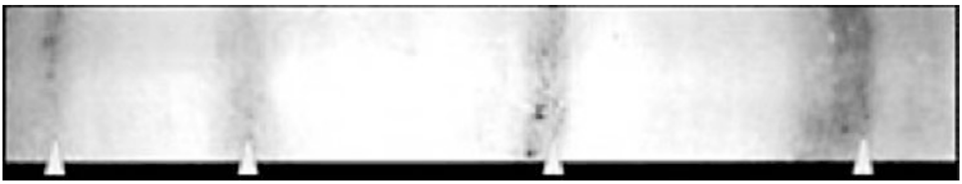


**Figure 3.6.** Section of an ice core drilled in the Kunlun Mountains of Western China. The thick lighter bands indicate heavy snowfall during the monsoon season around the year 1167 AD, while the thinner darker strips show layers of dust blown into the snowfield during the dry season (photo attributed to Lonnie Thompson: *http://www.pbs.org/wgbh/nova/warnings/stories/nojs.html*).

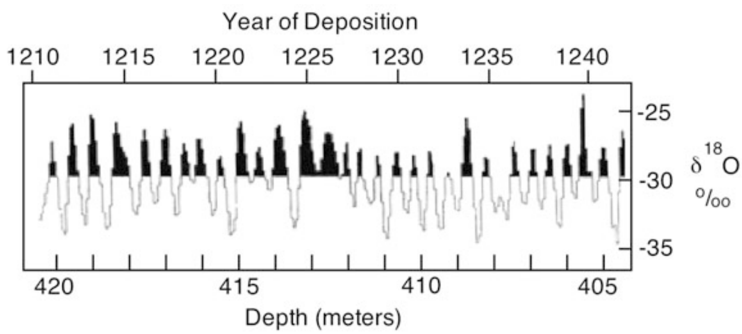



**Figure 3.7a.** Layering as evidenced by periodic variations in $\delta^{18}O$ (Dansgaard, 2005).

always straightforward and the resolution of individual years can be a very subjective process.

Other examples of visually observed ice core layers are shown in Figures 3.5 and 3.6.

The effect of volcanic eruptions on the annual variation of $\delta^{18}O$ is significant (Hammer, 1989). Figure 3.7b provides an excerpt from the $\delta^{18}O$ record for a core increment that shows very clear effects of large volcanic eruptions. In addition to $\delta^{18}O$, measurements of $\delta D$ and electrical conductivity have also been used to discern yearly layers.

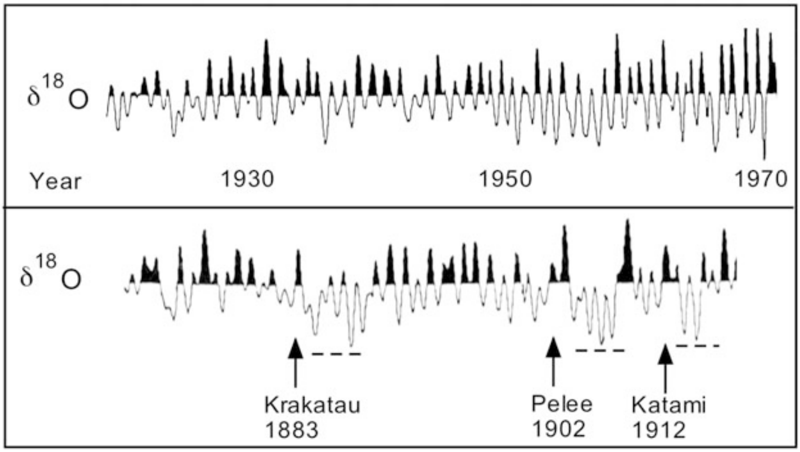



**Figure 3.7b.** Layering of $\delta^{18}O$ measurements at Station Crete, Greenland. The upper panel shows normal recent variation. The lower panel shows the effects of three large volcanic eruptions in the 19th century as patterns underlined by dashed lines.

According to Meese *et al.* (1997):

> "Electro-conductivity measurements (ECM) provide a continuous high-resolution record of low-frequency electrical conductivity of glacial ice, which is related to the acidity of the ice. The measurement is based on the determination of the current flowing between two moving electrodes with a potential difference of a few thousand volts. Strong inorganic acids such as sulfuric acid from volcanic activity and nitric acid controlled by atmospheric chemistry cause an increase in current. Conversely, when the acids are neutralized due to alkaline dust from continental sources or from ammonia due to biomass burning, the current is reduced. As such, results from ECM can be used for a number of different types of interpretations. The most important feature of the ECM data in relation to the depth–age scale is the spring/summer acid peak from nitric acid production in the stratosphere. Although ECM is an excellent seasonal indicator, as stated above, non-seasonal inputs from other sources may cause additional peaks that could be confused with the annual summer signal. In addition to being an annual indicator, ECM is also used for rapid identification of major climatic changes and has proved very useful in the identification of volcanic signals."

Climatologists can also detect annual layers by measuring the acidity of the ice, which is generally higher for summer snow, for reasons that remain somewhat obscure (Alley and Bender, 1998).

Rasmussen *et al.* (2006) counted annual layers using a multi-parameter approach as shown in Figures 3.8 and 3.9. Measurements of various impurities as well as ECM corroborated visually observed layers.

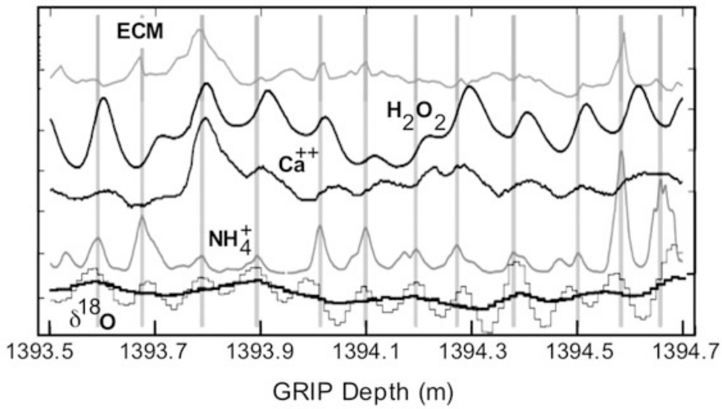



**Figure 3.8.** Example of a 1.2 m segment of GRIP data from about 8,800 YBP. Visually determined annual layer markings are shown as gray vertical bars. Annual layers were also identified as matching pairs of spring and summer indicators: spring was characterized by high dust content leading to peaks in $[Ca^{2+}]$ and dips in the $[H_2O_2]$ curve, while summer was characterized by high $[NH_4^+]$ and corresponding minima in the ECM curve. The annual layer identification procedure was supported by high-resolution $\delta^{18}O$ data (Rasmussen *et al.* 2006).

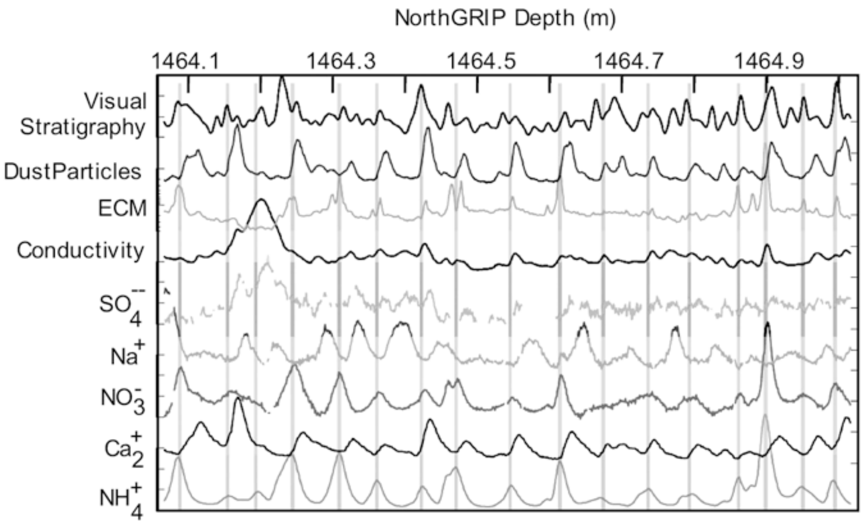



**Figure 3.9.** Example of data and annual layer markings (gray vertical bars) from visual stratigraphy during the early Holocene. A 0.95 m long section of NGRIP data is shown. Annual layers are marked at the summer peaks, which are defined by high $[NH_4^+]$ and $[NO_3^-]$. The spring is characterized by high dust mass leading to peaking $[Ca_2^+]$ and dips in the $[H_2O_2]$ profile, while the $[Na^+]$ peaks in late winter. The visual stratigraphy profile does not contain clear annual layers, but does contain peaks corresponding to almost every dust peak. The ECM anti-correlates strongly with the largest peaks in $[NH_4^+]$, but does not itself allow safe identification of annual layers.

### 3.2.5 Ice flow modeling

Ice sheets and glaciers are sedimentary deposits consisting of sequences of layers, deposited annually as snow accumulation. Snow layers sink into the ice mass and are subjected to continuous thinning. This occurs initially as a result of densification, by which the snow is transformed into ice, but later mainly due to flow-induced vertical compressive strain. In this process the layers are stretched horizontally until they are advected by the ice motion into an ablation zone where the ice is removed by melting or calving of icebergs. The oldest ice is found near the base and along the margin of the ice sheet. If the temperature reaches melting point at the ice sheet base, the oldest layer sequences may also have been removed by basal melting. Basal melting may drastically reduce the time range of the layer sequences left behind in the ice mass.

The age of an ice particle at any given position in the core is estimated by first estimating the path of the particle from the site of deposition on the surface, and then estimating the time required for the particle to travel along this path from the surface to its present position (see Figure 3.10). This requires modeling the dynamic and thermal history of the ice mass during the entire period elapsed since the ice particle was deposited at the surface. This depends upon past upstream histories of accumulation rate/ablation rate, ice thickness, ice temperature, and other ice flow parameters, and it becomes an increasingly difficult and uncertain task to perform the further back in time that the dating is extended. In addition, past changes in other boundary conditions (e.g., sea level in the case of an ice sheet terminating in the sea) must be considered (Reeh, 1989).

On an ice sheet dome or a horizontal plateau there is little horizontal ice motion and consequently no need to correct for advective transport for as long as the dome or crest position has remained constant. This is the basis for choosing drill sites on domes or slightly sloping crests, since at least the more recent parts of ice core records from such locations should be simpler to date and interpret. Nevertheless, the accumulation rate, ice thickness, internal ice temperature, and ice flow parameters are likely to have changed with time, even if the dome position has not. This causes temporal changes in the depth distribution of the vertical rate of straining of the layers, an effect which must be considered when calculating the time scale.

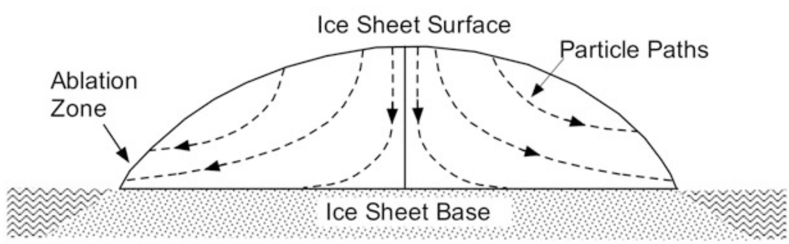



**Figure 3.10.** Ice particle flow paths.

The temperature of ice varies with depth. The temperature of subterranean ice is typically fairly constant for a significant depth (down to ~1,500 m depth), but it becomes warmer as depth increases and may reach melting point at the base (Oard, 2005).

Past variations in accumulation rate, ice thickness, ice temperature, etc. are typically disregarded in some models (steady state models). This is done not just to simplify the calculations, but also because our knowledge about past changes of ice sheet climate and dynamics is seldom good enough to justify application of hypothetical complicated time-dependent models for dating the ice.

To compute the age of an ice layer, one needs to estimate the rate of accumulation at the time it formed and the thinning function (i.e., the ratio of the current thickness of a layer to its initial thickness). The age of the ice at a given depth $z$ is then calculated from:

$$\text{Age(depth)} = \oint_0^{\text{Depth}} \frac{dz}{\text{Accumulation}(z) \times \text{Thinning}(z)}$$

The accumulation function has been modeled for various localities. However, it depends on past temperatures, which in turn depend upon chronology—so, some circular reasoning is involved. The thinning function has also been modeled, but a number of assumptions are made that are difficult to appraise (Parrenin *et al.*, 2001). One proceeds from such initial data as the snow accumulation rate, the temperature and viscosity of the ice, the velocity of ice movement, and bed relief features. Models typically assume steady state ice flow and the absence of major gaps in columns (Kotlyakov, 1996). Overall, the ice flow modeling process appears to this writer as some sort of black magic.

Parrenin *et al.* (2007a) modeled ice flow at Dome C and Dome Fuji with a 1-D mechanical model and an analytical velocity profile, taking into account variations in ice thickness and deducing the accumulation rate from the isotopic content of the ice. The poorly constrained parameters of these models were adjusted by utilizing independent age markers. They reconstructed changes in surface and bedrock elevation and found a surface elevation 120 m lower at the Last Glacial Maximum and an LGM ice thickness 160 m smaller than at present. They inferred a value of $0.56 \pm 0.19$ mm/yr for basal melting at Dome C. Annual layer thickness as a function of depth was the primary result of this model. It was found that layer thickness varied considerably with depth, ranging from about 3 cm for the uppermost 500 m to about 1.2 cm for depths of about 500 to about 1,800 m, and dropping down toward zero as the depth approached 3,000 m. The profiles of vertical velocity are highly nonlinear at both sites, which suggests complex ice flow effects, a consequence of the anisotropic behavior of the ice and the bedrock relief. It was concluded that the accumulation reconstructions based on the isotopic content of the drilled ice have reached their limits and accurate estimates of past accumulation rates are required for an accurate age scale. New independent proxies are needed to improve ice core chronologies and interpretations at low accumulation sites in Antarctica. Proposals for improved ice flow models were put forth, but the authors suggested that many hurdles remain to be overcome (Parrenin *et al.*, 2007a).

### 3.2.6 Other dating methods

#### *pH balances*

Precipitation during ice ages is markedly alkaline. This is due to the fact that extensive glaciation during an ice age lowers the ocean level by more than $\sim$100 m, thus exposing a larger portion of the continental shelves. Huge clouds of alkaline dust (primarily $CaCO_3$) from these shelves are blown across the landscape. However, this method is very approximate because it provides only age ranges, and the lag time between the onset of glaciation and increased alkalinity is uncertain.

#### *Radioactive dating of gaseous inclusions*

In this method one melts a quantity of glacial material from a given depth, collects the gases that were trapped inside, and then applies standard $^{14}C$ and $^{36}Cl$ dating. However, a large amount of ice must be melted to gather the requisite quantity of gases.

#### *Dating based on the oxygen/nitrogen ratio*

Kawamara (2009) pointed out that relative chronologies for Antarctic ice cores are typically assigned by continuous flow modeling of past snow accumulation rates and ice flow. To convert these relative chronologies to absolute chronologies, orbital tuning is employed, in which the parameters of the method are constrained by depth–age control points that are assigned by comparison with features in insolation curves. Kawamara *et al.* (2007) utilized a new procedure for estimating absolute chronologies based on the theory that $O_2/N_2$ in these cores is depleted relative to the atmospheric ratio because of physical fractionation during air bubble formation at $\sim$100 m depth. The magnitude of this depletion is claimed to be controlled by the magnitude of snow metamorphism, driven by local summer insolation when the layer was originally at the surface:

> "Although the exact mechanisms are currently not well understood, empirical evidence indicates that the $O_2/N_2$ variation is probably phase-locked to the local summer solstice insolation, with negligible climatic influences. Using this technique, the independent Dome Fuji and Vostok $O_2/N_2$ chronologies agree within 1 kyr, indicating robustness of the method."

Assuming the putative relationship between summer insolation and $O_2/N_2$ ratio is indeed correct, the beauty of this method is that one can calculate the chronology of insolation curves accurately, and therefore the absolute chronology does not depend on assigning dates to features in isotope depletion curves. At any

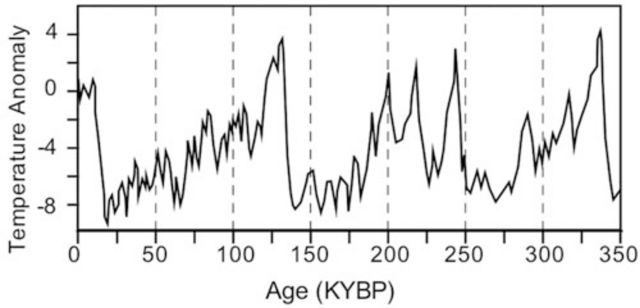



**Figure 3.11.** Chronology of Antarctic ice core temperatures (Kawamura, 2009).

depth, chronology is determined from the $O_2/N_2$ ratio, and isotope depletion at that depth is thereby assigned a date. While Kawamura has described this as orbital tuning, that is misleading because it does not assume that the astronomical theory is correct; it only assumes that the $O_2/N_2$ ratio is proportional to SH insolation. Their results are shown in Figure 3.11.

### 3.2.7 Synchronizing the dating of ice cores from Greenland and Antarctica

The timing of climatic events in the two hemispheres is of great importance in building a better understanding of climate change. Comparison of Greenland and Antarctic ice records can be accomplished using atmospheric gas records for correlation. Ice cores from high accumulation rate sites are preferable as they minimize uncertainties in the difference between the age of the gas and the age of the surrounding ice matrix (Δage). Atmospheric trace gases with lifetimes exceeding the inter-hemispheric mixing time and showing significant changes in the past can be considered as time markers on a global scale. The most prominent trace gases routinely measured on extracted air from ice cores are $CO_2$, $CH_4$, and $N_2O$. In addition, $\delta^{18}O$ has also been used as a marker. Atmospheric $CH_4$ and $\delta^{18}O$ have been the preferred markers because the reconstructed $CO_2$ concentration suffers from *in situ* production in Greenland ice cores and $N_2O$ shows sporadic artifacts occurring at depth intervals with elevated dust concentrations. $CH_4$ is of especial interest for three reasons: (a) the past atmospheric signal is reliably recorded in ice cores from both polar regions, (b) it shows large temporal concentration variations, and (c) it closely follows Greenland rapid climatic variability during the last glaciation and deglaciation (Blunier *et al.*, 2007; Loulergue *et al.*, 2007).

### 3.2.8 GISP2 experience

Meese *et al.* (1997) described the processes used to date GISP2 ice cores. Age dating of the GISP2 ice core was accomplished by identifying and counting annual layers using a number of physical and chemical parameters that included measurements using visual stratigraphy, the electrical conductivity method (ECM), laser light scattering from dust (LLS), oxygen isotopic ratios of ice ($\delta^{18}O$), major ion chemistry, and analysis of glass shards and ash from volcanic eruptions. Each of these parameters (with the exception of volcanic matter) exhibits a distinct seasonal signal. The definitive summer stratigraphic signal at the GISP2 site occurs in the form of coarse-grained depth hoar layers formed by summer solar irradiance. The depth–age relationship for GISP2 is shown in Figure 3.12. In the region around the GISP2 site the relief of the snow surface is remarkably flat. Sastrugi (surface irregularities resulting from wind erosion) several centimeters in height may be produced by storms, but subsequent deposition, sublimation, and densification tend to level the surface (Meese *et al.* 1997). Visual stratigraphy was the principal method, augmented by a variety of other techniques, used to elucidate yearly sequences in the ice core. Stratigraphy in the form of depth-hoar layer sequences remained continuous through the Holocene and into the glacial transition. At the height of the Ice Age, the stratigraphic signal was not the characteristic depth-hoar sequence, but rather cloudy bands resulting from significant changes in seasonal dust concentration in the ice. The ECM technique provided an excellent seasonal indicator.

During the late spring and summer in Greenland, there is an influx of dust resulting in part from dust storms that occur in both hemispheres during this period. A laser light scattering (LLS) technique was used in conjunction with other methods to discern annual layers in the core. It was claimed that the method can be used as an annual layer indicator in the Holocene and glacial periods even though the signal changes from one of depth hoar to layers of

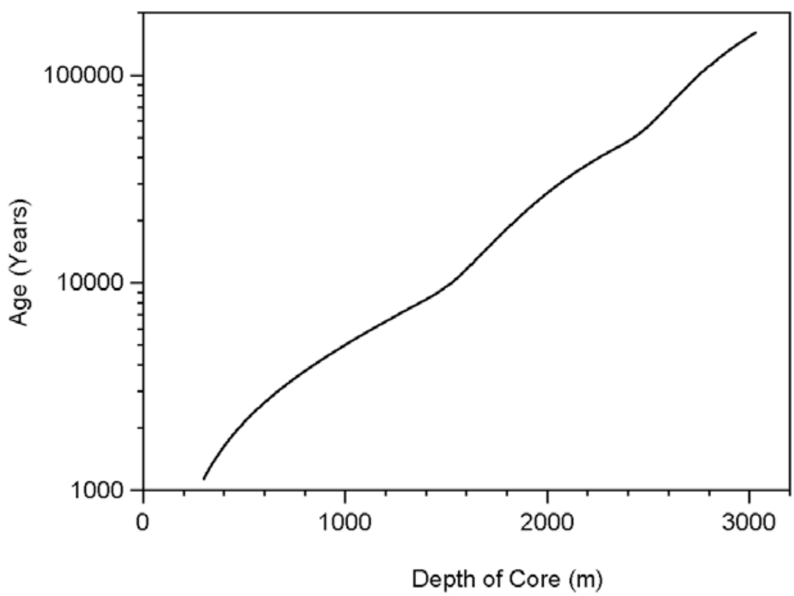



**Figure 3.12.** Depth–age relationship in GISP2.

increased dust concentration. LLS was a very valuable dating tool throughout most of the length of the core, particularly in the deeper ice at GISP2 where the other techniques either failed or became increasingly unreliable.

Additionally, $\delta^{18}O$ values were used to identify seasonal cycles to depths of 300 m. The effects of diffusion rapidly obliterated the seasonal signal in deeper ice. Most other parameters were useful to at least 600 m. Visual stratigraphy was a consistent parameter throughout most of the core. ECM and LLS were more valuable in some sections than others depending on the atmospheric chemistry and climate at that time.

### 3.2.9 Tuning

The process of dating sediment cores by comparing patterns of isotope variability with patterns of solar variability based on the astronomical theory is usually referred to as "orbital tuning". This is discussed in Sections 5.2 and 9.6. Orbital tuning has been extensively used to date ocean sediments and has also been used to date polar ice cores (Waelbroeck *et al.* 1995).

According to Parrenin *et al.* (2007b):

> "Unfortunately, layer counting is not feasible in central Antarctica where annual cycles are barely distinguishable. Comparison of paleoclimatic records to insolation variations (so-called orbital tuning methods) are generally applicable to a whole ice core, as long as the stratigraphy is preserved. On the other hand: (1) the accuracy in terms of event durations is poor, (2) the accuracy in terms of absolute ages is limited by the hypothesis of a constant phasing between the climatic record used for the orbital tuning procedure and the insolation variations (and, by definition, does not allow one to infer this phasing). The advantage is that the achieved accuracy does not decrease with depth (assuming the underlying mechanism stays constant). As a consequence, it is currently the most precise method to date the bottom of deep ice cores."

### 3.2.10 Flimsy logic

In general, the dependence of age on depth in ice cores is highly nonlinear with the lower regions of the ice core much more highly compressed than the upper parts. Most of the time range of an ice core is relegated to the lowermost few hundred meters. It is difficult to develop absolute standards for dating ice core and sediment data. Therefore, it is common practice in dating cores and sediments to compare the morphology of the time series curve (typically, isotope ratio vs. depth) at a site with other data for which (supposedly) firm estimates of signal vs. time have been derived. If the two curves have similar morphologies, one can argue that the dates corresponding to specific features in the reference curve can be attributed to corresponding features in the curve at the site that is being investigated. This is illustrated schematically in Figure 3.13.

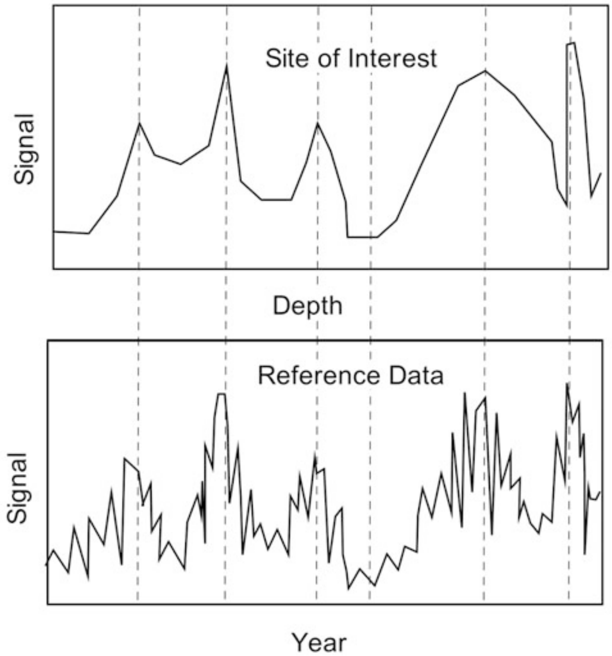



**Figure 3.13.** Comparison of features at the site of interest with features in reference data.

Although there are differences between the morphologies of the site and the reference, one can visually associate features of the two as shown by the dashed vertical lines. But, a question arises as the data become noisier: How subjective is this process and where does it pass from reasonable logic to the eye of the beholder?

Wunsch (1999) emphasized that "the purely random behavior of a rigorously stationary process often appears visually interesting, particularly over brief time intervals, and creates the temptation to interpret it as arising from specific and exciting deterministic causes." He went on to say:

> "One often sees discussions of apparent visual correlations between two or more climate time series. One must be extremely careful not to be misled by oscillations that are merely the happenstance of random variability and imply no causal connection at all. The human eye developed to find patterns in nature; it sometimes sees patterns where none exist. Red noise (strongly auto correlated) processes are particularly prone to generating oscillations that to the eye look related."

In his conclusion, Wunsch (1999) said:

> "Undoubtedly the real climate record contains physically significant trends and changes in spectral shape or energy levels. Two visually but statistically

insignificant correlated climate records may well be linked in a causal manner. Caution is required, however: short records of processes that are even slightly reddish in spectral character can easily lead to unwarranted, and incorrect, inferences if simple stochastic superposition is confused with deterministic causes. *Sometimes there is no alternative to uncertainty except to await the arrival of more and better data*" [emphasis added].

In a later paper, Wunsch (2003) further discussed the problem of relating climate curves, particularly in relating the timing of events at Antarctica to those at Greenland. He found that over long time spans (>10,000 years) the evidence is strong that Greenland changes lag Antarctic changes by perhaps 1,000 years. However, over shorter time intervals no correlation of Antarctica with Greenland can be made. Unfortunately, this paper is difficult to read.

A problem with much of the ice core data is that there is so much cross-fertilization between time scales from various sources that it is often difficult to determine the solid ground (if any) time scales rest upon.

The first (and perhaps most influential) means of relating curves was the development of the so-called SPECMAP in which ocean sediment data were dated by comparison with the astronomical theory (Imbrie *et al.*, 1984). Ocean sediment data can be dated back to about 30,000 years by radiocarbon measurements. For a number of years it was common to assume that the final peak of the previous interglacial period occurred 100 KYBP, and this was used as a marker. This was later raised to 125 KYBP. However, there is evidence that warming started as early as 140 KYBP (see Figure 6.3 and discussions in Sections 6.1.4, 6.2, and 6.5.2).

The magnetic polarity change that is believed to have occurred some 780,000 YBP can sometimes be useful to relate curves. But ocean sediment data date back to 3 MYBP and comparison with the astronomical theory ("tuning") has been the most widely applied method for dating over this long time period. However, much of the correspondence between the theory and the data seems to lie in the eyes of the beholders.

## 3.3 PROCESSING ICE CORE DATA

### 3.3.1 Temperature estimates from ice cores

#### *3.3.1.1 Correlation of $\delta^{18}O$ with temperature based on recent surface data*

As we pointed out in Section 3.1, the temperature at which ice was deposited on ice sheets in the past is believed to be in some way proportional to $\delta^{18}O$. The isotope ratio

$$\delta^{18}\mathrm{O} \equiv \left( \frac{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{Sample}}}{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{Reference}}} - 1 \right) \times 1{,}000$$

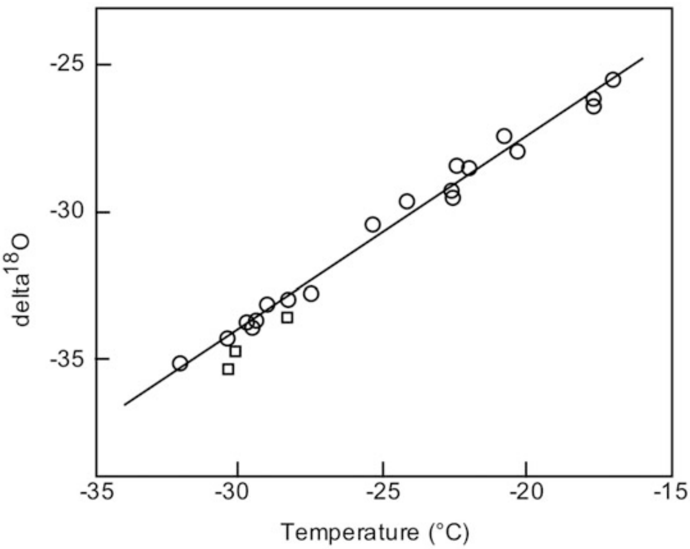



**Figure 3.14.** Dansgaard's correlation of $\delta^{18}O$ with temperature. The circles apply to south Greenland and the squares to north Greenland.

and its counterpart $\delta(D)$ are indicators of past temperatures that prevailed when snow was deposited at the site, which eventually agglomerated into an ice sheet. In the early days of ice core exploration, Dansgaard (2005) prepared a correlation between current surface temperature at various Greenland sites and the current values of $\delta^{18}O$ at these sites (see Figure 3.14). Dansgaard also measured $\delta^{18}O$, and $\delta(D)$ as well, for recently deposited ice at a large number of NH sites spanning a range of latitudes from 60° to 85° and found that, when they were plotted vs. current average temperature, the data were grouped around a straight line. If the same relationship between temperature and $\delta^{18}O$, or $\delta(D)$, held during the past few hundred thousand years (a rather large extrapolation), these straight line correlations between $\delta^{18}O$, or $\delta(D)$, and temperature can be used to infer past temperatures from measurements of $\delta^{18}O$, or $\delta(D)$, in the core. A number of such correlations evolved, and one of the recent ones was:

$$T(^\circ\mathrm{C}) = 1.45\ \delta^{18}\mathrm{O} + 19.7$$

$$T(^\circ\mathrm{C}) = 0.18\ \delta\mathrm{D} + 18$$

in which the $\delta$ are measured in units of ‰ (parts per thousand). This was the method of choice for converting isotope measurements to temperature for several decades. For example, according to Kotlyakov (1996):

> "The main method of paleotemperature estimation involves analysis of the stable isotopes ratios H/D and $^{16}O/^{18}O$ in ice. The isotopic composition of deposited snow depends on its formation temperature. It has been found

experimentally that a decrease in the content $^{18}O$ in East Antarctic ice (relative to the standard mean of sea water) by 1 percent corresponds to a cooling 1.5°C whereas a 6 percent D shift will correspond to a temperature drop of 1°C. Using these correlations, one may transform an isotope curve into one of paleotemperature."

However, the conversion of $\delta^{18}O$ or $\delta D$ measurements to temperature is far from straightforward due to a variety of confounding factors that may occur. While isotope ratios provide a qualitative indication of prevailing temperatures in the past, the quantitative accuracy of such correlations has been challenged. Other factors that affect isotope ratios during glacial periods include more extensive sea ice cover during glacial periods, which increases the distance from the moisture source and changes the isotopic composition of oceans during glacial periods.

Ideally, records of both surface temperature and the isotopic contents of precipitation should span a relatively long period at any site where an empirical relationship between $\delta$ and $T$ is sought. The only polar site for which suitable data are available is the South Pole station, where temperatures are available from 1957 to 1978 along with well-dated isotopic profiles. Mean annual and maximum deuterium ratios correlated well with corresponding mean annual and summer temperatures; however, winter temperature and deuterium minima were poorly correlated. Detailed curve matching of isotope–depth records from snow pits to temperature–time records from automated weather stations (AWS) and satellite temperature sensors provide additional support for the linear relationship of $\delta$ with $T$ (Shuman *et al.*, 2001). These short-term comparisons provide some support for the belief that isotopic ratios of accumulated snow reflect temperatures, especially for comparisons from summer to summer. Some noise is, of course, present.

In order to use the isotope signal as a paleothermometer, the present day spatial isotope–surface temperature relationship $\delta = aT + b$ defined over a certain region ($\delta$ stands for either $\delta D$ or $\delta^{18}O$ of the precipitation and $T$ for the surface temperature) the isotope–surface temperature slope is generally assumed to hold in time throughout the region. Present day isotope ratios and temperatures correlate very nicely as shown in Figure 3.15. This does not necessarily validate the relationship under past conditions, particularly during extensive glaciation.

Jouzel *et al.* (1997) reviewed the empirical estimates and theoretical models of the relationship between isotope ratios and temperature. They focused on polar areas and singled out Greenland where the GRIP and GISP2 drillings allowed empirical estimates to be obtained from paleothermometry and motivated modeling experiments (see Figure 3.17). In a more recent review, Miller *et al.* (2010) provided the data shown in Figure 3.16.

Jouzel *et al.* (2003) studied the relationship between temperature and isotope ratios in Antarctica. They examined all relevant information, focusing on the East Antarctic Plateau where both model and empirical isotope–temperature estimates are available. Based on the evidence presently available they concluded that, unlike the case of Greenland, the present day dependence of the isotope ratio on

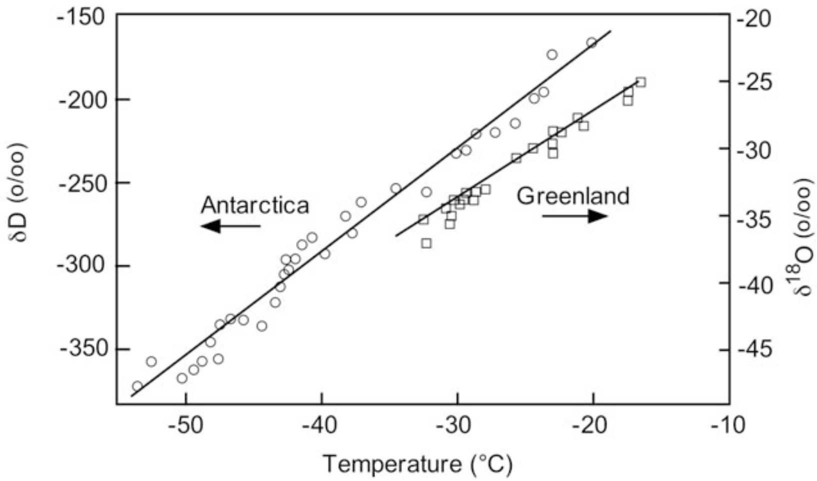



**Figure 3.15.** Present day correlations of $\delta^{18}O$ or $\delta D$ with temperature (Jouzel *et al.*, 1997).

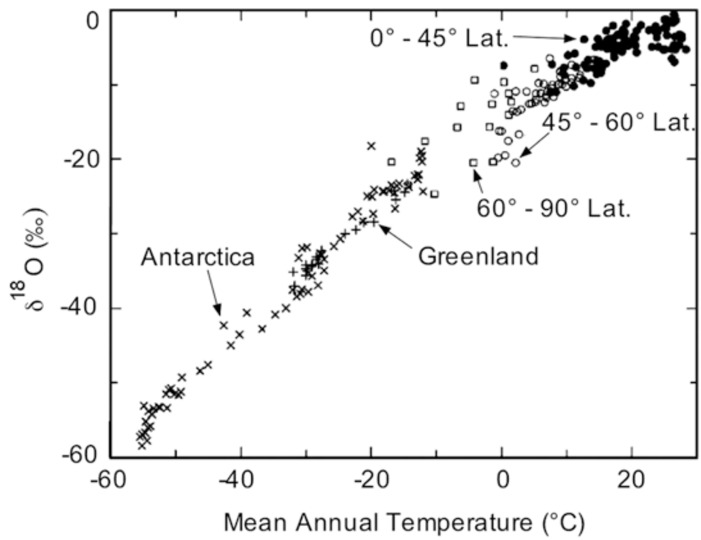



**Figure 3.16.** Relation between isotopic composition of precipitation and temperature in the parts of the world where ice sheets exist (Miller *et al.*, 2010).

temperature could probably be taken as a surrogate of this relationship at sites such as Vostok and EPICA Dome C (estimates within −10% to +30%).

Jouzel *et al.* (1997) developed a simple model that dealt with isotopic fractionation in an isolated air parcel traveling from an oceanic source toward a polar region. In this simple model, the condensed phase is assumed to form in isotopic equilibrium with the surrounding vapor and to be removed immediately

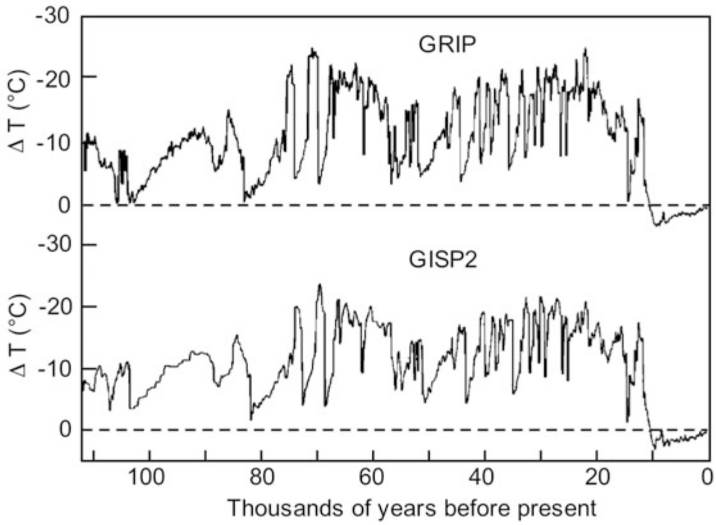



**Figure 3.17.** Comparison of estimated temperatures at two Greenland sites (Jouzel *et al.*, 1997).

from the parcel. With these assumptions, the isotope content of this precipitation is a unique function of the initial isotope mass and water vapor mass within the air parcel and of the water vapor mass remaining when the precipitation forms. This model leads to a family of curves like that in Figure 3.15, with the position of each curve dependent on the ocean temperature from which the original evaporation took place. The results correlate with the main features of the global distribution of isotopes in precipitation, namely, its seasonal and spatial characteristics, the observed relationships with local temperature or precipitation amount, and the strong link between $\delta^{18}O$ and $\delta D$. However, such a simple model can only roughly represent the complexity of dynamical and microphysical processes leading to the formation of individual precipitation events or changes in ocean surface characteristics, in surface topography, and in atmospheric circulation associated with important climatic changes, such as the transition between the Last Glacial Maximum and the Holocene.

#### *3.3.1.2 Temperature estimates from borehole models*

According to Cuffey *et al.* (1995):

> "Using both empirical data and physical models for isotope fractionation, paleoclimatologists have interpreted $\delta^{18}O$ to be a measure of environmental temperature $T$ at the core site, through a simple relation that we call the isotopic paleothermometer: $\delta^{18}O = AT + B$, where $A$ and $B$ are constants. There are two obstacles to making this interpretation sound. First, the coefficients $A$ and $B$ are not known *a priori* because many factors in addition to local environmental

temperature affect isotopic composition. These include changes in sea-surface composition and temperature, changes in atmospheric circulation, changes in cloud temperature, which may be different from changes in surface temperature, changes in the seasonality of precipitation, and post-depositional isotopic exchange in the snowpack. Second, all of these factors may vary through time in such a way that a single, linear relation between $\delta^{18}O$ and $T$ is inappropriate. Thus, there is strong motivation to seek paleotemperature information that is entirely independent of isotopic history to calibrate the paleothermometer.''

Temperatures in the upper $\sim$10 m of an ice sheet are primarily controlled by mean annual air temperature. Changes in air temperature propagate downward into the ice by diffusive heat flow and ice flow. The temperature profile through an ice sheet thus provides a record of past air temperature modified by heat diffusion and ice flow. The profile is readily measured in a borehole through the ice. Although the thermal properties of ice and firn are well known, there may be large uncertainties in ice flow in different areas of ice sheets. The availability of excellent dating at the Greenland summit, combined with the central location on a rather stable ice sheet, allows relatively accurate calculation of ice flow effects. Because of heat diffusion, conversion of the depth–temperature record of a borehole to a surface temperature history is a complex process and does not necessarily yield a unique result. However, methods have been developed that appear to yield good estimates of historical surface temperatures from borehole temperature profiles at benign sites where ice flow is not so problematic. Borehole analyses have been conducted for the GISP2 and GRIP.

During the summer of 1994, Cuffey *et al.* (1995) measured temperature in the 3,044 m deep GISP2 core hole (filled with liquid) from 70 m below the surface to the base of the ice sheet. At that time, thermal perturbation from drilling had decayed to less than 0.04°C, so the temperature in the borehole matched the temperature in the surrounding ice sheet at this accuracy and better. This depth corresponded to a time span of about 40,000 years.

Heat diffusion damps high-frequency temperature changes as they propagate from the surface down into the ice sheet. Therefore, the rapid environmental temperature changes that occurred in the past are damped out in the actual temperature vs. depth data in the ice sheet. While the isotope record in the core may contain a record of rapid fluctuations in the past, the subsurface temperature record only provides a filtered average. Such thermal averaging is more extensive for older climatic events. Therefore, the borehole analysis utilized a filtered version of the GISP $\delta^{18}O$ record, as shown in Figure 3.18. Thus, borehole isotope calibration is sensitive mainly to the long-term warming from full glacial conditions to the Holocene and to Holocene temperature changes, but does not reflect the wild oscillations in the $\delta^{18}O$ record.

Their procedure for estimating $A$ and $B$ in the isotopic paleothermometer was as follows. They used the filtered GISP2 $\delta^{18}O$ record ($\delta^{18}O$ vs. age or depth) and an initial guess for $A$ and $B$ to specify a 100,000-year history of surface environmental temperature. The initial guess for $A$ and $B$ was based on current data for

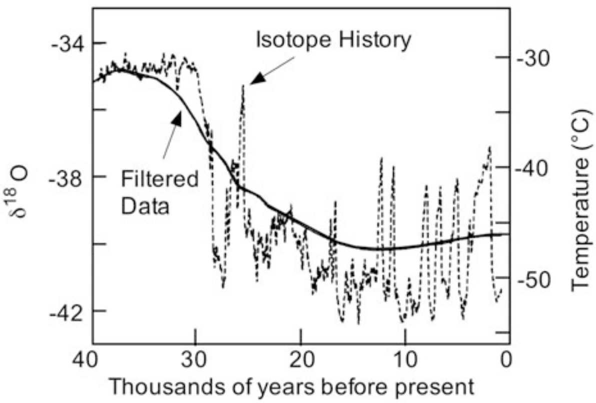



**Figure 3.18.** Filtered isotope data (Cuffey *et al.* 1995).

$\delta^{18}$O vs. $T$, as shown in Figure 3.18. They calculated subsurface temperatures using this $T$ vs. depth as the forcing function on the upper surface of the ice sheet in a linked heat flow–ice flow model. They then compared the modeled $T$ vs. depth with the GISP2 data and adjusted $A$ and $B$ to minimize the mismatch between modeled and measured subsurface temperatures. They found that using the conventional values of $A$ and $B$ based on current $\delta^{18}$O vs. $T$ correlations, they could not get good agreement between the curves of $T$ vs. depth from the heat flow–ice flow model and $T$ vs. depth from the isotope data. Instead, they had to reduce $A$ significantly, leading to the conclusion that past temperature variations corresponding to measured changes in $\delta^{18}$O were considerably greater than had been supposed based on current data for $\delta^{18}$O vs. $T$. They found that this result was robust to changes they imposed on the model and concluded that previous estimates of the temperature difference between the Ice Age and the Holocene were underestimates.

In a later paper, the authors refined their study, presented further details on their model, and extended the time scale to 50,000 YBP (Cuffey and Clow, 1997). They reaffirmed that the change in temperature from average glacial conditions to the Holocene was about 15°—about double the value inferred from isotopic thermometry using current data for the relationship between $\delta^{18}$O and $T$. One interesting aspect of their paper is that they found that the thickness of the Greenland ice sheet probably increased slightly during the deglaciation that occurred starting about 15,000 YBP. This was due to an increase in the snow accumulation rate due to the availability of moisture in the nearby atmosphere as deglaciation proceeded (see Figure 3.19).

Another borehole study found similar results for the difference between Ice Age and Holocene temperatures (Dahl-Jensen, 1998). One interesting result of this study was strong evidence of global warming centered around 900 AD (Medieval Warm Period) and cooling from 1500 to 1900, but with an upward bump around the midpoint of that interval (Little Ice Age).

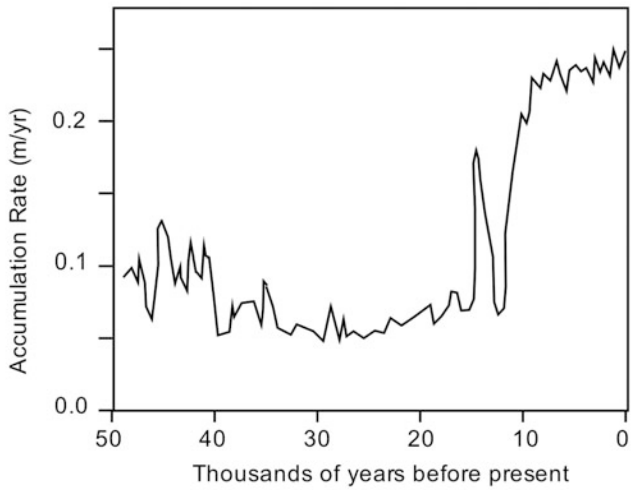



**Figure 3.19.** Rate of accumulation increased in the Holocene (Cuffey and Clow, 1997).

*Use of climate models*

An atmosphere general circulation model was used by Werner *et al.* (2000) to estimate Greenland temperatures during the LGM about 20 KYBP, and these results support the borehole estimates rather than the isotope correlations. This corroborates the belief that the temperature difference from today during the LGM was about twice as great during the LGM as the isotope correlations would predict. The most plausible explanation for this discrepancy is that during the LGM, it was so cold in the Greenland area that precipitation was greatly reduced during winter seasons. Thus, most of the precipitation occurred in summer. The contrast between summer and winter precipitation is illustrated in Figure 3.20. As this diagram shows, summer precipitation produces a lower isotope ratio than the yearly average.

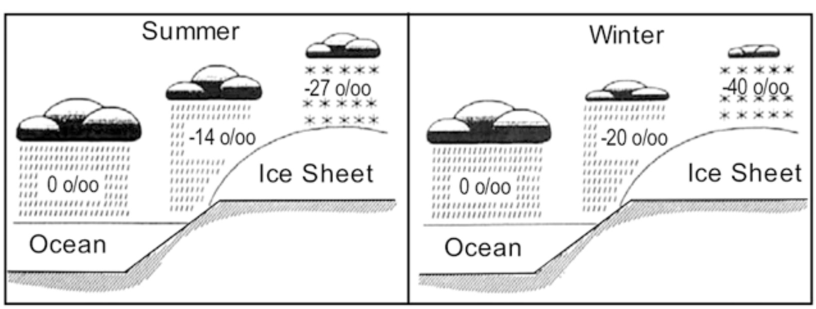



**Figure 3.20.** Difference between isotope ratios in summer and winter (adapted from Thorsteinsson).

*Accumulation change*

Past temperatures have also been estimated from the amount of accumulation of snow per year. Basically, as the temperature decreases, the saturation vapor pressure of water decreases and, as a result, there is less precipitation. However, changes in atmospheric circulation also affect the amount of precipitation at any locality (Jouzel *et al.*, 1997).

### 3.3.2 Climate variations

Ice cores can provide data on precipitation in the past (Kotlyakov, 1996). The rate of snow accumulation on large ice sheets depends on the temperature above the layer of ice-cooled air near the surface. The atmospheric moisture content shows a dramatic drop when the global temperature decreases. It has been estimated that under the colder conditions of a major ice age the amount of atmospheric deposition of snow on the glacier surface would have been 50% lower than during an interglacial period. This can be discerned by the evident reduction in layer thicknesses during glacial epochs.

In addition to reduced precipitation, it is believed that glacial epochs were characterized by stronger oceanic currents and winds, as well as higher dust content due to (a) sharper temperature gradients between continents and oceans, (b) expansion of deserts as water is transferred to ice sheets, and (c) the exposure of continental shelves due to lowering of the sea level. Evidence for this occurs in ice cores where the concentration of aerosols and dust is considerably higher during glacial periods.

### 3.3.3 Trapped gases

As polar snow is transformed to ice, atmospheric air is trapped in bubbles. Therefore, by extracting the gases contained in ice cores, data can be obtained on the composition of the atmosphere in the past—specifically, on the concentration of greenhouse gases. In the absence of melting, the closure of ice pores proceeds at a slow pace: in central East Antarctica this process may take as long as 4,000 years, during which time some exchange of air between the pores and the free atmosphere takes place. Consequently, the air extracted from polar ice cores is younger than the accompanying snow. Present day analytical procedures enable us to extract some gases from the ice—carbon dioxide ($CO_2$) and methane ($CH_4$)—and measure them with great accuracy.

Down to a depth of perhaps 1,200–1,400 m, the ice contains a high concentration of encapsulated gas bubbles. Up to 10% of the volume of the ice is compressed air, so that the density of the ice is about 0.83 as compared with a density of 0.93 for pure ice. The bubbles decrease in size with increasing depth until they disappear in the range 1,200–1,400 m. However, the air is still contained in the ice as a molecular complex at high pressure and, upon decompression, the bubbles reappear (Oard, 2005).

# 4

# Ice core data

Oard (2005) provides an excellent introductory overview of ice cores from the ice sheets at Greenland and Antarctica. The two great ice sheets presently existent on Earth are located where landmasses exist near the poles: Greenland and Antarctica. Both ice sheets store a huge amount of water, as indicated in Table 4.1. If the Antarctic ice sheet were to fully melt, the ocean level would rise about 68 meters. Full melting of the Greenland ice sheet would add another 7 meters. Since the average depth of the oceans is about 3,800 meters, there is considerably more water in the oceans than there is tied up in the ice sheets. However, the ice sheets account for about half the fresh water on the planet.

## 4.1 GREENLAND ICE CORE HISTORICAL TEMPERATURES

Figure 4.1 provides a rough topographical map showing the locations of several major ice core sites on Greenland. The characteristics of the various drilling sites are summarized in Table 4.2. Annual snowfall varies from over 70 cm/year of water (equivalent) in the extreme south, to 30–50 cm/year in the lower to mid range, to 10–30 cm/year in the north. At the highest point on Greenland, the annual mean temperature is $-30^\circ$C, varying between $-15^\circ$C in midsummer to $-41^\circ$C in midwinter.

The Joint European Greenland Ice Core Project (GRIP) drilled a 3,029 m ice core down to bedrock in central Greenland from 1989 to 1992 at 72°N. The ice cores contained records of past climate—temperature, precipitation, gas content, chemical composition, and other properties.

After five years of drilling, the Greenland Ice Sheet Project-2 (GISP2) penetrated through the ice sheet and 1.6 m into bedrock in July, 1993, recovering an ice core 3,053 meters in depth, about 28 km from GRIP. This was the deepest

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books, DOI 10.1007/978-3-642-30029-5_4, © Springer-Verlag Berlin Heidelberg 2012

**Table 4.1.** Characteristics of the Greenland and Antarctica ice sheets (Oard, 2005).

| *Property* | *Greenland* | *Antarctica* |
|---|---|---|
| Area ($10^6$ km$^2$) | 1.8 | 13.9 |
| Volume ($10^6$ km$^3$) | 2.9 | 29 |
| Average depth (m) | 1,600 | 1,900 |
| Maximum depth (m) | 3,370 | 4,200 |
| Current average precipitation (cm water per year) | 32 | 19 |
| Increase in height of oceans if completely melted (m) | 7 | 68 |

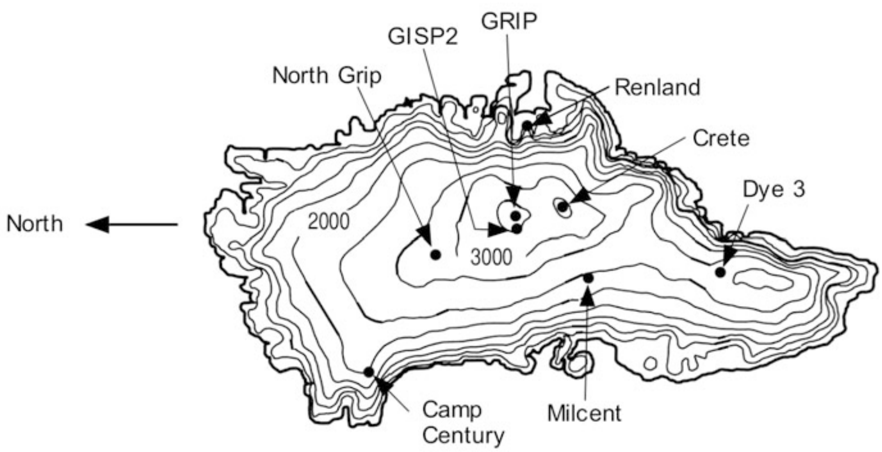



**Figure 4.1.** Greenland topographical map showing the locations of several major ice core sites. Numbers are elevations in meters (adapted from Oard, 2005).

ice core recovered in the world at the time. Data are available at

*http://www.gisp2.sr.unh.edu/DATA/Data.html*

GISP2 was located at the highest point on the Greenland ice sheet (3,208 m above sea level) on the ice divide of central Greenland. Here the ice extends almost vertically down to the bottom. This is the optimal place for drilling.

The similarity of the GISP2 and GRIP records is compelling evidence that the stratigraphy of the ice is reliable and unaffected by extensive folding, intrusion, or hiatuses from the surface to great depths. This agreement provides strong support for a climatic origin of even the minor features of the records (see Figure 3.17).

**Table 4.2.** Characteristics of major ice core sites in Greenland (adapted from Oard, 2005).

| *Ice core* | *Latitude* | *Date drilled* | *Surface elevation* (m) | *Ice thickness* (m) | *Core depth* (m) | *Average temperature* (°C) | *Accumulation* (cm/yr) |
|---|---|---|---|---|---|---|---|
| Camp Century | 77 | 1963–1966 | 1,885 | 1,390 | 1,390 | −24 | 38 |
| Milcent | 70 | 1973 | 2,450 | 2,350 | 398 | −23 | 50 |
| Crete | 71 | 1974 | 3,172 | 3,200 | 405 | −30 | 32 |
| Dye 3 | 65 | 1981 | 2,486 | 2,037 | 2,037 | −20 | 56 |
| Renland | 72 | 1988 | 2,340 | 324 | 324 | −18 | 50 |
| GRIP | 72 | 1990–1992 | 3,230 | 3,029 | 3,029 | −32 | 23 |
| GISP2 | 72 | 1989–1993 | 3,208 | 3,053 | 3,053 | −31 | 24 |
| NorthGRIP | 75 | 1999–2003 | 2,921 | 3,080 | 3,080 | −32 | 20 |

The Internet site *http://www.ncdc.noaa.gov/paleo/icecore/current.html* provides links to a multitude of ice core data at Greenland, Antarctica, and elsewhere. Data from the various Greenland ice cores are plotted in Figures 4.2 through 4.7. Figure 4.2 shows the GISP2 data for the past two centuries. There is good evidence for the Medieval Warm Period around 1000 AD and the Little Ice Age from about 1400 to 1850 AD. As Figure 4.3 shows, temperatures were remarkably stable over the past 10,000 years as the Earth emerged from the last ice age, but were sharply lower prior to that. Note the sudden sharp drop in temperature around 8,200 YBP. This event has also been observed in:

> "... a variety of other palaeoclimatic archives including lake sediments, ocean cores, speleothems, tree rings, and glacier oscillations from most of the Northern Hemisphere .... Today there is a general consensus that the primary cause of the cooling event was the final collapse of the Laurentide ice sheet near Hudson Bay and the associated sudden drainage of the proglacial Lake Agassiz into the North Atlantic Ocean around 8,400 YBP" (Rasmussen *et al.*, 2007).

Figure 4.4 shows temperature change over a 20,000-year period. The Dryas events are widely believed to have been associated with major calving of large ice sheet segments. It is possible, however, that a comet impact about 12,900 YBP may have contributed to the Younger Dryas (Kennett *et al.*, 2009). The 8,200 YBP event is shown with an arrow. Figure 4.5 extends the data to 40,000 years. Two things

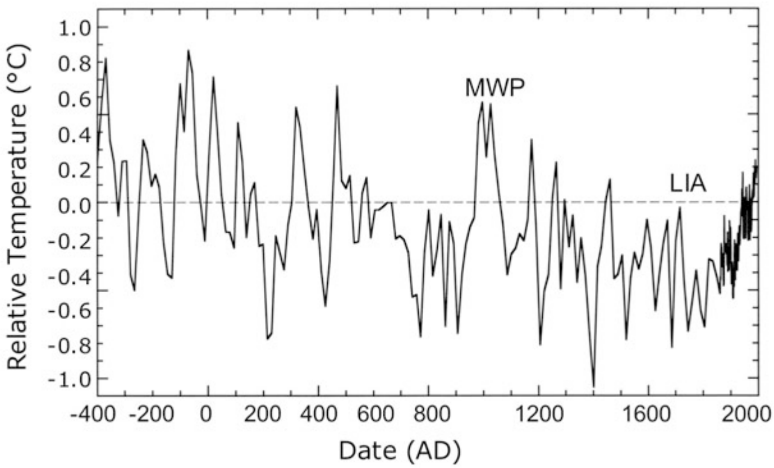



**Figure 4.2.** GISP2 estimates of global temperatures over the past two centuries. The Medieval Warm Period and Little Ice Age are evident (M&M, p. 3; Grootes *et al.*, 1993).

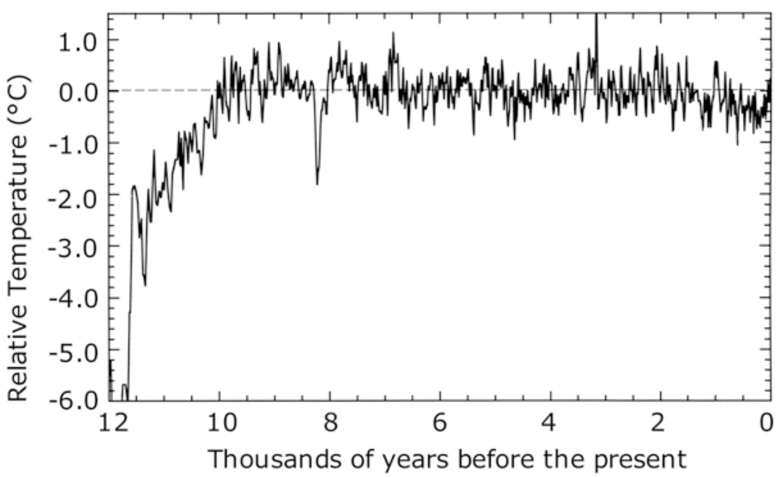



**Figure 4.3.** Ice core estimates of global temperatures during the past 12,000 years (M&M, p. 3).

stand out in this figure: (1) evidence of an ice age prior to about 10,000 years ago and (2) occasional dramatic upward jumps in temperature during the Ice Age. There does not seem to be an entirely satisfactory explanation for these wild oscillations. Figure 4.6 shows GISP2 data extending back 100,000 years. This figure clearly shows that temperatures fluctuated rather wildly throughout the last ice age. Finally, Figure 4.7 shows the longest term data, dating back to the last interglacial prior to the most recent ice age.

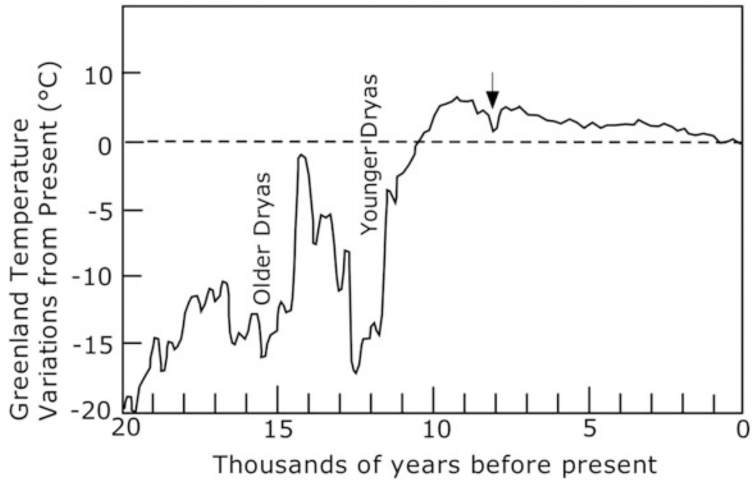



**Figure 4.4.** Greenland temperature history from GRIP over 20,000 years (smoothed data).

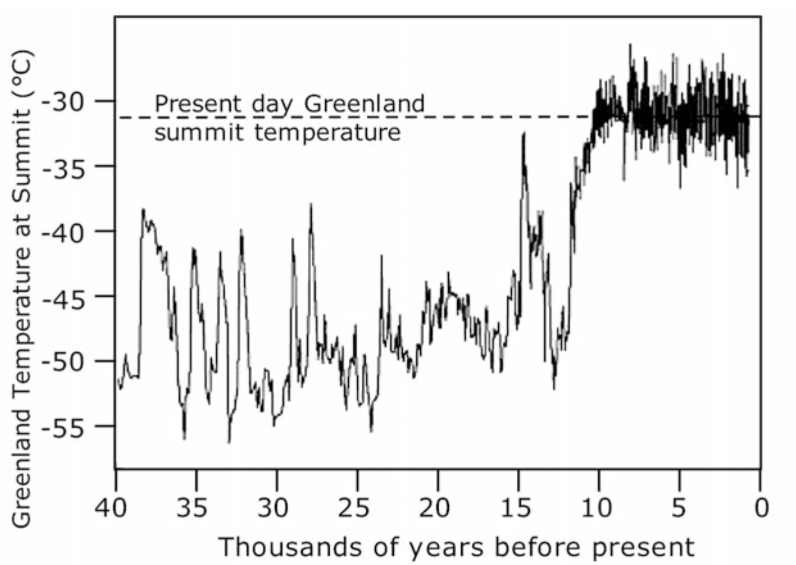



**Figure 4.5.** GISP2 ice core results taken at Greenland summit over 40,000 years (adapted from *http://www.mos.org/soti/icecore/studies.html*).

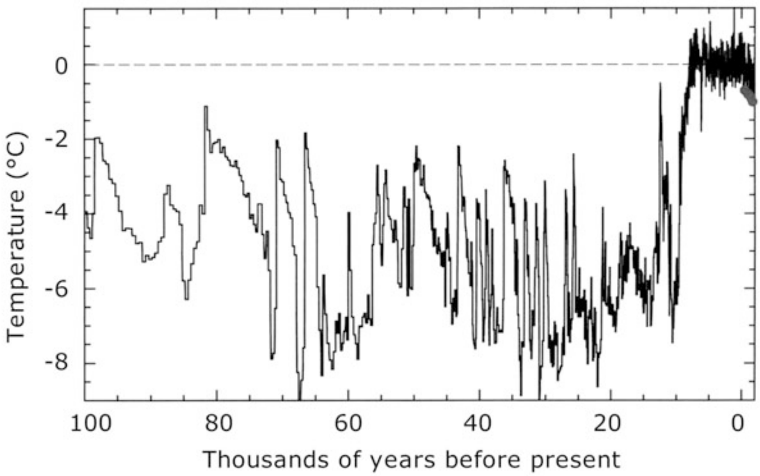



**Figure 4.6.** Global temperature estimates from GISP2 ice cores over 100,000 years (M&M).

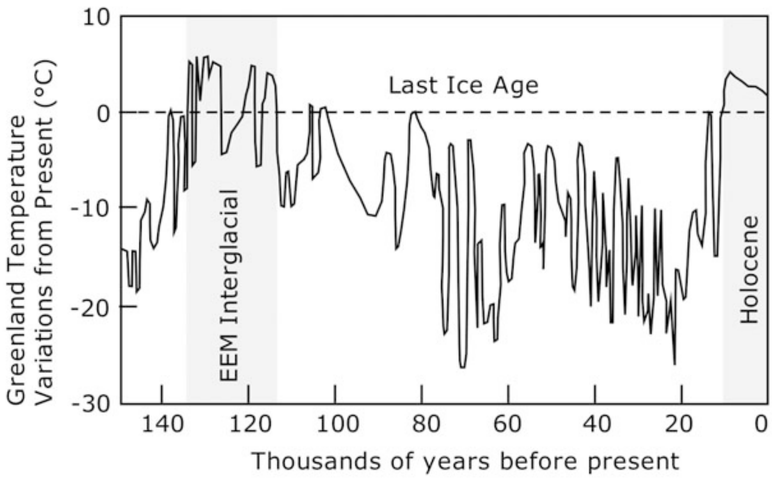



**Figure 4.7.** Greenland temperature history from GRIP (smoothed data) over 150,000 years. Interglacial periods are shown by gray shading.

## 4.2 ANTARCTICA ICE CORE HISTORICAL TEMPERATURES

### 4.2.1 Vostok and EPICA data

Antarctica is the coldest and windiest place on Earth. It sits over the Earth's southern pole and is covered by an ice sheet up to 4 km thick and over 4,000 km across. It contains 70% of the Earth's fresh water and 90% of its ice, and has existed in roughly its present form for around 15 million years. The ice sheet is

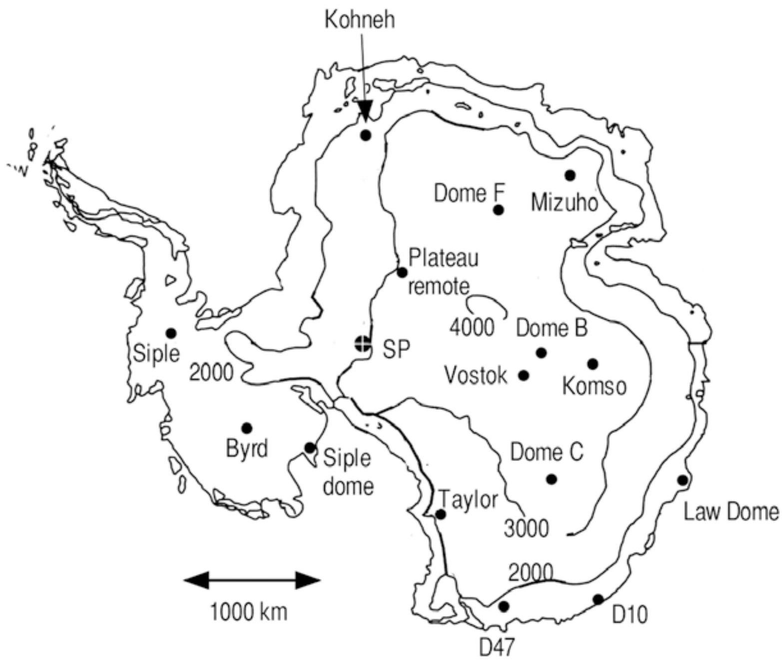



**Figure 4.8.** Antarctic topographical map showing the locations of several major ice core sites (adapted from Oard, 2005).

bisected into two unequal parts by the Transantarctic Mountains. The larger East Antarctic Ice Sheet (EAIS) contains 26 million $m^3$ of ice—enough to raise global sea level by 60 m if it melted. The much smaller and less stable West Antarctic Ice Sheet (WAIS) contains 3 million $m^3$ of ice and could contribute 7 m to global sea level rise (Naish).

Figure 4.8 provides a rough topographical map showing the locations of several major ice core sites in Antarctica. The characteristics of the various drilling sites are summarized in Table 4.3. Annual snowfall is much lower than in Greenland, averaging about 5 cm/year over the main dome area (Dome F to Dome C). However, it reaches over 60 cm/year of water (equivalent) near Law Dome on the coast. Temperatures are much colder than in Greenland—for example, the average temperature at Vostok is $-55°C$.

Vostok ice core data covering ~400,000 years are shown in Figure 4.9. Data from EPICA Dome C over ~800,000 years are shown in Figure 4.10.

Masson-Delmotte *et al.* (2010) revisited EPICA Dome C data and made several new additions. They corrected previous temperature estimates for the change in elevation, as shown in Figure 4.11. They also characterized each of the last eight interglacial and glacial maximum periods in terms of temperature, $CO_2$, dust, and other variables.

**Table 4.3.** Characteristics of major ice core sites in Antarctica (adapted from Oard, 2005).

| *Ice core* | *Latitude* | *Date drilled* | *Surface elevation* (m) | *Ice thickness* (m) | *Core depth* (m) | *Average temperature* (°C) | *Accumulation* (cm/yr) |
|---|---|---|---|---|---|---|---|
| Byrd | −80 | 1968 | 1,530 | 2,164 | 2,164 | −28 | 12 |
| D10 | −67 | 1974 | 235 | 310 | 303 | −14 | 15 |
| Dome C (old) | −75 | 1977–1978 | 3,240 | 3,400 | 950 | −54 | 3.8 |
| Komsomolskaya | −74 | 1983 | 3,498 | 3,550 | 850 | −53 | 50 |
| Mizuho Station | −71 | 1984 | 2,230 | ~2,000 | 700 | −23 | 10 |
| Dome B | −77 | 1988 | 3,600 | 3,460 | 780 | −58 | 3.1 |
| D47 | −67 | 1988–1989 | 1,550 | 1,700 | 870 | −25 | 30 |
| Law Dome | −66 | 1991–1993 | 1,370 | 1,220 | 1,196 | −22 | 70 |
| Taylor Dome | −77 | 1994 | 2,365 | 1,811 | 554 | −43 | 6 |
| Dome F | −82 | 1995–1996 | 3,810 | 3,090 | 2,503 | −58 | 6 |
| Vostok | −72 | 1998 | 3,490 | 3,700 | 3,623 | −55 | 2.3 |
| Siple Dome | −82 | 1996–1999 | 621 | 1,010 | 1,003 | −22 | ~8 |
| Dome C (new) | −75 | 2001–2003 | 3,233 | 3,300 | 3,200 | −54 | 3.4 |

### 4.2.2 Homogeneity of Antarctic ice cores

There is good evidence that the various ice cores taken in Antarctica yield similar results. Figure 4.12 compares Vostok data (Figure 4.9) with EPICA Dome C data (Figure 4.10) and it can be seen that the results are very similar.

Watanabe *et al.* (2003) presented a climate isotopic record from a core successfully recovered by Japanese drillers in 1995 and 1996 at Dome Fuji in East Antarctica, which is about 1,500 km from the Vostok site. The Dome Fuji core extends back to about 330 KYBP allowing a detailed comparison with Vostok over the last three glacial–interglacial cycles, including three successive deglaciations. The methods of Parrenin *et al.* (2001) were used to provide a chronology for the Dome Fuji core, and this was taken to be a valid chronology despite involving considerable orbital tuning. Using this chronology, tie points were made between Fuji $\delta^{18}O$ curves and Vostok $\delta D$ curves, as shown in Figure 4.13. The entire Vostok core could then be dated by interpolation. The resultant $\delta D$ curves are compared with Fuji $\delta^{18}O$ curves as a function of age in Figure 4.14.

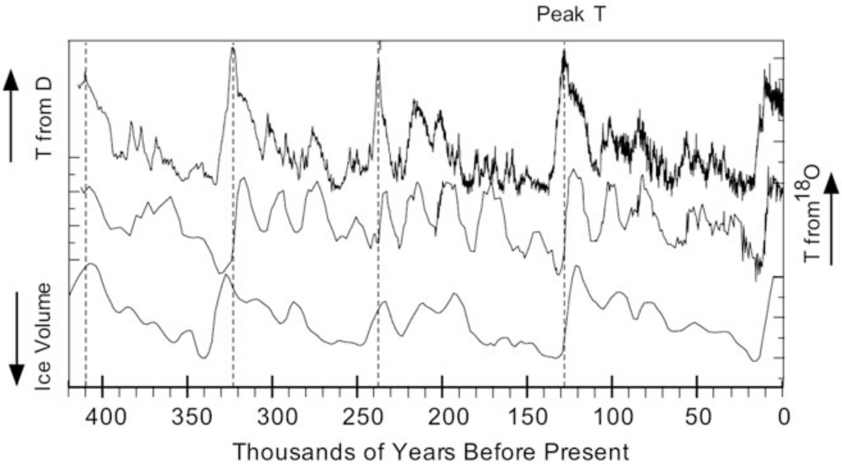



**Figure 4.9.** Vostok ice core data. The upper curve is variation of temperature as interpreted from δD vs. depth of the ice core. The middle curve is the $\delta^{18}O$ profile in the atmosphere from gas bubbles. The lower curve of ice volume implied by $\delta^{18}O$ in ocean sediments is provided for comparison (Petit *et al.*, 1999).

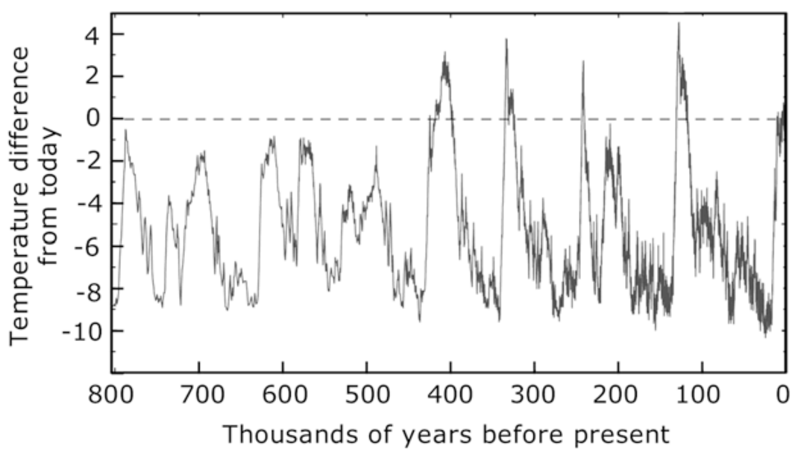



**Figure 4.10.** Estimated temperature difference from today at EPICA Dome C vs. age (EPICA, 2004).

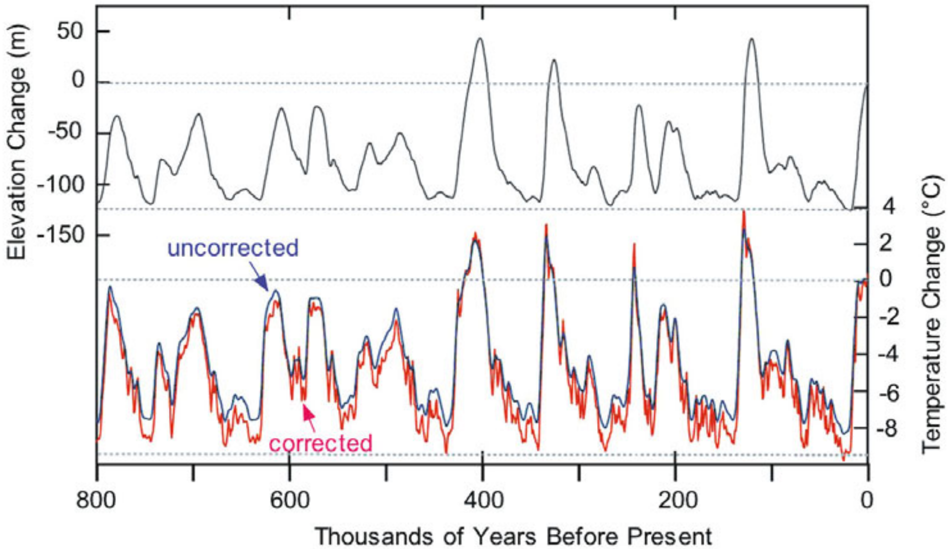



**Figure 4.11.** EPICA Dome C temperature data corrected for elevation changes (Masson-Delmotte *et al.*, 2010).

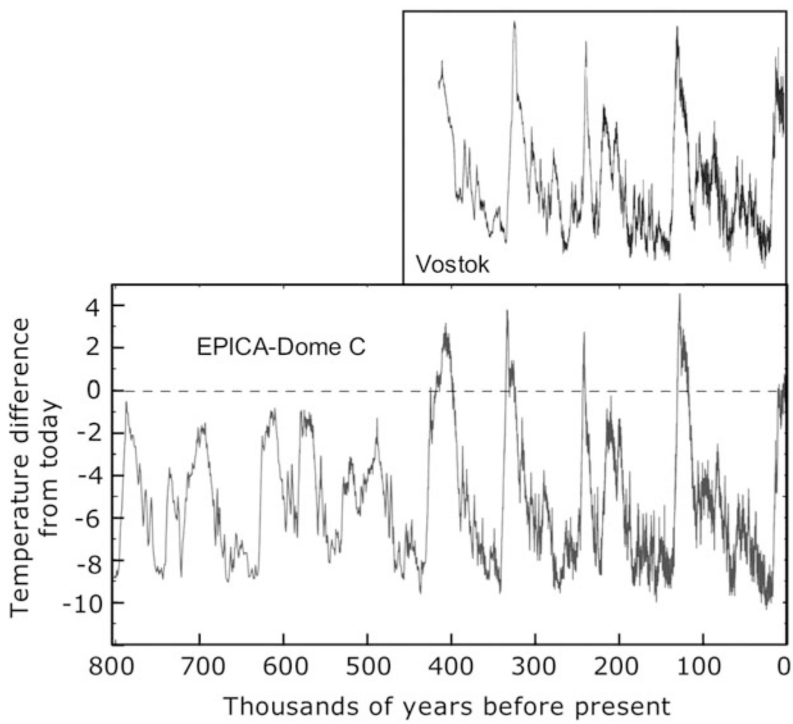



**Figure 4.12.** Comparison of Vostok and Dome C ice core data.

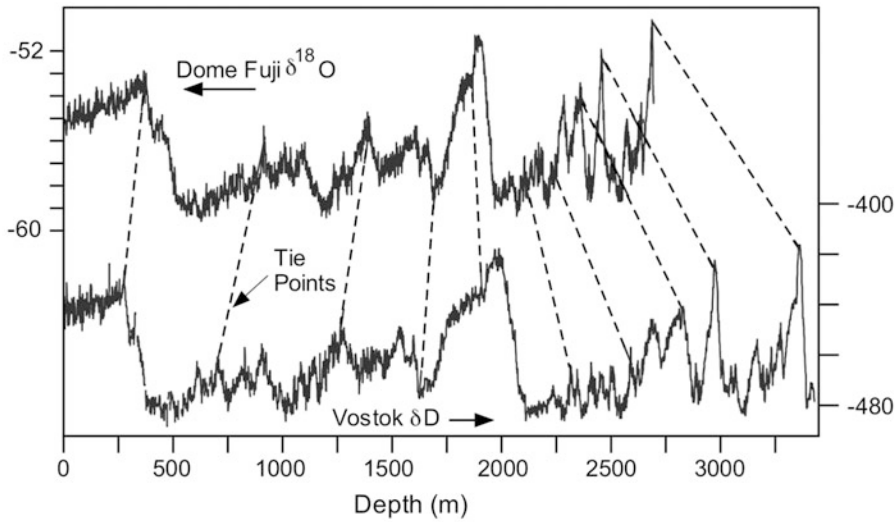



**Figure 4.13.** Comparison of Vostok and Dome Fuji isotopic records of $\delta^{18}O$ as a function of depth (Watanabe *et al.* 2003).

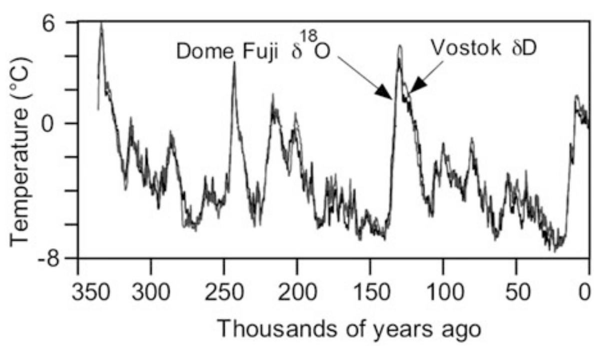



**Figure 4.14.** Comparison of Vostok and Dome Fuji isotopic records of $\delta^{18}O$ as a function of time after scaling, as shown in Figure 4.12.

## 4.3 NORTH–SOUTH SYNCHRONY

### 4.3.1 Direct comparison of Greenland and Antarctica ice core records

A central issue in climate dynamics is whether major changes in the Earth's climate originate in one or both hemispheres, and how the climates of the hemispheres are coupled during major climate changes. In this connection, we can utilize Northern Hemisphere ice core data that go back as far as 150,000 years, Antarctica ice core data that date back up to 800,000 years, and ocean sediment data that presumably represent worldwide conditions over several million years. Of particular interest is a comparison of Greenland and Antarctic ice core data over the past 150,000 years, which encompasses the last ice age and the previous interglacial period. A comparison of NH and SH climate synchrony over the past 50,000 years was reported by Blunier *et al.* (1998). Of critical importance in such studies is the absolute accuracy of time scales, particularly when they are based on comparing the composition of entrapped gases. That is because of the relatively large time lag of the entrapped air relative to the ice in which it is stored in Antarctic cores. Despite the great difficulties involved, Blunier *et al.* (1998) claimed that they established absolute chronological scales that allow comparison of the two sites with an accuracy of about 100 years, depending on the age:

> "Because of the rapid mixing time of the atmosphere (~1 year between hemispheres), large-scale changes in the concentration of long-lived atmospheric gases are essentially globally synchronous. This synchronicity provides a tool for correlating ice core chronologies and thereby comparing the timing of climate and other environmental change, recorded by various proxies in the ice, between the hemispheres. The correlation is complicated by the fact that air is trapped in bubbles 50 to 100 m below the surface, creating an age offset between the trapped air and the surrounding ice. This age offset (Δ-age) must be corrected for when comparing the timing of climate events recorded in the ice by stable isotopes or other proxies."

The value of Δage for Greenland sites was estimated to be around 800 years whereas for Antarctica it ranged from 6,100 years in recent times to 6,300 years at earlier times. Their result is shown in Figure 4.15. This work was extended to a 90,000-year period in a later publication as shown in Figure 4.16. The $CH_4$ data in Figure 4.16 are very similar for Antarctica and Greenland. This indicates that rapid mixing of atmospheric gases does indeed occur. However, the $\delta^{18}O$ data for Greenland and Antarctica show significant differences.

The data in Figure 4.16 indicate that over the past 90,000 years the Earth has been predominantly in an ice age, with the current interglacial period starting about 15,000 years ago. However, the Ice Age in Greenland was interspersed with about two dozen so-called Dansgaard–Oeschger (D-O) events characterized by sudden warming followed by slow cooling with an overall duration of a few thousand years and a Greenland temperature amplitude of up to 15°C. Despite the qualitatively different temperature patterns between Greenland and Antarctica, there appears to be a correlation between major discontinuities in Greenland and slope changes in Antarctica. The seven vertical lines shown in Figure 4.16 indicate where major sudden temperature increases occurred in Greenland. There seems to be a causal relationship between these occurrences and temperature patterns in Antarctica. The data in Figure 4.16 suggest that each sudden increase in temperature in Greenland was preceded by a rather slow moderate temperature rise in Antarctica for a few thousand years. Each sudden rise in Greenland occurs near the end of a more protracted rise in Antarctica.

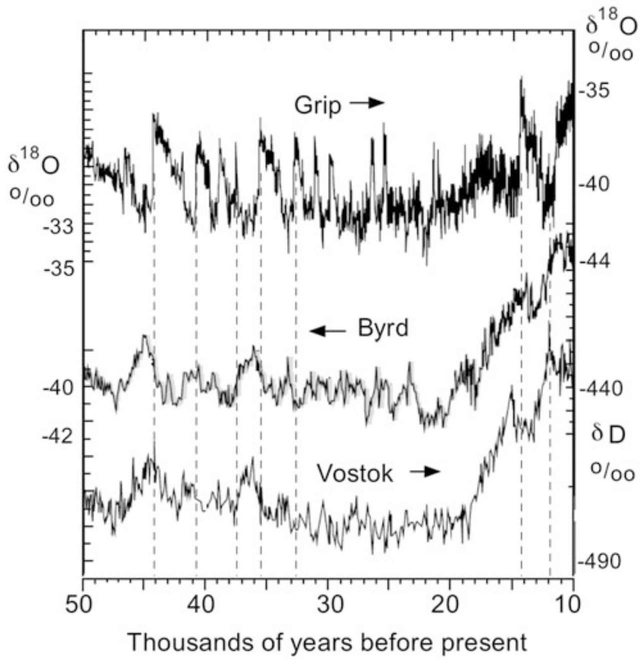



**Figure 4.15.** Comparison of Greenland and Antarctica isotope records. Dashed lines indicate the onset of selected major sudden heating (Dansgaard–Oeschger) events in the NH (Blunier *et al.* 1998).

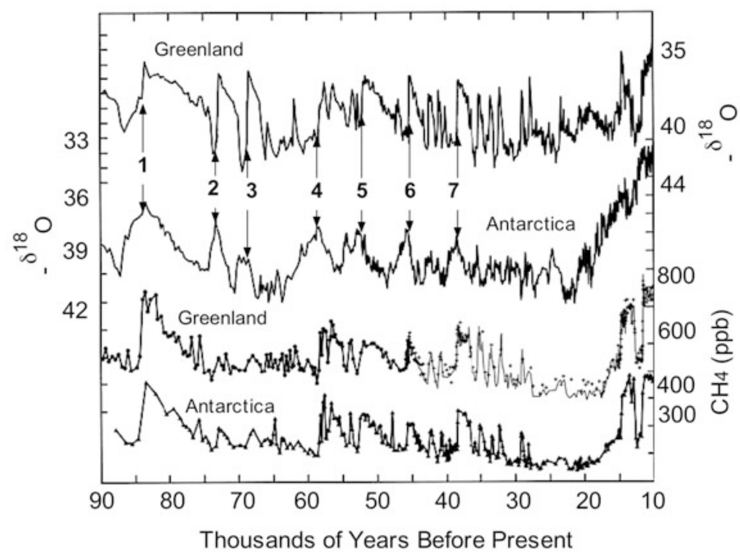



**Figure 4.16.** Isotopic and $CH_4$ data from Greenland and Antarctica on the GISP2 time scale (Blunier and Brook, 2001).

The EPICA Community compared data covering 125,000 years from three Antarctic sites with NGRIP data from Greenland. The results are similar to those shown in Figures 4.15 and 4.16. As in the case of Figures 4.15 and 4.16, the occasional sharp rises in Greenland data also appear to be preceded by slower more gradual increases in Antarctica (EPICA, 2006).

### 4.3.2 Interpretation in terms of ocean circulation

It has been proposed that there is a correlation between temperature patterns in Antarctica and Greenland due to a connection between them via heat transport via ocean currents known as the *bipolar seesaw* (see, e.g., Barker and Knorr, 2007; Toggweiler and Lea, 2010). While a number of papers mention the bipolar seesaw hypothesis, the descriptions of this hypothesis seem to be variable. It appears to involve a slow buildup of heat in the Antarctic that stimulates the flow of heat toward Greenland via thermohaline circulation and, when some nonlinear threshold is exceeded, the NH undergoes a rather sudden and decisive heating. As this process proceeds, heat is drawn away from Antarctica and it starts to cool. This reduces the flow of heat to the NH. In addition, meltwater in the Greenland area interferes with North Atlantic Deep Water (NADW) formation, reducing thermohaline circulation. Thus, the NH begins to cool. Meanwhile, circulation away from Antarctica is impeded so it begins to slowly warm again.

However, Wunsch (2003) provided a dissenting view. He pointed out that when one attempts to synchronize two time series (in this case temperature variations in Greenland and Antarctica), visual comparison of features could be very misleading. The association of a feature on one time series with a corresponding feature on a second time series can be a very subjective process, which he demonstrated with examples. If the innate errors in chronology in Figures 4.15 and 4.16 are comparable with the time scale over which relationships between north and south are sought, claims that there is time phasing between north and south records must be subject to considerable doubt. Thus, pinpointing the time phasing of features in the Greenland and Antarctica isotope time series may not be as accurate as has been claimed. Furthermore, Wunsch claimed that sudden changes in Greenland are not necessarily correlated with changes in Antarctica, and may have been generated by changes in winds. He claimed there is no evidence of a bipolar seesaw. However, Figures 4.15 and 4.16 are fairly convincing to this writer and, unless some improper procedure was used in assessing these chronologies, it is difficult to dispute the apparent relationship between north and south.

A Comment on Wunsch's paper was published about a year later (Huber *et al.*, 2004). This Comment claimed that abrupt shifts in atmospheric methane concentration are observed to occur at the same time (within $\sim$30 yr) as changes in Antarctic and Greenland temperature. New data on the nitrogen and argon isotopic composition of gases trapped in Greenland ice cores show that all of the abrupt $\delta^{18}O$ shifts studied thus far were accompanied by gas isotope anomalies. This suggests that the large temperature changes were global in nature and were not merely associated with local wind variability. A later paper by Wunsch (2006) is discussed in Section 8.6.2.

### 4.3.3 Seasonal variability of precipitation

A number of papers have pointed out that ice core data reflect the seasonal precipitation patterns that existed at the location where the ice cores were obtained. For example, Gildor and Ghil (2002) said: "Proxy records from ice cores are commonly assumed to represent annual mean averages. These averages, however, may be biased toward a particular season, due for example to a change in distribution of precipitation." Krinner and Werner (2003) discussed the fact that borehole analysis suggests that Greenland temperatures were colder than indicated by ice core measurements at the Last Glacial Maximum (LGM). They claimed: "changes in the seasonal precipitation timing in Central Greenland might have caused a warm bias in the LGM water isotope proxy temperatures."

Of greater interest is the recent paper by Laeppele *et al.* (2011) which proposes that ice cores taken in Antarctica are determined by local insolation variability, and "cannot be used to support or contradict the Milankovitch hypothesis that global climate changes are driven by Northern Hemisphere summer insolation variations." This paper is written in a rather confusing manner and it was difficult for this writer to interpret exactly what the authors propose. As far as I can tell, they seem to be proposing the following: Precipitation in Antarctica in local winter months (as measured in the late 20th century) is roughly double that in local summer months. Furthermore, summer ablation reduces summer accumulation. Thus, the ice core records in Antarctica represent winter accumulation to a greater extent than summer accumulation. As the Earth proceeds through its elliptical orbit about the Sun, periods when the Sun is closest to the Earth in austral summer will produce warmer summers but lengthier winters, since the Earth passes through apogee more slowly than perigee. Hence the Antarctic ice core record will produce colder temperatures when the summers are warmer in Antarctica and the summers are cooler in the NH. Therefore, they conclude that Antarctic ice cores will reveal the same apparent temperature pattern as if Antarctic temperatures were driven by NH climate variations but, in reality, they are driven by local Antarctic winter conditions. Since Antarctic winter occurs at the same time as NH summer, it is not possible to distinguish the cause of Antarctic climate change.

In support of their claim that Antarctic climate variability is driven by local Antarctic conditions and is not a result of transfer from NH climate change, they "pose the question of how Northern Hemisphere solar forcing is transferred to the Southern Hemisphere, and why Southern Hemisphere local insolation changes have no imprint on the Antarctic temperature record." They claim: "Variations in greenhouse gas concentrations are too weak to explain the interhemispheric link; there exists no evidence that atmospheric dynamics can directly transfer the orbital signal to the Southern Hemisphere, and changes in thermohaline circulation are thought to favor an asymmetric pattern." What is strange here is that they attribute their claim that "variations in greenhouse gas concentrations are too weak to explain the interhemispheric link" to Lorius *et al.* (1990), because the latter paper provides exactly the opposite viewpoint. Lorius *et al.* said "the climate change during the past few hundred thousand years was linked with changes of greenhouse-gas concentration" and "changes in the $CO_2$ and $CH_4$ content have played a significant part in the glacial–interglacial climate changes by amplifying, together with the growth and decay of the Northern Hemisphere ice sheets, the relatively weak orbital forcing and by constituting a link between the Northern and Southern Hemisphere climates." Lorius *et al.* (1990) concluded "$\sim 50 \pm 10\%$ is a reasonable estimate for the overall contribution of the greenhouse gases to the Vostok temperature change over the last climate cycle. This means that 3°C of the 6°C in the glacial–interglacial change at Vostok could be attributed to the greenhouse effect."

Another weakness of the theory of Laeppele *et al.* (2011) is that the connection of length of austral winter to ice core isotope results is almost nonexistent. Furthermore, as shown in Section 4.3.4, Hansen *et al.* (2010) have provided a credible estimate of forcings in worldwide glacial–interglacial transitions based on the assumption that the trigger to stimulate transitions occurs via solar variability in the NH, and then extends worldwide due to various secondary effects.

### 4.3.4 Worldwide effects of changes originating in the NH

We can propose the following sequence of events leading to ice age–interglacial transitions. A trend is initiated via peak summer solar intensity at latitudes roughly in the range 60°N to 70°N, which begins either a cooling or a heating cycle, depending on the sign. This impacts the ability of surface snow and ice to survive the summers and expand over periods of thousands of years. Once started, a cooling trend produces secondary effects. Nascent ice sheets begin to form, increasing global albedo. Ice packs expand. Sea level begins to drop, replacing sea by land, thus increasing global albedo further. Vegetation in the NH suffers, also contributing to increased albedo. The concentrations of greenhouse gases (water vapor, $CO_2$, and $CH_4$) decrease, producing further cooling worldwide. These effects spread southward, gradually providing cooling to the entire planet. Hansen *et al.* (2010) estimated that the forcings in going from a full interglacial to a glacial maximum would be:

- Changes in albedo due to ice sheets, replacement of ocean by land, and changes in vegetation $\sim 3.5\,W/m^2$
- Changes in $CO_2$, $CH_4$, and $N_2O$ concentrations $\sim 3\,W/m^2$.

However they did not take into account changes in humidity, dust levels, or cloudiness. Nevertheless, there is enough forcing to account for worldwide climate changes without invoking the theory of Laeppele *et al.* (2011).

## 4.4 INTERGLACIALS

Ice ages tend to end rather abruptly compared with their slow rate of formation over many tens of thousands of years. A number of studies have been carried out in an attempt to understand why this occurs, but none of them are entirely satisfactory. Details on terminations of ice ages are presented in Section 10.2.3. The durations required for the transition from glacial to interglacial conditions in the last nine deglaciations are listed in Table 10.5. On average, the duration of the transition from glacial to deglacial conditions is about 6,000 years. There are some indications that the Southern Hemisphere may be significantly involved in the deglaciation process. However, as Wolff *et al.* (2009) said,

> "... the detailed sequence of events that leads to a glacial termination remains controversial. It is particularly unclear whether the northern or southern hemisphere leads the termination .... The reason for the spacing and timing of interglacials, and the sequence of events at major warmings, remains obscure."

Interglacial periods are of great interest because we are presently in one, and there is widespread concern that rising $CO_2$, generated by human activity, may amplify and extend this climate period with negative consequences for civilization. It is therefore relevant to review data on past interglacials with particular emphasis on $CO_2$ levels and prevailing temperatures.

Holden *et al.* (2009) reported:

> "Ice core evidence indicates that even though atmospheric $CO_2$ concentrations did not exceed 300 ppm at any point during the last 800,000 years, East Antarctica was at least 3–4°C warmer than pre-industrial ($CO_2$ ~280 ppm) in each of the last four interglacials. During the previous three interglacials, this anomalous warming was short lived (~3,000 years) and apparently occurred before the completion of Northern Hemisphere deglaciation."

Holden *et al.* (2009) presented a speculative theory to explain this based on meltwater-forced slowdown of the Atlantic Meridional Overturning Circulation (AMOC) during glacial terminations. Thornalley *et al.* (2011) provided evidence that during the period ending the last ice age (16–10 KYBP) significant fluctuations occurred in global overturning circulation. Although this paper received a great deal of hype on Internet blogs (e.g., "Dramatic ocean circulation changes revealed"[1]), the results did not seem very impressive to this writer.

Sime *et al.* (2009) presented oxygen isotope data from three sites in Antarctica showing that the change in isotope content was considerably greater in the previous three deglaciations than in the present deglaciation. They analyzed the relationship between isotope index and temperature at the three sites and concluded "that maximum interglacial temperatures over the past 340 kyr

[1] *www.physorg.com/news/2011-01-ocean-circulation-revealed.htm*

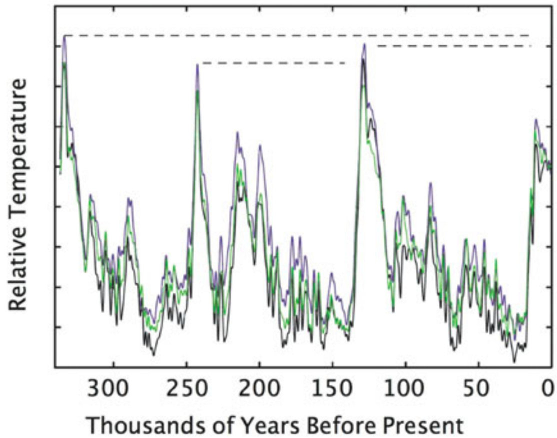



**Figure 4.17.** Relative temperatures of the last four interglacials. The previous three interglacials were significantly warmer than the present one, even though the $CO_2$ concentration was comparable (Sime *et al.*, 2009).

were between 6°C and 10°C above present-day values'' and ''there are serious deficiencies in our understanding of warmer than present day climates.'' A simplified version of their data is shown in Figure 4.17.

Masson-Delmotte *et al.* (2011) provided ice core data comparing the present interglacial with the previous interglacial for several sites in Antarctica. The results are shown in Figure 4.18.

Kopp *et al.* (2009) concluded that sea level during the previous interglacial was 6–9 m higher than during the present interglacial. This was presumably due to the warmer temperatures. Kopp *et al.* said: ''With polar temperatures, 3–5°C warmer than today, the last interglacial stage (~125 kyr ago) serves as a partial analog for 1–2°C global warming scenarios.'' Thus, they implied that such a 1–2°C global warming today could raise the oceans by perhaps several meters. Clark and Huybers (2009) echoed this theme. However, it is not clear why previous interglacials had higher temperatures with about the same concentration of $CO_2$ and, therefore, it is far from clear that increased $CO_2$ should produce conditions like that of the past interglacial. Clark and Huybers asked: ''Why was sea level so much higher 125,000 years ago?''

They suggested: ''one possibility is that ice sheets have multiple potential steady states for a given climate.'' They mention ''the global temperature was apparently 1.5–2°C warmer than the pre-anthropogenic global average of the past 10,000 years despite there being essentially no difference in atmospheric greenhouse-gas concentrations.'' However, this conclusion suggests that global average temperatures are not in lockstep with $CO_2$ concentrations and may vary significantly at different times for the same $CO_2$ concentration. They went on to say ''that the climate of the last interglacial might, by coincidence, provide a reasonable analog for establishing ice-sheet sensitivity to global warming'' and this

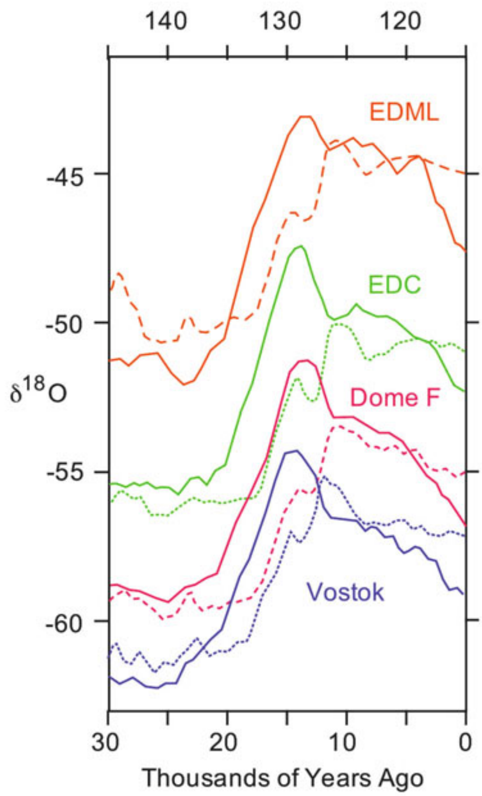



**Figure 4.18.** Comparison of $\delta^{18}O$ at several Antarctic sites. Dashed curves are for the present interglacial (use time scale at bottom) and solid curves are for the previous interglacial (use time scale at top). EDC = Epica Dome C. EDML = EPICA Dronning Maud Land.

implies "that the equilibrium response of sea level to 1.5–2°C of global warming could be an increase of 7–9 meters." They didn't seem to see that there is a logical impasse here. If changes in $CO_2$ concentration accompany glacial–interglacial transitions, why indeed did the $CO_2$ concentration not rise sharply above 300 ppm during warmer interglacials? And if rising $CO_2$ toward 400 ppm has produced the modest global warming of the past century, how is that connected to the warming of past interglacials when $CO_2$ remained below 300 ppm? Nor did they consider the possibility that the present interglacial has not yet reached its maximum temperature independent of $CO_2$, and perhaps (who knows?) is now extending temperatures upward to emulate previous interglacials regardless of $CO_2$. Ultimately, the relationship between $CO_2$ concentration and global temperature remains poorly understood.

Tzedakis *et al.* (2009) attempted to characterize the various interglacials of the past 800,000 years. As they discussed, there is no airtight procedure for defining when a given period is an interglacial. They took data from Figure 4.19 and

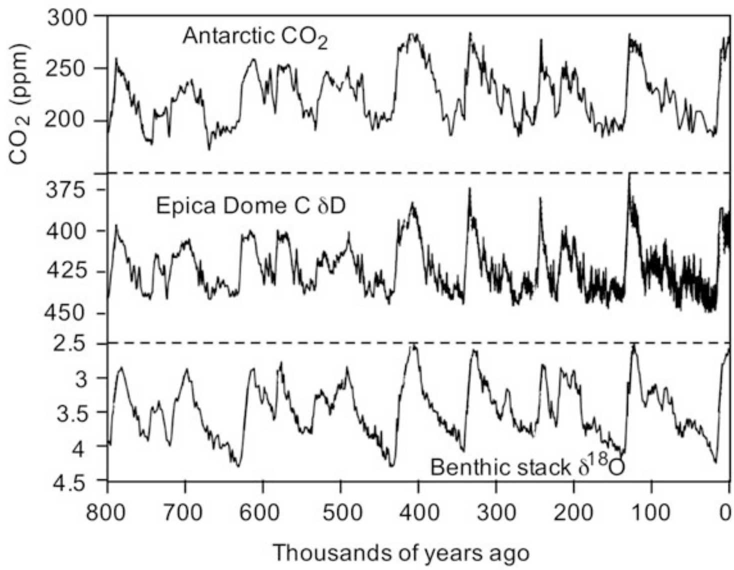



**Figure 4.19.** $CO_2$, Epica Dome C $\delta D$, and benthic stack $\delta^{18}O$ for the past 800,000 years (Tzekadis *et al.*, 2009).

plotted $CO_2$ concentration vs. benthic $\delta^{18}O$ for all significant peaks in Figure 4.19. They found that these divided into two groups. One group which they labeled "warm interglacials" had $CO_2$ concentrations above 260 ppm, and the majority of these also had benthic stack $\delta^{18}O$ values below 2.8‰. Another set had $CO_2$ concentrations below 260 ppm and all of them had benthic stack $\delta^{18}O$ values above 2.8‰. These were labeled "cool interglacials". Except for the extended interglacial period from about 240 to 190 KYBP, all of the interglacials more recent than ~420 KYBP were warm interglacials. All of the previous interglacials, as well as the period from about 240 KYBP to 190 KYBP, were cool interglacials.

Miller *et al.* (2010) said:

> "During the penultimate interglaciation, ~130 to ~120 ka ago, ... Arctic summers were ~5°C warmer than at present, and almost all glaciers melted completely except for the Greenland Ice Sheet, and even it was reduced in size substantially from its present extent. With the loss of land ice, sea level was about 5 m higher than present, with the extra melt coming from both Greenland and Antarctica as well as small glaciers."

Yet the measured $CO_2$ concentration during this period was still less than 300 ppm!

Uriarte (2009) discussed the penultimate interglaciation at some length. He indicated "that at the height of that interglacial epoch, global temperatures were between 1°C and 2°C warmer than today." However in some localities, models suggest that it may have been warmer. "In England, ... many fossils of hippopotamuses and other animals only found today in tropical and subtropical regions have been found. In Greenland, ice cores indicate temperatures of 5°C higher than today ...." He also said that "the surface waters of many seas were between 2 and 3°C warmer than today, and sea level was 4–6 m higher.

Marsh (2008) pointed out that variability of high-latitude solar input does not explain why an ice age should terminate and, since $CO_2$ concentration tends to lag the temperature, he suggested that variable $CO_2$ also does not cause a termination. He presented $^{10}$Be data that are compatible with the notion that increased solar activity leading to less penetration of cosmic rays into the atmosphere may have been a cause of the previous interglacial about 130,000 years ago. However, this single time period is not adequate to show cause–effect and, in order to provide a more convincing argument, he would have to show a rise and fall of $^{10}$Be data in lockstep with ice age–interglacial cycles over at least several cycles.

## 4.5 DATA FROM HIGH-ELEVATION ICE CORES

According to Wikipedia:

> "The non-polar ice caps, such as found on mountain tops, were traditionally ignored as serious places to drill ice cores because it was generally believed the ice would not be more than a few thousand years old, however since the 1970s ice has been found that is older, with clear chronological dating and climate signals going as far back as the beginning of the most recent Ice Age.
>
> Mountain ice cores have been retrieved in the Andes in South America, Mount Kilimanjaro in Africa, Tibet, various locations in the Himalayas, Alaska, Russia and elsewhere. Mountain ice cores are logistically very difficult to obtain. The drilling equipment must be carried by hand, organized as a mountaineering expedition with multiple stage camps, to altitudes upwards of 20,000 feet (helicopters are not safe), and the multi-ton ice cores must then be transported back down the mountain, all requiring mountaineering skills and equipment and logistics and working at low oxygen in extreme environments in remote third world countries. Scientists may stay at high altitude on the ice caps for up to 20 to 50 days setting altitude endurance records that even professional climbers do not obtain. American scientist Lonnie Thompson has been pioneering this area since the 1970s, developing lightweight drilling equipment that can be carried by porters, solar-powered electricity, and a team of mountaineering-scientists."

A number of news releases since 2002 claimed that the ice core drilled in the Guliya ice cap in Tibet in the 1990s reaches back to 760,000 years, but this writer was not able to find any verification of that claim.

Thompson *et al.* (2005) reviewed data on $\delta^{18}$O from high-elevation ice cores at moderate latitudes. Most of these ice cores date back a comparatively short time (10 to 26 KYBP). However, the Guliya core from Tibet reached back to 125 KYBP.

According to them, "these ice core histories provide compelling evidence that the growth (glaciation) and decay (deglaciation) of large ice fields in the lower latitudes are often asynchronous, both between the hemispheres and with high latitude glaciation that occurs on [long] timescales." They concluded that, despite the fact that global-scale cooling occurred during the last ice age, precipitation was the primary driver of glaciation in low latitudes. There appear to be many excursions in the $\delta^{18}O$ profiles that most likely derive from changes in precipitation patterns. However, several of the records show a sharp (positive) increase in $\delta^{18}O$ between 10 and 15 KYBP, which do appear to be responsive to the worldwide deglaciation that took place. Nevertheless, the Guliya record from Tibet does seem to demonstrate precipitation change as a major factor in mid-latitude ice records. Ice core records have been systematically recovered from mid-latitude high-elevation ice fields across the Tibetan Plateau (Thompson *et al.* 2006).

## 4.6 CARBON DIOXIDE

Petit *et al.* (1999) measured the $CO_2$ content of gases encased in the Vostok ice core and found the results shown in Figure 4.20. The peaks and valleys of the $CO_2$ vs. time curve are quite similar to the temperature vs. time curve. These results show a basically repeatable pattern in which the concentration of $CO_2$ in the atmosphere ranges from about 180–200 ppm during glacial peak periods and about 280 ppm during interglacial periods.

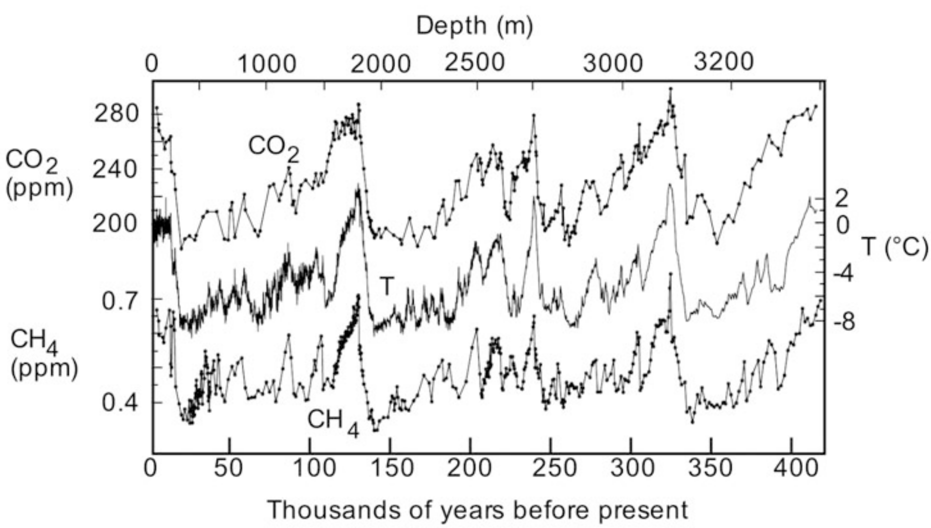



**Figure 4.20.** Vostok (Antarctica) record of $CO_2$, $CH_4$, and temperature (from $\delta D$) (Petit *et al.*, 1999).

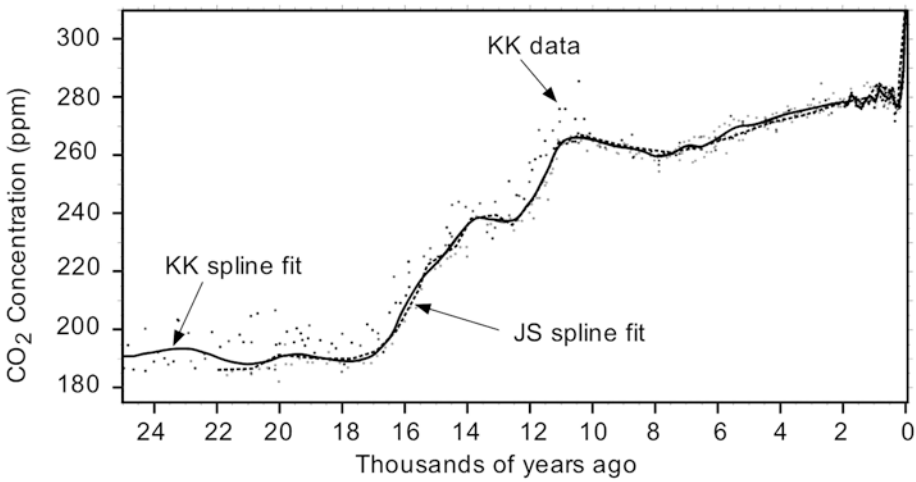



**Figure 4.21.** Variation of $CO_2$ concentration since the LGM. The KK data and spline fit were based on 10 ice core results from Krumhardt and Kaplan (2010). The JS spline fit is to 4 ice core results (Joos and Spahni, 2008).

However, there is some evidence that $CO_2$ concentration rise (or fall) lags temperature rise (or fall) that occurs during periods of increased glaciation or warming at Antarctica. The time lag was estimated to be ~500 years by Roper (2006), $800 \pm 200$ years by Caillon *et al.* (2003), 1,300–5,000 years by Mudelsee (2001), 800 years by Monnin *et al.* (2001), and 400–1,000 years by Fischer *et al.* (1999). That would seem to imply that increased $CO_2$ is mainly an effect, not a cause of temperature change, although it would provide positive feedback and thus be both a primary effect and a secondary cause.

As the Last Glacial Maximum (LGM) faded and the Earth warmed, the $CO_2$ concentration rose in response. Analysis of several ice cores led to the time dependence of $CO_2$ concentration over the past 25,000 years as shown in Figure 4.21.

Skinner (2006) provided a recent review of the subject of glacial–interglacial $CO_2$ cycles. He emphasized that, even though it is clear that changes in atmospheric $CO_2$ were tightly coupled to global climate change throughout the past ~800,000 years, the mechanisms responsible for these changes in $CO_2$ concentration "remain a mystery". Archer *et al.* (2000) came to similar conclusions:

> "In spite of the clear importance of $pCO_2$ as an amplifier or even a primary driver of the glacial cycles, and the additional motivation provided by the threat of future climate change, we remain ignorant of the mechanisms responsible for the glacial/interglacial $CO_2$ cycles .... Fifteen years after the discovery of major glacial/interglacial cycles in the $CO_2$ concentration of the atmosphere, it seems that all of the simple mechanisms for lowering $pCO_2$ have been eliminated."

Sigman and Boyle (2000) echoed this sentiment: "... we have not yet identified the cause of these variations in $CO_2$."

A number of blogs on the Internet would have you believe that the explanation for the similarity between $CO_2$ and $T$ curves results simply from the difference in solubility of $CO_2$ in the oceans as a function of temperature. However, detailed analysis shows that this effect is insufficient to account for the change from about 180–200 ppm under full glacial conditions to about 280 ppm under full interglacial conditions.

Although most of the carbon on Earth is incorporated into $CaCO_3$ in rocks, this carbon pool is too stable to account for $pCO_2$ changes over glacial cycles. Carbon in the terrestrial biosphere is available on shorter time frames but, in order to deplete $pCO_2$ by 100 ppm, the terrestrial biosphere and soil carbon reservoirs would have to approximately double in size over about 10,000 years. Instead, measurements of the $\delta^{13}C$ from deep-sea $CaCO_3$ suggest that the terrestrial biosphere released carbon during glacial times—the wrong direction to explain lower glacial $pCO_2$. The only remaining candidate driver for atmospheric $CO_2$ change is the oceans. They can hold enough carbon to absorb the atmospheric decrease and can change on 1,000 to 10,000-year timescales (Archer *et al.*, 2000).

Archer *et al.* (2000) described two mechanisms that have been proposed to account for $pCO_2$ changes in glacial–interglacial $CO_2$ cycles (GICC). One proposed mechanism to lower glacial $pCO_2$ is based on an increased rate of biological productivity in surface waters of the oceans, leading to storage of carbon in the deep sea due to sinking particles. Either an increase in the ocean inventory of nutrients ($PO_4^{3-}$ and $NO_3^-$) or a change in the ratio of nutrient to C in phytoplankton could have stimulated the ocean's biological pump in this way. Models of the ocean carbon cycle indicate that the $pCO_2$ is extremely sensitive to the biological pump at high latitudes and relatively insensitive to low-latitude forcing. Since iron availability limits phytoplankton growth in remote parts of the ocean, a dustier more iron-rich glacial climate would have intensified biological productivity in surface waters of the oceans. A second mechanism to lower glacial $pCO_2$ is to change the pH of the whole ocean, converting seawater $CO_2$ into $HCO_3^-$ and $CO_3^-$, which are unable to evaporate into the atmosphere. The pH of the ocean is controlled by any imbalance between the influx of dissolved $CaCO_3$ from chemical weathering on land and the removal of $CaCO_3$ by burial in the deep sea.

Skinner (2006) pointed out that the magnitude of the marine carbon reservoir and its interaction with atmospheric $CO_2$ suggests a major role for the oceans in GICC. While a simplistic model might suggest that the increased solubility of $CO_2$ in a colder glacial ocean would account for the reduction of $CO_2$ during ice ages, detailed models indicate that this would only amount to about 30 ppm of the total 80–100 ppm reduction. Furthermore, even this moderate reduction in $CO_2$ would be counteracted by the reduced solubility of $CO_2$ as the oceans became saltier during ice ages, as well as by a large reduction in the terrestrial biosphere when land is covered by ice under glacial conditions. Thus, the net reduction in $CO_2$ during glacial conditions due to solubility, land changes, and salinity is probably more like ~10 ppm. Therefore, Skinner argued: "the bulk of the GICC remains to be explained by more complex inter-reservoir exchange mechanisms." He suggested that "the most viable proposals involve either the biological or physical 'carbon pumps' of the ocean" and, regardless of which mechanism is invoked, GICC involves changes in the sequestration of $CO_2$ in the deepest marine reservoirs.

Given the magnitude and dynamism of the deep-sea carbon reservoir, it is almost certain that past glacial–interglacial fluctuations in atmospheric $CO_2$ have relied at least in part on changes in the carbon storage capacity of the deep sea. Skinner (2006) described three main types of conceptual models that have been offered to explain GICC:

(1) Biological pump models demonstrating increased export of organic carbon to the deep sea, either via increased nutrient availability at low latitudes or via increased efficiency of nutrient usage at high latitudes.
(2) Models to show the reduced ventilation of $CO_2$ of water exported to the deep Southern Ocean, either via sea ice capping or via a change in ocean interior mixing efficiency.
(3) Models to show changes in ocean chemistry and carbonate imbalance, possibly involving changes in the ratio of organic carbon and carbonate fluxes to the deep sea.

According to Skinner (2006), individually each of these approaches has difficulties in explaining the pattern and magnitude of past GICC, and it is likely that all three have participated to some extent. For example, Stephens and Keeling (2000) noted that outgassing of $CO_2$ from the oceans is enhanced when partial pressure in the atmosphere is low, producing a high gradient between ocean and atmosphere. This acts in opposition to the innate increase in solubility when the oceans are colder. As a result, the sea ice cover of the Southern Ocean south of 55°S during glacial winters would have to be very high to produce a significant decrease in $pCO_2$ due to ice capping. They estimated that if the sea ice cover of the Southern Ocean south of 55°S during glacial winters was as high as 99%, it could account for a 65 ppm reduction in $pCO_2$. However, Maqueda and Rahmstorf (2002) found that sea ice coverage maximizes at 92% using a sophisticated climate model, corresponding to a $CO_2$ decrease of only 35 ppm. They therefore concluded that the increase of sea ice in the Southern Ocean could explain only a moderate portion of the $CO_2$ decrease during glacial periods.

According to Skinner (2006), one factor from these models that emerges as being fundamental is the competition between carbon export from the surface ocean to lower depths vs. carbon reflux by the overturning circulation of the ocean. This tug-of-war between these two processes, one biological and one physical, essentially determines the balance of carbon input to and output from the deepest marine reservoirs. This ultimately determines the magnitude of $pCO_2$ in the atmosphere. The thermohaline circulation of the oceans plays an important role in this process. The formation of North Atlantic Deep Water represents an efficient mechanism for mixing $CO_2$ deep into the ocean interior. The return flow of deep water to the surface occurs primarily in the Southern Ocean representing a net reflux of carbon to the atmosphere. Thus, the Southern Ocean plays a pivotal role in controlling the overall efficiency of oceans' physical carbon pump. Any model to explain the GICC must provide scenarios for these oceanic processes.

A number of interesting new ideas regarding GICC, which are unfortunately beyond the scope of this book, can be found at *www.atmos.umd.edu/~cabo/METO658A/dlove.ppt*

Lisiecki (2010) presented an extensive review of estimates of variability of $CO_2$ concentration over the past 800,000 years. It was found that benthic $\delta^{13}C$ data provide a good record of deep-ocean carbon storage and, thus, atmospheric $pCO_2$. This study found that the difference between $\delta^{13}C$ data in the deep Pacific and intermediate North Atlantic provided a good correlation with $CO_2$ levels recorded in Antarctic ice cores.

Sigman *et al.* (2010) asserted:

> "... the cause of the $pCO_2$ variation must be resolved if we are to understand its place in the causal succession that produces glacial cycles .... The ocean is the largest reservoir of $CO_2$ that equilibrates with the atmosphere on the thousand-year timescale of glacial/interglacial changes in $pCO_2$, so the ocean must drive these changes. $CO_2$ was more soluble in the colder ice-age ocean, which should have lowered $pCO_2$ by ~30 ppm, but much of this appears to have been countered by other ocean changes (in salinity and volume) and a contraction in the terrestrial biosphere. The most promising explanations for the bulk of the $pCO_2$ decrease involve ocean biogeochemistry and its interaction with the ocean's physical circulation."

Sigman *et al.* (2010) concluded:

> "Global climate and the atmospheric partial pressure of carbon dioxide ($pCO_2$) are correlated over recent glacial cycles, with lower $pCO_2$ during ice ages, but the causes of the $pCO_2$ changes are unknown. The modern Southern Ocean releases deeply sequestered $CO_2$ to the atmosphere. Growing evidence suggests that the Southern Ocean $CO_2$ 'leak' was stemmed during ice ages, increasing ocean $CO_2$ storage. Such a change would also have made the global ocean more alkaline, driving additional ocean $CO_2$ uptake. This explanation for lower ice-age $pCO_2$, if correct, has much to teach us about the controls on current ocean processes."

Bouttes *et al.* (2011b) employed a model "of intermediate complexity" to investigate the causes of the increase in $pCO_2$ following the LGM. They included the following factors: (1) fertilization of marine biology by iron deposited from the dusty atmosphere; (2) extension of the Antarctic ice sheet past continental shelves, thus forming sea ice over deep ocean and allowing brines left over from sea ice formation to sink to the deep ocean; and (3) stratification of the ocean due to sinking of brines resulting in reduced upward diffusion of dissolved $CO_2$. They claimed that these factors were able to generate the increase of $CO_2$ content in the atmosphere from 190 ppm at the LGM to 260 ppm at the start of the Holocene. However, their model does not seem to be unique and its parameters seem to be rather arbitrarily chosen. Brovkin *et al.* (2011) also modeled the changes in $CO_2$ concentration during glacial cycles.

Chikamoto *et al.* (2011) found that enhanced solubility of $CO_2$ during the LGM only accounted for a 20–23 ppm decrease in $CO_2$ concentration. They also found that "neither a weakening of North Atlantic Deep Water formation nor an increase of Antarctic Bottom Water (AABW) formation causes a large atmospheric $pCO_2$ change. A marked enhancement in AABW formation is required to represent the reconstructed vertical gradient of dissolved inorganic carbon during LGM conditions."

Marchitto *et al.* (2007) made radiocarbon measurements of corals and planktonic foraminifera which indicated that the radiocarbon activity ($\delta^{14}C$) of the atmosphere during the latter part of the last glacial period ($\sim$30–40 KYBP) was very high, and around 30 KYBP it began to steadily decrease toward present day low values. Models indicate that the rate of production of $^{14}C$ in the atmosphere by cosmic rays was too small to account for the observed high levels of $^{14}C$ during the period prior to 30 KYBP unless there was a significant decrease in the uptake of $^{14}C$ by the deep ocean. According to Marchitto *et al.* (2007), "This requires a concomitant $^{14}C$ depletion in a deep-ocean dissolved inorganic carbon reservoir that was relatively well isolated from the atmosphere. Renewed ventilation of this reservoir could theoretically explain the drop in atmospheric $^{14}C$ and the rise in atmospheric $CO_2$ across the last deglaciation" (the past $\sim$15,000 years). This is a very appealing picture; however, it has some difficulties that were glossed over by Marchitto *et al.* (2007). Figure 4.22 shows that $\delta^{14}C$ began decreasing around 30 KYBP, well before the maximum ice buildup at the LGM (about 20 KYBP). From 30 to 20 KYBP, ice sheets continued to expand and $CO_2$ concentration remained low. So, why did $\delta^{14}C$ decrease from $\sim$700 to $\sim$400‰ during this period? On the other hand, it is noteworthy that during the period shown in gray in this figure (about 17 to 14 KYBP) the $CO_2$ concentration in the atmosphere jumped up from about 190 ppm to almost 240 ppm while $\delta^{14}C$ decreased from about 380 to about 180‰ over this same period, which would be in line with the conclusions of Marchitto *et al.* (2007).

As we have seen, the dramatic rise and fall of $CO_2$ concentration in glacial–interglacial cycles remains difficult to explain although several aspects of the process have been discussed in the literature. In particular, the results of Marchitto *et al.* (2007) are very important in pointing to oceanic processes that store and release $CO_2$.

At about the same time that Marchitto *et al.* (2007) published their paper, Stott *et al.* (2007) published relevant results. They "used radiocarbon ($^{14}C$) dating to establish the timing of the deep-sea and tropical–surface ocean temperature changes during the last glacial termination and compared this history with the timing of $CO_2$ change and deglacial warming in the southern high latitudes during

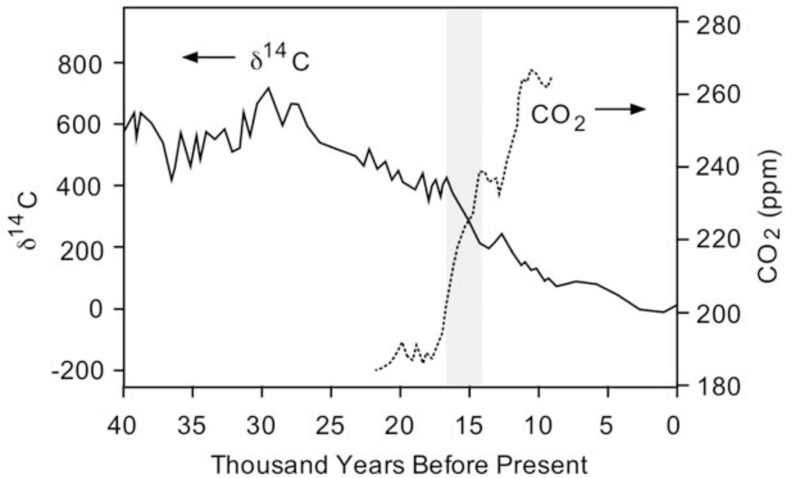



**Figure 4.22.** Variation of $\delta^{14}C$ and $CO_2$ concentration during the past 40,000 years (Marchitto *et al*., 2007).

the last glacial termination.'' Some of their results are shown in Figure 4.23. They particularly noted that the deep Pacific temperature as measured by benthic species in ocean sediments, and the South Pacific SST (around 45°S off the coast of Chile) both revealed a remarkable 2°C temperature rise while the tropical SST remained at glacial levels during the period from about 19 to 17 KYBP. As Stott *et al.* (2007) pointed out, if atmospheric $CO_2$ was the main driver of deglacial temperature changes, the ensuing rise in temperature should be global and work from the top down; deep-sea temperatures would "reflect this with an appropriate lagged relation that would account for the response time between $CO_2$ forcing and the turnover time of deep waters.'' The fact that deep-sea and South Pacific surface temperatures rose prior to tropical sea surface temperatures suggests that $CO_2$ was not a cause of this warming. Stott *et al.* (2007) suggested that the explanation for the early warming in the Southern Hemisphere could involve increasing springtime solar insolation during the austral spring that influenced the retreat of sea ice. They hypothesized that these forcings promoted enhanced ventilation of the deep sea and the subsequent rise in atmospheric $CO_2$. However, their curve for "averaged mean longitude spring insolation (21 August to 20 November) at 65°S'' seems strange to this writer. In fact, their insolation curve lies almost exactly on the peak solar curve for 65°N (or equivalently, the duration of summer at 65°S) and it is not clear how they arrived at this curve. The yearly variation of insolation for early spring at 65°S would be as shown in Figure 4.24. From 20 to 15 KYBP, the insolation actually decreased whereas, according to the model of Stott *et al.* (2007), it was increasing.

Timmermann *et al.* (2009) carried out climate model simulations of the last 21,000 years in an effort to identify the driving forces for deglaciation in the Southern Hemisphere after the LGM. They concluded:

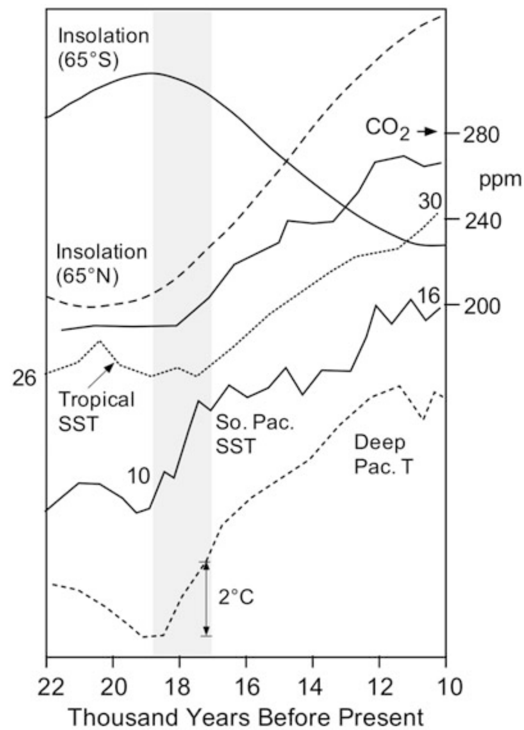



**Figure 4.23.** Variation of temperatures and $CO_2$ since the LGM. Tropical Pacific SST changed from about 26 to about 30°C over this period. South Pacific (45°S off the Chile coast) SST changed from about 9 to about 16°C over this period. Deep-Pacific temperature rose by about 2°C over the short interval shown by the gray area near 18 KYBP (Stott *et al.*, 2007). Note that the insolation curves are *not* those of Stott *et al.* and widely differ from them.

> "... orbitally driven insolation changes in the Southern Hemisphere, combined with a rise in atmospheric $pCO_2$, were sufficient to jump start the deglacial warming around Antarctica without direct Northern Hemispheric triggers. Analyses of sensitivity experiments forced with only one external forcing component (greenhouse gases, ice-sheet forcing, or orbital forcing) demonstrate that austral spring insolation changes triggered an early retreat of Southern Ocean sea ice starting around 19–18 ka BP. The associated sea ice–albedo feedback and the subsequent increase of atmospheric $CO_2$ concentrations helped to further accelerate the deglacial warming in the Southern Hemisphere."

However, there are some aspects of this analysis that seem strange to this writer. A key element in the analysis is the timing of the putative rise in solar insolation that is claimed to have triggered the retreat of sea ice and released $CO_2$ from the southern ocean. Timmermann *et al.* (2009) refer to two estimates of solar insolation: "Averaged austral spring insolation at 63°S using a fixed-length season

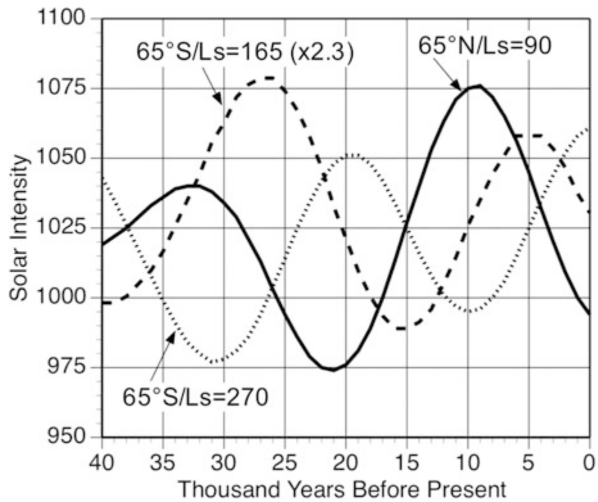



**Figure 4.24.** Variation of peak solar intensity over the past 40,000 years. The solid curve is for northern midsummer, the dotted curve is for southern midsummer, and the dashed curve is for southern spring.

and fixed angle season.'' It is not clear to this writer what these phrases mean. Figure 4.25 shows some of their results. The strange thing is that the solar forcing presented by Timmermann *et al.* (2009) for ''austral springtime insolation forcing at 63°S using a fixed calendar season'' looks exactly like the curve for peak solar intensity at 65°N as calculated by this writer.

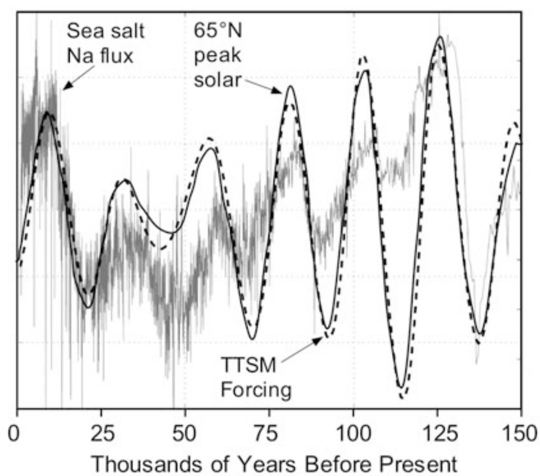



**Figure 4.25.** Sea salt sodium flux measured from the EPICA Dronning Maud Land ice core and solar forcing as reported by Timmermann *et al.* (2009). This forcing was based on ''austral springtime insolation forcing at 63°S using a fixed calendar season.'' The solid line is peak solar intensity at 65°N as calculated by this writer (the vertical scale is arbitrary).

## 4.7 SUDDEN CLIMATE CHANGES

Ice core data provide incontrovertible evidence that there have been very strong sudden climate changes during the various ice ages (see Figures 4.5, 4.6, and 4.12). According to Figures 4.5 and 4.6, temperature excursions have occurred at Greenland amounting to tens of degrees, up and down, within a few decades or centuries. Such rapid climate changes cannot possibly be due to slowly changing solar input and, hence, scientists have sought explanations outside the realm of the astronomical theory, typically based on changes in ocean currents. There is an extensive literature on these sudden climate changes.

Dansgaard–Oeschger events are rapid climate fluctuations involving a sudden warming in a very short time (a few decades) followed by a gradual cooling back to initial conditions over the next ~1,500 years. Twenty-three such events have been identified over the last glacial period (between ~110,000 and 23,000 YBP). Sudden intense cold dry phases also occasionally affected Europe and the North Atlantic region, and possibly many other parts of the world. These so-called "Heinrich events" were first recognized as the traces of ice surges into the North Atlantic, based on ice-rafted debris found in high-latitude sediments (Heinrich, 1988). They also show up in the Greenland ice cores and some are also detectable in the European pollen records and distant Antarctic ice cores. Figure 4.26 shows numbered Heinrich events that occurred over the past 100 KYBP. Wilson *et al.* (2000) provide a good description of Heinrich events. They discussed two models that have been proposed for their origin. One model is based on the accumulation of geothermal and frictional heat at the base of the ice sheet, leading to large-scale generation of large icebergs that cool the NH. The other model presupposes some external cooling mechanism leading to expansion of the ice sheets to the point where they break off at the edges and generate many large icebergs that cool the NH.

A number of scientists have investigated these sudden climate changes and provided rational explanations for them, mostly in terms of changes in ocean flows. Section 8.6 discusses these models. Most of that work deals specifically with rapid climate change events that occurred during the most recent ice age and its aftermath. But if there are forces operating that can change the climate by such a large amount in so short a time, it would seem likely that these forces may also be involved in longer term glacial–interglacial cycles. This implication does not seem to have been emphasized by modelers of short-term fluctuations.

Around 14,000 years ago, a rapid global warming and moistening of climates began, perhaps occurring within the space of only a few years or decades. Conditions in many mid-latitude areas appear to have been roughly as warm as they are today, although many other areas—while warmer than during the Late Glacial Cold Stage—seem to have remained slightly cooler than at present. Forests began to spread back and the ice sheets began to retreat. However, after a few thousand years of recovery, the Earth was suddenly plunged back into a new and very short-lived Ice Age known as the "Younger Dryas", which led to a brief resurgence of ice sheets (see Figure 4.4). The main cooling event that marks the

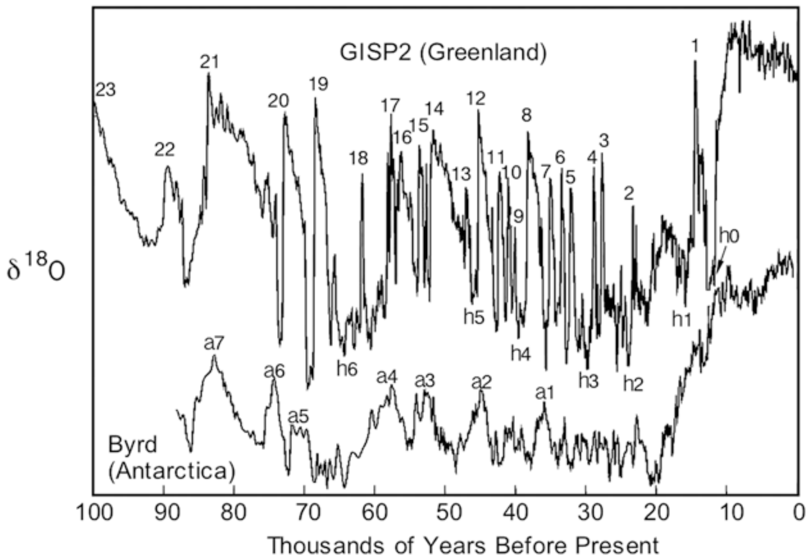



**Figure 4.26.** Sudden climate change events at Greenland and Antarctica. Numbered peaks are D-O events. Heinrich events are shown as h-numbered minima. Warming in Antarctica is shown as a-numbered events (adapted from Alley, 2007).

beginning of the Younger Dryas seems to have occurred within fewer than 100 years. After about 1,300 years of cold and aridity, the Younger Dryas seems to have ended in the space of only a few decades when conditions became roughly as warm as they are today (Adams *et al.*, 1999; Adams, 2002).

The start of the present warm phase (i.e., the Holocene) followed the sudden ending of the Younger Dryas, about 11,500 years ago (see Figure 4.4). Forests quickly regained the ground that they had lost to cold and aridity. Ice sheets again began melting though, because of their size, they took about 2,000 more years to disappear completely. The Earth entered several thousand years of conditions warmer and moister than today; the Sahara and Arabian Deserts almost completely disappeared under vegetation cover, and in northern latitudes forests grew slightly closer to the poles than they do at present. This phase, known as the "Holocene Optimum" occurred between about 9,000 and 5,000 years ago, although the timing of the warmest and moistest conditions probably varied somewhat between different regions. Other fluctuations during the Holocene have been reported (Adams, 2002).

A number of sudden climate transitions occurred during the Younger Dryas–Holocene stepwise change around 11,500 years ago, which seems to have occurred over a few decades. Of particular note is the event at 8,200 YBP (see Figures 4.3 and 4.4). The speed of these changes is probably representative of similar but less well-studied climate transitions during the last few hundred thousand years. These events almost certainly did not take longer than a few centuries. Various mechanisms, involving changes in ocean circulation, in atmospheric concentrations of greenhouse gases or haze particles, and in snow and ice cover, have been invoked to explain these sudden regional and global transitions. We do not know whether such changes could occur in the near future as a result of human effects on climate. Phenomena such as the Younger Dryas and Heinrich events might only occur in a glacial world with much larger ice sheets and more extensive sea ice cover. All the evidence indicates that most long-term climate changes occur in relatively sudden jumps, rather than as incremental changes (Adams *et al.*, 1999). More recently, there have been smaller climate variations such as the Medieval Warm Period and Little Ice Age (see Figure 4.2).

A topic of considerable concern today for the climate in the near future is the question of how stable the climate was in past interglacial periods. The climate during the Holocene has been very stable, as Figure 4.3 demonstrates. However, Figure 4.7 shows that large variations in climate apparently occurred during the Eemian interglacial period and it is not clear how the Eemian interglacial differed from the Holocene.

# 5

# Ocean sediment data

## 5.1 INTRODUCTION

According to Wright (1999):

> "Marine stable isotope records provide the basis for much of our understanding of past climates. During the past four decades of research, the exploitation of climatic information contained in marine stable isotopes led to the generation of a global network of marine stable isotope records. In particular, oxygen isotope records have been used to estimate past water temperatures, ice sheet sizes, and local salinity variations, while carbon stable isotope records have been used to provide constraints on water mass circulation patterns, oceanic nutrient levels, and atmospheric $pCO_2$ concentrations. From these down-core records came a realization that the major features in marine stable isotope records were recognizable in almost all cores; and thus, if they were synchronous, these features could be used as a tool to correlate cores on a global scale. Demonstrating synchrony and establishing a numerical time scale for these changes were the first two hurdles in establishing a stable isotope-based stratigraphic scheme. Success in both of these areas resulted in stable isotope records becoming the most frequently used stratigraphic tool for the correlating Quaternary climate records. Most of the stable isotope-based stratigraphic schemes are built on the marine oxygen isotope record, even though variations in the marine carbon isotope records were often globally synchronous as well."

This may be an overly optimistic appraisal for, although the qualitative synchrony of marine stable isotope records has been fairly well established, the accuracy of various numerical time scales remains open to discussion, particularly because time scales have typically been tuned by comparison with the astronomical theory.

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books, 171
DOI 10.1007/978-3-642-30029-5_5, 

According to Monica Bruckner:

> "Foraminifera, also known as forams, and diatoms are commonly used microbial climate proxies. Forams and diatoms are shelled microorganisms found in aquatic and marine environments. There are both planktic (floating in the water column) and benthic (bottom dwelling) forms. Foram shells are made up of calcium carbonate ($CaCO_3$) while diatom shells are composed of silicon dioxide ($SiO_2$). These organisms record evidence for past environmental conditions in their shells. Remains of foram and diatom shells can be found by taking sediment cores from lakes and oceans, since their shells get buried and preserved in sediment as they die. The chemical make-up of these shells reflects water chemistry at the time of shell formation. Stable oxygen isotope ratios contained in the shell can be used to infer past water temperatures. These oxygen isotopes are found naturally in both the atmosphere and dissolved in water. Warmer water tends to evaporate off more of the lighter isotopes, so shells grown in warmer waters will be enriched in the heavier isotope. Measurements of stable isotopes of planktic and benthic foram and diatom shells have been taken from hundreds of deep-sea cores around the world to map past surface and bottom water temperatures.
>
> Researchers may also use foram and diatom population dynamics to infer past climate. Relative abundance as well as species composition in particular areas may indicate environmental conditions. Typically, warmer weather will cause organisms to proliferate. In addition, since each species has a particular set of ideal growing conditions, species composition at a particular site at a particular time may indicate past environmental conditions."

A steady rain of shells from small, surface-dwelling animals falls continually, eventually building up hundreds of meters of sediment. These sediments preserve the shells of these small animals for millions of years. The most important of these animals—foraminifera (or forams for short)—construct their tiny shells from a form of calcium carbonate ($CaCO_3$). Carbonate originally dissolved in the oceans contains oxygen whose atoms exist in two naturally occurring stable isotopes, $^{18}O$ and $^{16}O$. The ratio between these two isotopes is dependent on past temperatures. When carbonate solidifies to form a shell, $\delta^{18}O$ varies slightly, depending on the temperature of the surrounding water. Unfortunately, there are complications. While the value of $\delta^{18}O$ in forams changes from its mean value as the water temperature changes from its mean value, the mean value of $\delta^{18}O$ in the oceans varies widely with location. This variability arises because, when water evaporates, the lighter molecules of water (those with $^{16}O$ atoms as compared with those with $^{18}O$) tend to evaporate first. Therefore, water vapor is more depleted (fewer $H_2{}^{18}O$ molecules) than the ocean from which it evaporates. Thus, the ocean has more $^{18}O$ in places where water evaporates heavily like the sub-tropics and less $^{18}O$ where it rains a good deal like the mid-latitudes (Schmidt, 1999).

Similarly, when water vapor condenses (to produce rain, for instance), the heavier molecules ($H_2{}^{18}O$) tend to condense and precipitate first. So, as water vapor makes its way poleward from the tropics, it gradually becomes increasingly depleted in the heavier isotope. Consequently, snow falling at higher latitudes has much less $H_2{}^{18}O$ than rain falling in the tropics. Changes in climate that alter the global patterns of evaporation or precipitation can therefore cause changes to the background $\delta^{18}O$ ratio at any locality that can interfere with the inference of past temperature change from isotope ratios.

Palaeoclimate reconstruction from the study of forams has resulted from basically three types of analysis: (1) oxygen isotope composition of calcium carbonate, (2) relative abundance of warm- and cold-water species, and (3) morphological variations in particular species resulting from environmental factors. Most studies have focused on oxygen isotope composition.

If a marine organism's calcium carbonate is crystallized slowly in water, $^{18}O$ is slightly concentrated in the precipitate relative to that remaining in the water. This fractionation process is temperature dependent, with the concentrating effect diminishing as temperature increases. When the organism dies, the external shell of the organism sinks to the seabed and is laid down, with millions of others as sea floor sediment (calcareous ooze), thus preserving a temperature signal (in the form of an oxygen isotopic ratio) from the time when the organism lived. If a record of oxygen isotope ratios is built up from cores of ocean sediment, the cores can be dated. Standard techniques used to date oceanic sediment cores include paleomagnetic analysis and radioisotope studies, such as radiocarbon and uranium series dating methods.

Empirical studies relating the isotopic composition of calcium carbonate deposited by marine organisms to the temperature at the time of deposition have demonstrated the following relationship:

$$T = 16.9 - 4.2(\delta c - \delta w) + 0.13(\delta c - \delta w)^2$$

in which $T$ was the water temperature (°C) in which the sample precipitated, $\delta c$ is the departure from current standard seawater of $\delta^{18}O$ in the carbonate sample, and $\delta w$ is the departure from current standard seawater of the water in which the sample precipitated. While $\delta c$ can be measured accurately, it is difficult to estimate $\delta w$ because it pertains to millions of years ago. During glacial times, seawater was isotopically heavier (i.e., enriched in $^{18}O$) compared with today because large quantities of isotopically lighter water were landlocked in huge ice sheet formations. Thus, the expected increase in $\delta c$ due to colder sea surface temperatures during glacial times is complicated by the increase in $\delta w$.

By analyzing isotopic records of deep-water organisms, one can attempt to resolve how much of the increase in $\delta c$ for surface organisms was due to decreases in surface temperature and how much was due to continental ice sheet formation. It is expected that bottom-water temperatures ($\sim -1$°C to 2°C) have changed very little since glacial times (the Last Glacial Maximum being about 20,000 KYBP) and increases in $\delta c$ for deep-water organisms would reflect mainly changes in the isotopic composition of the glacial ocean.

In the past, as always, the abundance of any species of planktic (surface-dwelling) forams depended on the local sea surface temperature. Thus, planktic forams represent a proxy for past sea surface temperatures. One of the most remarkable proxies is the ratio of oxygen isotopes in benthic (bottom-dwelling) forams. This ratio in ancient sediments is believed to reflect the total amount of ice that existed on the Earth at the time the seabeds were formed. This ratio is therefore interpreted as a proxy for global ice. To the extent that temperature and global ice track each other, the measurements of $^{18}$O from planktic and benthic forams may be similar. But, one must be careful in examining data, since some records may reflect extreme local conditions. In general, the $^{18}$O signal in benthic forams primarily measures total ice volume best. In planktic forams there is a much larger contribution from water temperature. Unfortunately, changes in the isotopic composition of ocean reservoirs are not the only complications affecting simple temperature interpretation of $\delta c$ variations. The assumption that marine organisms precipitate calcium carbonate from seawater in equilibrium is sometimes invalid. However, by careful selection of species either with no vital effects or where the vital effects may be quantified, this problem can hopefully be minimized.

In a recent paper, Lisiecki *et al.* (2008) discussed the assumption that benthic $\delta^{18}$O represents the phase of ice volume change despite the fact that benthic $\delta^{18}$O is also affected by deep-water temperature change. They raised the question of how to extract an ice volume signal from benthic $\delta^{18}$O records using an accurate age model and discussed a number of attempts to do this. They concluded: "Generating a robust age model for benthic $\delta^{18}$O or ice volume without the assumptions of orbital tuning remains an important, unsolved problem." However, they showed a graph that compared radiometrically dated sea level estimates with an orbitally tuned benthic $\delta^{18}$O stack over the past 250,000 years and the correlation was quite good with minor discrepancies. This was put forth as a basis for assuming that benthic $\delta^{18}$O can be interpreted as representing ice volume.

In addition to stable isotope analyses, the reconstruction of paleoclimates can also be achieved by studying the relative abundances of species or species assemblages and their morphological variations.

As we pointed out in Sections 3.1 and 3.2.2, measured $^{18}$O/$^{16}$O ratios are compared with a standard $^{18}$O/$^{16}$O ratio in order to determine historical climate variations from ice cores. The resulting oxygen isotopic variations are expressed in delta notation, $\delta^{18}$O, where

$$\delta^{18}\mathrm{O} \equiv \left( \frac{\left(\dfrac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\text{Sample}}}{\left(\dfrac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\text{Reference}}} - 1 \right) \times 1{,}000$$

and its counterpart $\delta$(D) are indicators of past temperatures or ice accumulations.

For ocean sediments, one analyzes the oxygen isotope content of carbonate samples precipitated in the distant past by calcite-secreting organisms (foraminifera, corals, mollusks) and the oxygen isotope ratio in these carbonates reflects the ratio in the water that the organisms lived in. Note that the length of sediment cores is typically about 10 to 15 m, in contrast to the depth of up to 3,000 m in ice cores. The standard used in this case was not Standard Mean Ocean Water (or SMOW), but was so-called PDB, a crushed belemnite (*Belemnitella americana*) from the Peedee formation (Cretaceous) in South Carolina. The original PDB material has long since been exhausted, but other standards have been calibrated against PDB and are used as an intermediate reference standard through which a PDB value can be calculated. Models have been developed to relate paleotemperature to this isotope ratio (Wright, 1999).

M&M provided the following estimate of the depletion of $^{16}O$ during a major ice age.[1] There is evidence that the level of the oceans was more than 100 m lower during the last major ice age (~20,000 years ago) due to the agglomeration of ice in glaciers. The average depth of the oceans is 3,800 m. Thus, about $100/3{,}800 \sim 2.6\%$ of the original oceans became stored as ice during the height of the last ice age. Measurements indicate that the water vapor that evaporates from oceans is roughly $40‰ = 4\%$ enhanced in $^{16}O$. Therefore, the remaining ocean water (after removal of 2.6% via evaporation and deposition onto glaciers) is enriched in $^{18}O$ by about $4\% \times 2.6\% \sim 0.1\% = 1‰$. According to M&M, this agrees with typical depletion levels observed in sediments from glacial maximum periods.[2] To the extent to which this effect dominates, $^{18}O$ is a valid proxy for global ice volume. M&M further pointed out that, since the mixing time for seawater around the world is about a thousand years, the $^{18}O$ records in the northern Atlantic are similar to those in the equatorial Pacific. However, M&M also cautioned that isotopic separation could also reflect local temperatures and other climate conditions, even if global glaciation has not changed appreciably. Thus, the derivation of ice volume from isotope ratios may not be as straightforward as this simple discussion suggests:

> "Time series of the $\delta^{18}O$ of foraminiferal calcite tests provide an important record of climate change. Foraminiferal $\delta^{18}O$ is a function of the temperature and $\delta^{18}O$ of the water in which it forms, and the $\delta^{18}O$ of seawater is a function of global ice volume and water salinity. (The scaling between $\delta^{18}O$ and these two factors can vary with patterns of sea ice formation, evaporation, and precipitation.) Owing to the observed similarity of most marine $\delta^{18}O$ records and the global nature of the ice volume signal, $\delta^{18}O$ measurements also serve as the primary means for placing marine climate records on a common timescale. Stacks, which are averages of $\delta^{18}O$ records from multiple sites, improve the signal-to-noise ratio of the climate signal and make useful alignment targets

[1] J. D. Wright provided a similar estimate at *http://geology.rutgers.edu/~jdwright/JDWWeb/2000/Wright2000.pdf*

[2] However, note that Wilson *et al.* (2000) pointed out "the last glaciation was equivalent to removing a 165 m layer from the oceans, and the net drop in sea level around the world was only 115 m. This was because the water loading [during the LGM] caused the crust beneath the oceans to drop by ~50 m.

and references for comparison. Benthic $\delta^{18}O$ records should produce a better stack than planktic records because the deep ocean is more uniform in temperature and salinity than surface water. Less local and regional climatic variability improves the accuracy of alignment and produces a better estimate of average $\delta^{18}O$ change. While a stack alone cannot [resolve] the relative contributions of ice volume and temperature to the benthic $\delta^{18}O$ signal, a good stack does provide an accurate estimate of how much total change must be explained" (Lisiecki and Raymo, 2005).

As Clark *et al.* (2006) pointed out,

> "For any given species of benthic foraminifera, variations in $\delta^{18}O$ ... reflect some combination of local to regional changes in water mass properties (largely deep-water temperature) and global changes in seawater resulting from the growth and decay of land ice. Determining how much each of these components contributes to any given $\delta^{18}O$ benthic record, however, remains ambiguous."

While it has generally been assumed that variations in $\delta^{18}O$ mainly record changes in ice volume, as Clark *et al.* (2006) emphasized: "Nevertheless, the relative contributions of temperature and ice volume to this stacked record still remain unconstrained, requiring other strategies to isolate the global ice volume signal." They estimated that there was a "60/40 ice volume/deep-water temperature contribution to the global $\delta^{18}O$ signal over the last several glacial cycles, with a globally integrated deep-water cooling of 2.5°C during glaciations."

## 5.2 CHRONOLOGY

The conversion of depth in sediments to age is a vital element of data processing. One problem is that most age models are based on aligning with the astronomical theory and, if that is done, it reduces the value of the data as a test for the astronomical theory. As it turns out, most of the age models in the literature are compounded from bits and pieces of basic information, loosely sewn together, with orbital tuning often used as the thread to hold the whole thing together. Interpolation between assigned time points is necessary. Tracing each element of basic information back to its origins is often difficult.

Assigning an age to each position along the sediment core depends on correlating the stratigraphy to a reference sequence that has been dated by independent methods. Initially, objective dating was limited to radiocarbon dates on sediments younger than about 30,000 years. A notable marker point in the records was the high temperature of the last interglacial which occurred about 135,000 YBP, as suggested now by other evidence. An additional time marker point was added by measuring the position of a polarity change (due to reversal of the Earth's geomagnetic field) in deep-sea cores and assigning an age of 780,000 years to this point based on radiometric (K/Ar) age estimation of the polarity change in lava flows. Earlier reversals have also been used.

According to Wright (1999):

> "Another major advancement in refining the oxygen isotope-based stratigraphy came with the observation that the climate/$\delta^{18}O$ calcite changes matched orbital insolation patterns. Hays *et al.* (1976) compared climate records from the Southern Ocean with the insolation curves and demonstrated that the climate changes were paced by insolation changes and, therefore, that they could be used to explain the cyclic nature of climate change during the past 2 million years. One implication of the "Pacemaker" discovery is that the calculation of past insolation cycle variations could be used as the basis for a numerical time-scale. Imbrie *et al.* (1984) developed what is now called the SPECMAP $\delta^{18}O$ record by averaging $\delta^{18}O$ calcite records from various localities to reduce noise. The resulting $\delta^{18}O$ curve was assigned ages by tuning (i.e. adjusting the $\delta^{18}O$ patterns to match the predicted patterns based on the current astronomic calculations for orbital variations)."

However, the degree of correlation between solar insolation and features in the SPECMAP $\delta^{18}O$ record lies somewhat in the eye of the beholder. A simplistic approach is to align the isotope record to the insolation curve, but with a time lag for the isotope record. Other methods depend on simple models for ice buildup as described in Section 9.6.

Yet, of equal importance is the fact that once a solar insolation model is used to assign a chronology to the sediment core, the resultant dated SPECMAP $\delta^{18}O$ record loses some of its value in testing the astronomical theory because of circular reasoning. Whether orbital tuning was a major advancement remains arguable.

Because benthic and planktic data records tend to be noisy, the common practice is to create a stack, which is an average of data taken at many sites. Such stacks would presumably average out local noise and leave a smoothly varying residual signal representing global climate change. For example, the stack presented by Lisiecki and Raymo (2005) contained benthic $\delta^{18}O$ records from 57 globally distributed sites covering the past 5.3 million years. These sites were well distributed in latitude (60°N to 50°S), longitude (but predominantly in the North and South Atlantic Oceans), and depth in the Atlantic and Pacific, as well as two sites in the Indian Ocean. The problem in aligning the data is that it is difficult to estimate the sedimentation rate at each site and independently arrive at a chronology for the data. One has a curve of variable $\delta^{18}O$ vs. depth in the sediments at each site, but it is difficult to convert depth to age. Therefore, following the usual practice, L&R assumed that the paleoclimate signals contained in all 57 of the records provided the same basic underlying isotope data, but with differing variable sedimentation rates. If this assumption is correct, the features (peaks, valleys, abrupt changes in slope) of all the records should correspond to the same occurrences in the paleoclimate. Therefore, their first step in producing the stack was to align and adjust all of the records by matching corresponding features, particularly peaks. They set up an automated correlation algorithm to do this, but some judgment was needed to determine which features correspond to one another and to distinguish noise from isotopic features. The result is a curve with $\delta^{18}O$ on the vertical axis and an arbitrary scale on the horizontal axis, averaged over the 57 sites for which data were included. Conversion of the scale of the horizontal axis to a time scale is a critical step in data processing.

While ocean sediments provide data on $\delta^{18}O$ vs. depth, the conversion of depth to age is difficult for ages $>\sim$50,000 years. John Imbrie is perhaps the world's leading expert on the analysis of ocean sediments. He said:

> "Variations in the oxygen isotope content ($\delta^{18}O$) of late Quaternary deep-sea sediments mainly reflect changes in continental ice mass, and hence provide important information about the timing of past Ice Ages. Because these sediments cannot yet be dated directly beyond the range of radiocarbon dating (40,000–50,000 years), ages for the $\delta^{18}O$ record have been generated by matching the phase of the changes in $\delta^{18}O$ to that of variations in the Earth's precession and obliquity. Adopting this timescale yields a close correspondence between the time-varying amplitudes of these orbital variations and those of a wide range of climate proxies, lending support to the Milankovitch theory that the Earth's glacial–interglacial cycles are driven by orbital variations" (Imbrie *et al.*, 1993).

The process of dating sediment cores by comparing with predictions of the astronomical theory is usually referred to as "orbital tuning".

Tuning was proposed initially by Hays *et al.* (1976). Their tuning procedure adjusted the time scale by small amounts, within the range of error of radiometrically determined dates. M&M referred to such a procedure as "minimal tuning". However, M&M pointed out:

> " . . . since that seminal paper, tuning has . . . become ever more complex and diverse. It has been expanded to become the primary mechanism for determining a timescale, using a large number of adjustable parameters."

The major interest in deriving a time scale for ocean sediments and ice cores is to test theories that purport to explain the occurrence of and transitions between glacial and interglacial periods, particularly the astronomical theory. Therefore, the use of tuning would seem to be a form of circular reasoning that assumes the answer, uses it to adjust the data, and then claims agreement between theory and experiment. M&M seemed to indicate that they believed that minimal tuning is a reasonable process, but questioned the more elaborate forms of tuning. The unfortunate thing is that it takes a good deal of effort to ferret out how many time scales reported in numerous papers are primary and independent and how deeply tuning has penetrated into the adjustment of time scales.

In order to convert the depth scale to a time scale, a collage of different techniques is typically applied, some of which involve utilization of previous dating studies. This makes the task of tracing dating procedures back to origins more difficult. One example is the study by Lisiecki and Raymo (2005) who relied on previous chronologies over the past 135 KYBP by graphically comparing features with previously dated sediment studies:

- The top 22 KYBP of the stack were dated by correlating key features to a previous $^{14}C$-dated benthic $\delta^{18}O$ record and assuming that all ocean sediment sites display the same features at the same times.
- From 22–120 KYBP, the stack was aligned with a high-resolution benthic $\delta^{18}O$ record of a site that was dated by correlating millennial-scale features in the planktic $\delta^{18}O$ curve to the features in the ice $\delta^{18}O$ from the GRIP ice core that were dated by layer counting. Here, the assumptions are (1) that the Greenland ice core chronology is the same as the ocean benthic chronology and (2) that chronologies are the same at all benthic sites.
- The age of the termination of the previous ice age (the one preceding the last ice age) was taken from U–Th dating of coral terraces. This is now accepted to be $\sim$135 KYBP.

Lisiecki and Raymo (2005) derived chronologies for earlier times with an orbital-tuning model based on previous work by Imbrie *et al.* (1984), in which the rate of change of ice volume in ice sheets (as inferred from the derivative of the isotope record) was expressed in terms of a forcing function: the insolation curve calculated for 65°N, with two parameters that were age-adjusted to allow a long-term increase in ice volume over the past few million years. This procedure is discussed in some detail in Sections 9.6.1 and 9.6.2. However, Lisiecki and Raymo (2005) adjusted the two constants ($B$ and $T$) in the Imbrie model to increase with time toward the present because the data suggest a long-term increase in global ice over the past few million years. Whereas Imbrie *et al.* found a best fit with $B = 0.6$ and $T = 17{,}000$ years for the time period over the past 150,000 years, Lisiecki and Raymo (2005) used $B = 0.3$ and $T = 5{,}000$ years for the time period from 5.3 to 3.0 MYBP, a linear increase to $B = 0.6$ and $T = 15{,}000$ years from 3.0 to 1.5 MYBP, and constant values of $B = 0.6$ and $T = 15{,}000$ years from 1.5 MYBP to the present. This had the effect of compressing the time scale at early times and stretching it out during more recent times. Then, by overlaying the $\delta^{18}O$ curve on the ice model curve, they established a time scale for the $\delta^{18}O$ curve. This, of course, required an elastic horizontal axis for the $\delta^{18}O$ curve so that the features of each glaciation–deglaciation transition could be matched to the features in the ice model curve. One portion of their fitting procedure is illustrated in Figure 5.1.

The agreement between the model and the data is notable. But the significance of this result is not obvious. On the one hand, the fact that a model as simplistic as the Imbrie model (Sections 9.6.1 and 9.6.2) could lead to this degree of correlation is impressive. On the other hand, the parameters of the Imbrie model were adjusted to get a best fit. Furthermore, the absolute time scale is tied to the astronomical theory via the Imbrie ice model with arbitrarily chosen parameters. This approach seems to lie somewhere between mathematical curve fitting and a

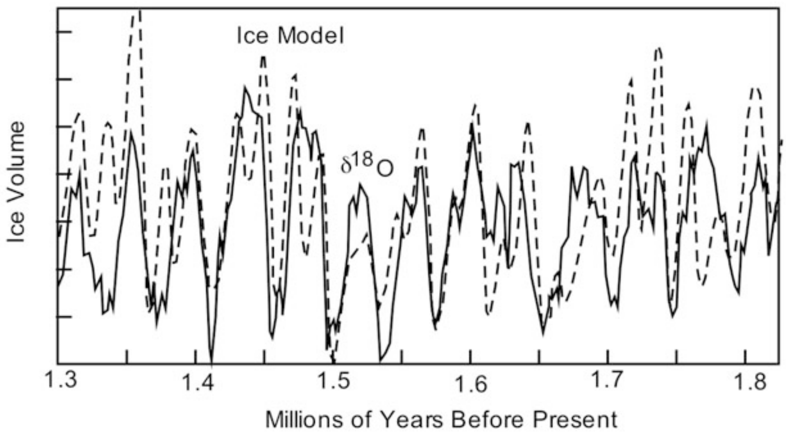



**Figure 5.1.** Fit of a portion of the $\delta^{18}O$ curve to the ice model of Lisiecki and Raymo (2005).

physical model, but it is not immediately obvious where it lies between these extremes.

Of course, it would be extremely desirable to develop a chronology that does not depend on orbital tuning. As Huybers and Wunsch (2004) (H&W) said:

> "Inference concerning past climate change relies heavily upon the assignment of ages to measurements and events recorded in marine and ice cores as well as to a variety of isolated markers in the geological record. Sedimentation and snow accumulation are analogous to strip-chart recorders, marking the past climate state in a large variety of physical variables. These records tend to be noisy and blurred by bioturbation [the displacement and mixing of sediment particles] and a variety of diffusive-like processes. The major difficulty however, is that these strip-chart recorders run at irregular rates, stop completely, or even rewind and erase previous sections. If depth is taken as a simple proxy for time, irregularities in sedimentation stretch and squeeze the apparent timescale, and so distort the signals being sought. To the degree that the changes in rates are proportional to the signals themselves, one has a challenging signal demodulation problem. It is not an exaggeration to say that understanding and removing these age–depth (or age model) errors is one of the most important of all problems facing the paleoclimate community. Timing accuracy is crucial to understanding the nature of climate variability and the underlying cause and effect."

H&W attempted to understand the nature of some of these age model errors, and then apply that insight to construct a time scale for marine sediment cores spanning the last 780,000 years. They pointed out: "To avoid circular reasoning, an age model devoid of orbital assumptions is needed." A number of previous studies utilized mean sediment accumulation rates for multiple stratigraphies,

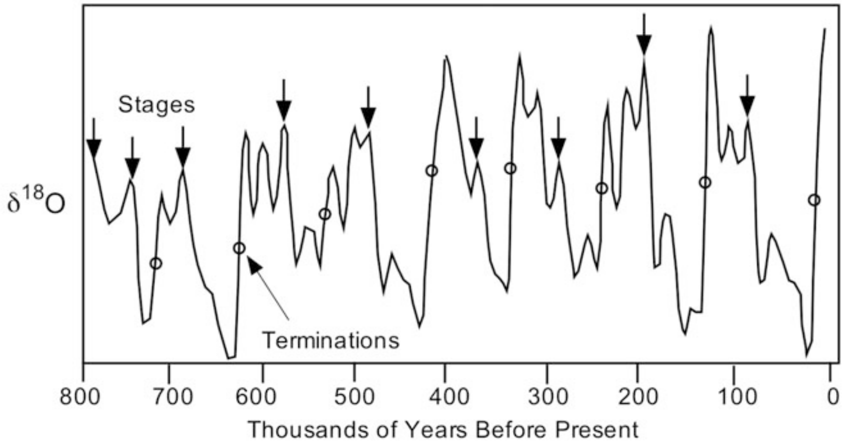



**Figure 5.2.** Assignment of stages and terminations by H&W. Stages are designated by arrows and terminations are defined by circles.

which they termed "depth-derived ages". However, it was claimed that none of these were entirely satisfactory. H&W extended the depth-derived approach to 21 sediment cores and added an allowance for down-core sediment compaction. In their model, they defined an "event" as a feature that can be uniquely identified in the $\delta^{18}O$ vs. depth curve for each site. If an age is fixed to an event, it becomes an *age control point* (ACP). Two types of events were utilized, *stages* and *terminations*. Stages were defined as local minima or maxima in the $\delta^{18}O$ vs. depth curve using the numbering system originally suggested by Imbrie *et al.* (1984).

All the stages utilized in their study corresponded to peaks in the $\delta^{18}O$ vs. depth curve. Terminations were defined as an abrupt shift from glacial to interglacial conditions where the assigned depth was the midpoint between the local $\delta^{18}O$ minimum and maximum. Figure 5.2 shows the eight termination midpoints and nine stages that were visually identified in each $\delta^{18}O$ record. H&W developed a model for the sediment accumulation rate that included three terms: (1) a mean sedimentation rate, (2) stochastic variability about the mean sedimentation rate, and (3) a systematic term due to sediment compaction with age. However, the procedure by which they obtained best values for the stochastic and systematic terms was complex and difficult to follow.

## 5.3 UNIVERSALITY OF OCEAN SEDIMENT DATA

M&M emphasized that the pattern of variation of oxygen isotope content with time over 800,000 years is remarkably similar in sea floor records from around the world. In Figure 5.3 we show 10 measured $^{18}O$ records from forams taken from regions that include the Pacific, Atlantic, and Indian Oceans. Since the ages of the samples are not known, M&M assumed that the sedimentation rate for each

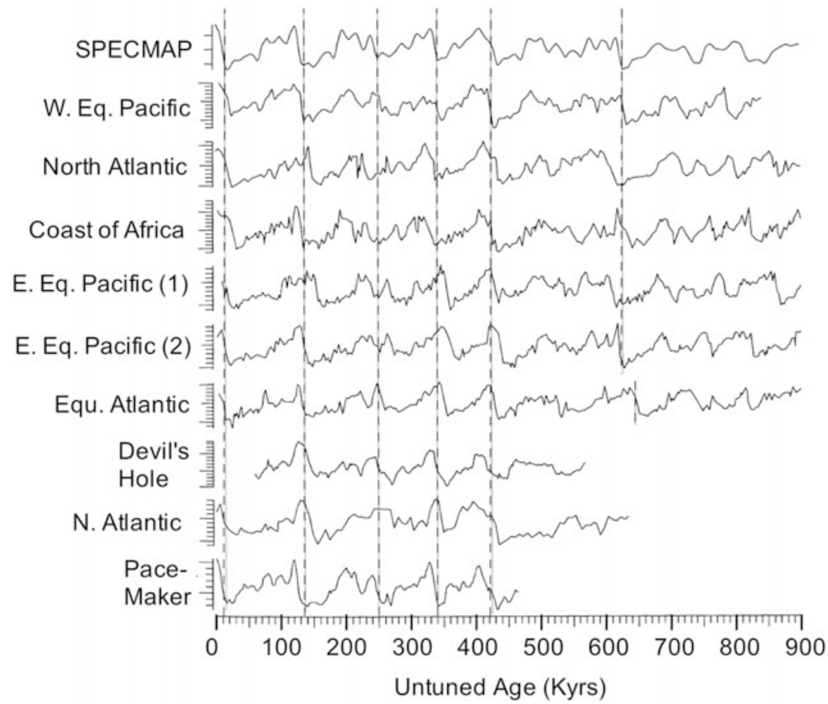



**Figure 5.3.** Universality of oxygen isotope patterns from forams from around the world (adapted from M&M with permission of Praxis Publishing).

location was constant and that time scales were chosen for each such that the ice age terminations (vertical dashed lines) occurred at roughly the same times. The fact that the terminations do not line up precisely with each other suggests that sedimentation was not perfectly constant for each record. M&M felt it remarkable that the pattern of oxygen isotope variations appears to be so similar around the world. It is noteworthy that the terminations of ice ages often appear to be abrupt.

## 5.4 SUMMARY OF OCEAN SEDIMENT ICE VOLUME DATA

An influential early attempt to extract the underlying $^{18}O$ signal from multiple records was the SPECMAP Stack (Imbrie *et al*. 1984; M&M). The "stack" was a combination of five $^{18}O$ records from five cores from the Indian, Atlantic, and Pacific Oceans. M&M pointed out: "although the time scale for this stack is now known to contain serious errors in the period older than 600 KYBP it is still a widely-used template for more recent times." Each interglacial period is allocated an odd number, beginning with the present as Stage 1 and counting backwards.

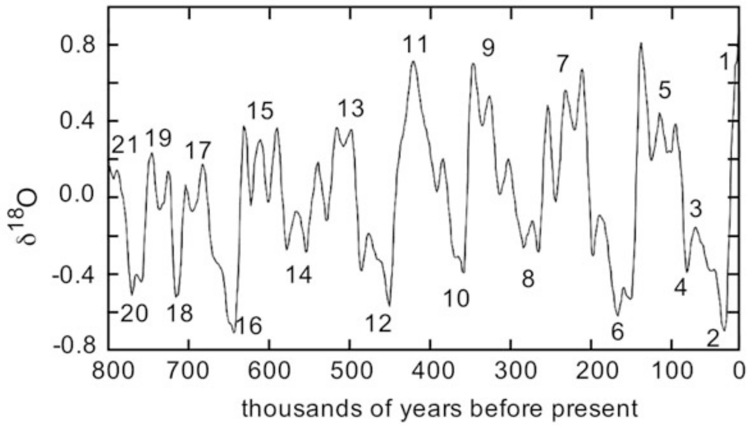



**Figure 5.4.** SPECMAP showing marine isotope stage numbers (adapted from M&M by permission of Praxis Publishing).

Glacial periods are represented by even numbers. The only exception is a small warming that was assigned as Stage 3 (see Figure 5.4).

M&M claim that there is strong evidence that the sedimentation rate was constant at Site 806 and no tuning was needed to establish the chronology. They presented the data shown in Figure 5.5. Huybers and Wunsch (2004) developed an ocean sediment time series that included 21 sediment cores and that was corrected for sediment compaction to avoid tuning in establishing the chronology. Site 806 was one of the 21 sites used. Roe (2006) used this time series to compare with the astronomical theory (see Section 10.2.3).

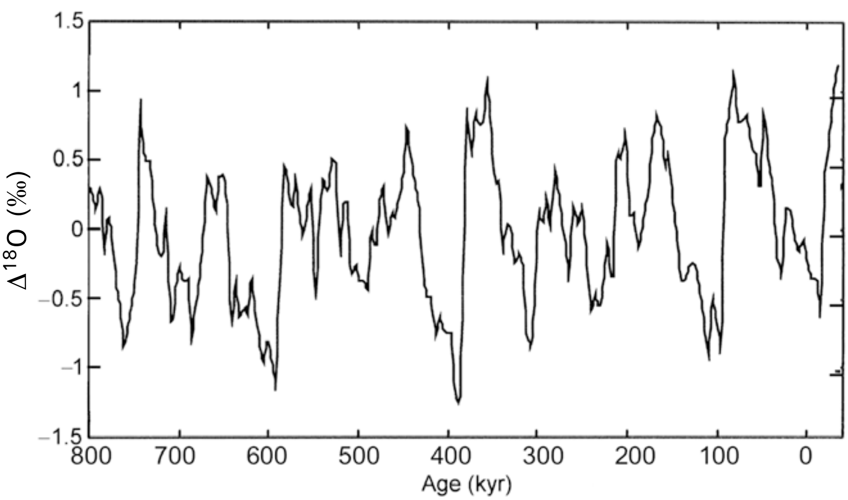



**Figure 5.5.** $\delta^{18}O$ for Site 806 (adapted from M&M, p. 257, with permission of Praxis Publishing).

Bintanja *et al.* (2005) provided an analysis of marine sediment data. The $\delta^{18}O$ data from deep benthic sediments that vary from glacial to interglacial conditions are mainly affected by two mechanisms (aside from local hydrographical influences):

(1) Changes in the oxygen isotope composition of oceans because the ice sheet contains an excess of $^{18}O$, leaving the oceans depleted in $^{18}O$ in proportion to the ice sheet volume (ice sheet part).
(2) Changes in the uptake of $^{18}O$ by benthic foraminifera that depend on local deep-water temperature at the time of crystallization of their shells (deep-water part).

Previous attempts to resolve these two effects involved the use of independent temperature and sea level records. Evidence and models suggest that the glacial deep ocean was 2–3°C colder than today. Bintanja *et al.* (2005) developed an alternative model for estimating the contributions of each of the two major effects. They argued that, on glacial–interglacial time scales, the main contributors to the mean benthic oxygen isotope record—Northern Hemisphere ice sheet isotope content and the local deep-sea temperature—are both strongly related to Northern Hemisphere mid-latitude to sub-polar surface air temperatures. This constrains the magnitude of surface air temperatures, which enabled them to separate the ice sheet and deep-water parts. Based only on $\delta^{18}O$ data, they provided reconstructions of actual climate variables such as surface air temperature, global sea level, ice volume, and ice isotope content. They utilized data from Lisiecki and Raymo (2005), which we plotted previously in Figure 5.6. They found that the ice sheet part was typically about 60% of the total during the past million years or so, although this dropped sharply (but briefly) during interglacial periods (see Figure 5.7).

## 5.5 OCEAN SEDIMENT DATA AND POLAR ICE CORE DATA COMPARED

In previous sections, we presented isotope data from Greenland ice cores, Antarctic ice cores, and ocean sediments. Greenland ice cores date back to about 140 KYBP. Antarctic ice cores date back to 400 to 800 KYBP, and ocean sediment data date back beyond 2.7 MYBP.

Ocean sediment data based on benthic forams are time series of $\delta^{18}O$ that are believed to primarily represent changes in deep-ocean oxygen isotope content; hence, they are assumed to measure total ice volume on the Earth.

The raw data from Greenland and Antarctica are predominantly time series of $\delta^{18}O$ and $\delta D$, respectively. Various investigators have interpreted these data as representing regional temperatures. Therefore, in comparing ice core data with ocean sediment data, we are comparing quantities that are not equivalent. According to the Imbrie model (Section 9.6.2) there are time lags between variations in solar intensity and ice sheet formation (42,500 years) or destruction (10,600 years).

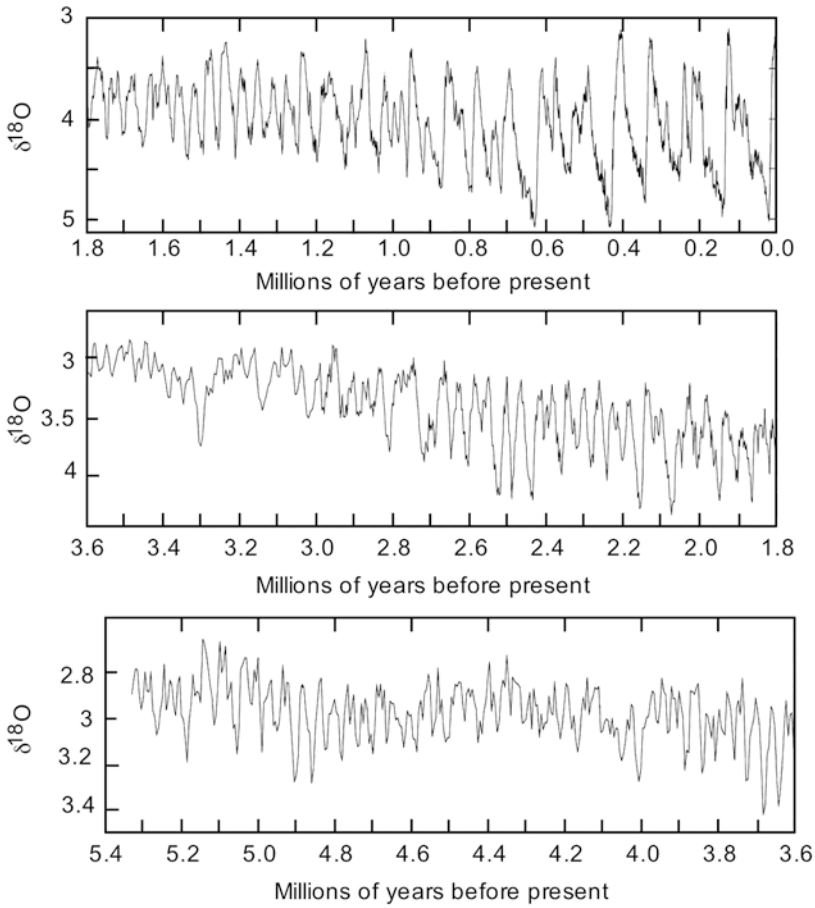
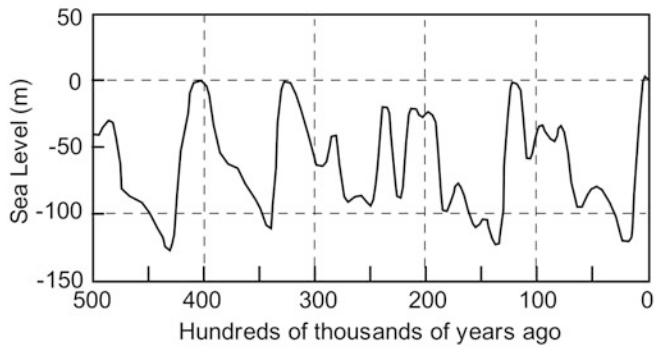



**Figure 5.6.** Isotope data from a stack of 57 records as derived by Lisiecki and Raymo (2005).

Furthermore, ice volume is an integral over relatively rapid variations in solar intensity that lead to slower variations in ice volume. Therefore, one might expect *a priori* that ocean sediment data would show less variation than ice core data and significant time lags, particularly during the buildup of ice sheets. Figure 5.8 shows a comparison of ocean sediment data with Antarctic ice core data. Ocean sediment data are indeed smoother and show less high-frequency variation; however, some of this is due to averaging a stack of data from different localities. But there is no evidence at all of significant time lags between these datasets. This is a conundrum. If ice core data represent temperature and sediment data represent ice volume, why are the two curves in Figure 5.8 so similar? It would seem that one of the following possibilities must be true: (i) ocean sediment data respond more to temperature than has been realized, (ii) ice core data respond more to ice volume than has been realized, and (iii) the chronologies used in both cases have



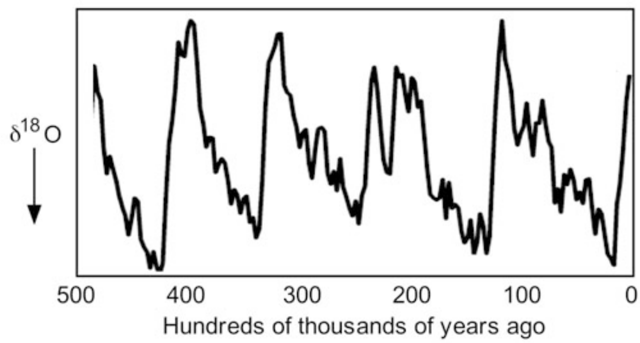




**Figure 5.7.** Comparison of variation of $\delta^{18}O$ data from Lisiecki and Raymo (2005) (lower graph) with estimated sea level (inverse of ice volume) from Bintanja *et al.* (2005) over the past 500,000 years (upper graph).

been tuned to the point where they all agree with one another. Possibility (iii) seems more likely to this writer.

Parrenin *et al.* (2007b) compared their Antarctic ice core data with ocean sediment data. In their Figure 3, the two curves of isotope ratio vs. time for 800,000 years were compared. They said:

> "[The benthic record] contains a sea level part and a temperature part and as a consequence is older than [the Antarctic record] by several thousands of years. For an easier comparison, we thus shifted it by 3,000 years towards older ages. This 3,000-year phase is the observed phase of both records during the last deglaciation."

This claim of a mere 3,000-year time lag between temperature and ice volume does not fit well with the models in Section 9.6 that suggest much longer time lags. However, Lisiecki and Raymo (2005) seemed comfortable with benthic and Antarctic time series overlaying one another. Lang and Wolff (2011) "compiled 37 ice, marine and terrestrial palaeoclimate records covering the last 800,000 years in order to assess the pattern of glacial and interglacial strength, and termination

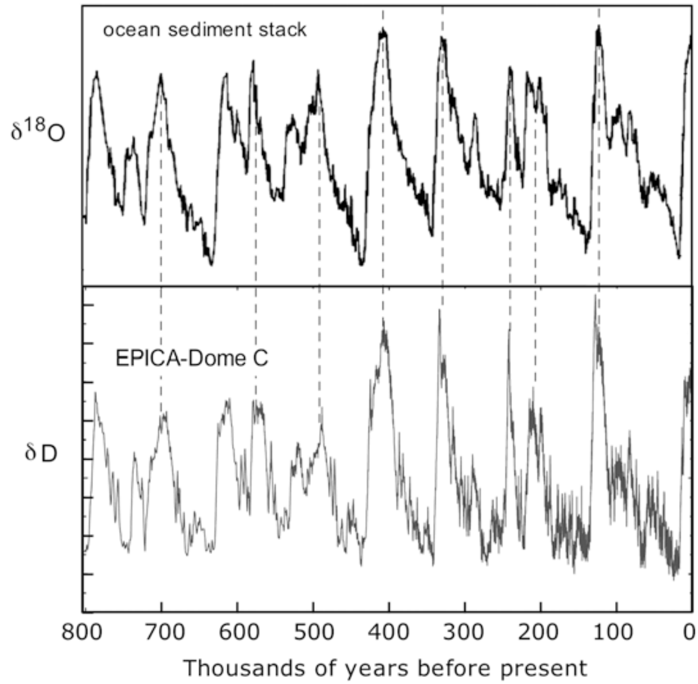



**Figure 5.8.** Comparison of ocean sediment data (Lisiecki and Raymo, 2005) with Antarctica EPICA Dome C data. Vertical scales represent the D isotope ratio at Antarctica and the O isotope ratio in ocean sediments.

amplitude. Records were selected based on their length, completeness and resolution, and their age models were updated, where required ...." It was concluded that "the main result of this work is the compiled datasets and maps of interglacial strength which provide a target for modeling studies and for conceptual understanding."

## 5.6 HISTORICAL SEA SURFACE TEMPERATURES

As we pointed out in Section 5.1, the oxygen isotope content of planktic forminafera are sensitive to ocean temperatures and, since they dwell near the surface, their remains may provide a proxy for sea surface temperature. Kipp (1976) determined the current abundances of shells of various species in top-sediment core samples from throughout the Atlantic Ocean. Their maps showed that the contours of abundance closely paralleled those of surface water temperature. Kipp (1976) developed a mathematical relationship that related water temperature to the abundance of various species. A group of marine geologists and geochemists in a program named CLIMAP determined the relative abundances of planktic foraminifera from many sediment cores at various locations at the time of the Last Glacial Maximum (LGM). When temperatures were calculated using the Imbrie and Kipp correlations, it was found (to the surprise of many) that tropical ocean temperatures during the LGM were only about 1.5°C cooler than those during interglacial times.

As Broecker (2002) pointed out, the full range of ocean temperatures should be considered. The coldest temperatures in polar regions are constrained by the freezing point of seawater. Once the temperature drops to −1.8°C, sea ice will form. That did not change during the LGM. Presuming that the CLIMAP findings are correct, it would seem that tropical ocean temperatures also did not change during the LGM. But this does not necessarily mean that mid-latitude sea surface temperatures did not change during the LGM. In fact, the results indicated that sea surface temperatures were 2–4°C colder at the LGM for latitudes greater than about 45° in both the NH and the SH. Broecker concluded: "taken together with the temperature change at high elevation, this seems to be telling us that the Earth's cold sphere moved in on the Earth's warm sphere both from above and from the poles."

However, the reported small decrease in tropical sea surface temperatures during the LGM has been challenged. One study found that the isotope make-up of planktic species is also dependent on the pH of the ocean, which increases during glacial times. This would suggest that the actual decrease in the temperature of tropical seawater was more like 3°C than 1.5°C. Other methods for paleothermometry have been proposed that also lead to lower tropical sea surface temperatures, some of them suggesting that they were 2°C to 5°C colder than today.

## 5.7 ICE-RAFTED DEBRIS

Bischof (2000) wrote a book on ice-rafted debris as a source of data on past climates, ocean currents, and prevailing winds. Ice rafting is the drift of floating ice in the ocean from one place to another:

> "Wherever ice forms in contact with the land, whether as icebergs calving from a glacier that overrode and incorporated bedrock fragments into the ice, or as sea ice that forms when seawater freezes in contact with unconsolidated sediments in coastal environments, terrigenous debris from the ice's place of origin becomes embedded in the ice."

As floating ice moves with ocean currents and is propelled by winds, the incorporated particles drop to the sea floor when the ice melts or when icebergs break up or turn over. Eventually, all the incorporated debris gets deposited on the ocean floor during the lifetime of the floating ice:

> "Over the course of decades, centuries and thousands of years, a continuous archive of iceberg and sea ice drift has formed in the deep-sea sediments. The

> petrographic composition of the ice rafted debris (IRD) in these sediments reveals the place of the ice's origin and allows a reconstruction of the surface currents of the past. Since the motion of icebergs and sea ice is controlled by the atmospheric and oceanic circulation, the dispersal paths of IRD from known sources permit the reconstruction of the past ocean surface currents and winds."

Bischof (2000) shows some impressive graphs of lithologic diversity, grams of lithic grain per gram of sediment, and the size of the largest dropstone in ice rafted debris over a time period that spans the Last Glacial Maximum and the Holocene. In each case there is a dramatic drop in these variables over a relatively short time at the end of the last ice age.

Ice-rafted debris provides additional information that complements ocean sediment data based on biologically induced isotope variations. While ice-rafted debris tends to be limited to the most recent ice age and its aftermath, it provides information on ocean currents and winds that could not be inferred from conventional sediment data or ice cores. One of the interesting findings from ice-rafted debris is that surface currents in the Norwegian Sea generally switched from northwards during interglacials to southwards during glacials. Evidently, this propelled polar climates southward during glacial periods. What is not clear is whether this was a cause or an effect of glaciation.

Bond *et al.* (2001) utilized ice-rafted debris to study patterns of climate variation during the Holocene and reported a 1,500-year cycle that some think persisted in a weak form down to the recent past (MWP and LIA).

# 6

# Other data sources

## 6.1 DEVIL'S HOLE

### 6.1.1 Devil's Hole data

Devil's Hole is an open fault zone adjacent to a major groundwater discharge area in south-central Nevada; it is located approximately 115 km westnorthwest of Las Vegas, Nevada. This open fissure is lined with a thick (>0.3 m) layer of dense calcite that has precipitated continuously from calcite-supersaturated groundwater. These deposits exist down to depths in excess of 130 m below the water table (which is ~15 m below land surface) and are believed to correspond to a time span of more than the past 500,000 years (Winograd *et al.*, 1992).

Winograd *et al.* (1992) claimed that the $\delta^{18}O$ variations in calcite from the cave most likely reflect isotopic variations in atmospheric precipitation falling on groundwater recharge tributary areas to Devil's Hole. Isotopic variations in atmospheric precipitation are believed to reflect changes in average winter–spring land surface temperature, the season during which recharge is most likely to have occurred. Higher $\delta^{18}O$ values reflect warmer temperatures, and lower values reflect a colder climate.

Winograd *et al.* (1992) reported on results from a 36 cm long core of vein calcite that was recovered from about 30 m below the water table. This core contained pure calcite, and there were no apparent interruptions to the deposition process. They analyzed samples for $^{18}O$ and $^{13}C$ at 285 points along the core. The sampling interval (1.26 mm) represented an average time interval of about 1,800 years. Absolute ages were established at 21 places along the core by measuring the ratios of the radioactive isotopes of uranium and thorium. ($^{238}U$ decays to form $^{230}Th$, which decays with a half-life of 77,000 yr; the ratio gives a measure of the age.) Ages between these points were estimated by interpolation. Dating was accomplished radiometrically with high precision using thermal-ionization mass-

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books, 191
DOI 10.1007/978-3-642-30029-5_6, 

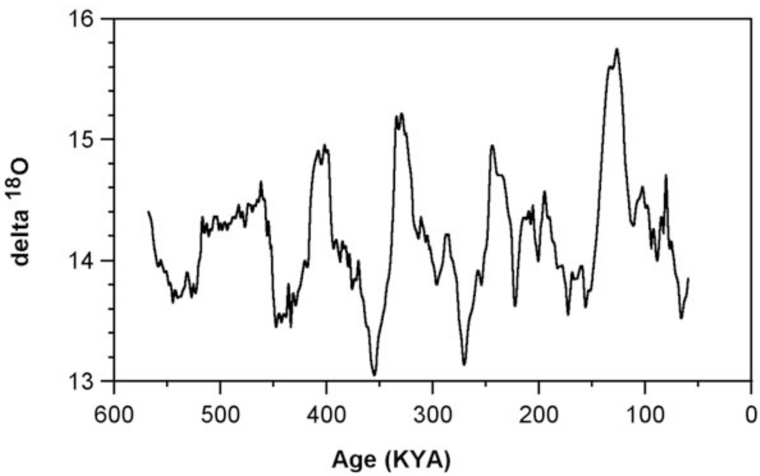



**Figure 6.1.** Measured oxygen isotope variability at Devil's Hole (Landwehr *et al.*, 1997).

spectrometric (TIMS) uranium series methods (Ludwig *et al.*, 1992). The dating has been independently verified using $^{231}$Pa analyses. These data are unique amongst all proxy data for past temperatures in that independent radiometric age determination was available throughout the entire length of the core. The results are shown in Figure 6.1.

Winograd *et al.* (1992) compared the Devil's Hole results with the Vostok, Antarctica ice core deuterium record and the SPECMAP deduced from $\delta^{18}$O values of planktic foraminifera. All three records show similar overall patterns with relatively rapid shifts from full glacial to interglacial climates followed by a gradual return to full glacial conditions. However, Winograd *et al.* (2002) emphasized minor differences between the records that appear to this writer to be in the noise. The fact that the records from widely divergent sites are similar suggests that the Devil's Hole data represent global rather than regional trends. However, questions have been raised about the conversion of the isotope data to temperature (Coplen, 2007).

### 6.1.2 Devil's Hole data and ocean sediment data compared

When Winograd *et al.* published the first major Devil's Hole paper in 1992, they pointed out that there appeared to be several discrepancies between the timing of glacial–interglacial transitions and the predictions of the astronomical theory, suggesting that the astronomical theory had deficiencies. Imbrie *et al.* (1993) (noted defenders of the astronomical theory) immediately responded with a rebuttal. They argued that if the Devil's Hole chronology were applied to ocean cores, it would "require physically implausible changes in sedimentation rate." They also argued that "spectral analysis of the Devil's Hole record shows clear evidence of orbital influence" and they concluded that "transfer of the

Devil's Hole chronology to the marine record is inappropriate, and that the evidence in favor of Milankovitch theory remains strong.'' Imbrie *et al.* (1993) noted that:

> ''The general resemblance of the Devil's Hole $\delta^{18}O$ record to that of the ocean [sediments] is striking. Indeed, the coherency is so high that it is tempting to overlook how different the physics underlying each record must be and jump to the conclusion that they are in fact synchronous. The SPECMAP marine $\delta^{18}O$ stack is an average of many open-ocean records in which values become heavier during glacial intervals, mainly because of storage of fresh water as ice. In contrast, the $\delta^{18}O$ data [from Devil's Hole] reflect the isotopic distillation of atmospheric moisture, a process linked to local precipitation temperature. Values in this record therefore become lighter during glacial intervals. But to interpret these data properly as an air temperature signal, one must make assumptions not only about the isotopic composition of the oceanic moisture source (which changes over a glacial cycle), but also about air-parcel trajectories at the relevant seasons.''

Imbrie *et al.* (1993) suggested that Winograd *et al.* (1992) did not adequately discuss these complex issues. Imbrie *et al.* (1993) compared the chronology from Devil's Hole with the chronology they had derived from the SPECMAP based on ocean sediment data by associating similar features in the two datasets. While the overall patterns were similar, it was found that the Devil's Hole ages for two SPECMAP glacial intervals, Stages 6 and 10, were significantly older (see Figure 6.2).

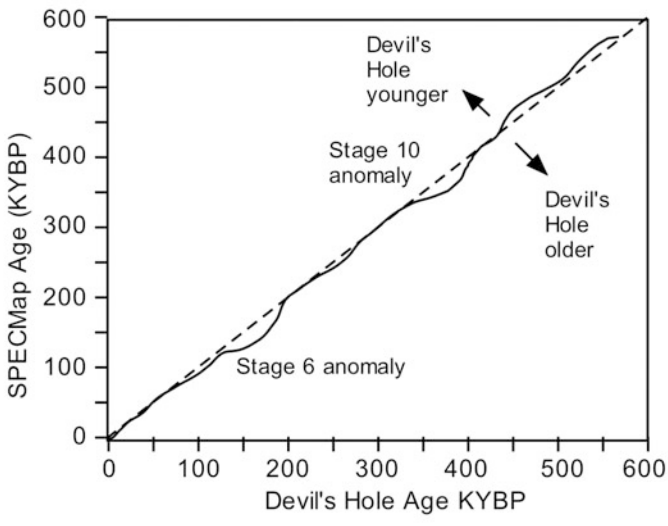



**Figure 6.2.** Comparison of ages from Devil's Hole with ages from SPECMAP.

They considered three possible explanations for these differences: (1) that the $\delta^{18}O$ events recorded in these groundwater and oceanic records are synchronous, and the Devil's Hole chronology is wrong; (2) that the events are synchronous, and the SPECMAP chronology is wrong; or (3) that the events are not synchronous, and both chronologies are right. They did not seem to consider the possibility that the data in both cases are too inherently noisy to make such comparisons meaningful. The arguments that follow are complex, but Imbrie *et al.* (1993) favored explanation (3). They also concluded that the Devil's Hole data are not necessarily in conflict with the astronomical theory based on spectral analysis.

Winograd and Landwehr (1993) (W&L) responded to the published comment in *Nature* (Imbrie *et al.*, 1993). It is noteworthy that *Nature* chose not to publish the W&L response on the specious grounds "that it would be of interest only to specialists working in this field." This makes no sense because (a) *Nature* is full of articles that are so narrow, so abstruse, and so specialized as to be incomprehensible to the majority of scientists, (b) the validity of the astronomical theory of ice ages is of widespread interest, and (c) *Nature* had already published one critique and in fairness should have allowed a rebuttal. But we know from the so-called "hockey stick" controversy regarding the variability of the Earth's climate over the past 2,000 years (see Section 11.1.2 or Rapp, 2008) that some scientists are in a position to exert influence on what gets published in journals (and what is rejected). In the end, W&L issued a *USGS Report* instead of a response in *Nature*.

In defense of their chronology, W&L quoted no less an authority than the renowned Wally Broecker who stated that "... the new Devil's Hole chronology is more firm than any other available isotopic age in this range. Nowhere else has a high degree of concordance between $^{234}U$–$^{238}U$ and $^{230}Th$–$^{234}U$ ages been achieved. No other archive is better preserved. No other record has so many stratigraphically ordered radiometric ages." While Imbrie *et al.* (1993) focused on spectral properties in the frequency domain, W&L emphasized that it is the *timing* of ice ages as determined in their paleoclimate record that cannot be reconciled with the astronomical theory. In addition to the problem of timing, W&L pointed out that the Devil's Hole record indicates three other challenges to the astronomical theory: (1) the duration of interglacial climates is closer to 20,000 yr than the predicted 10,000 yr duration; (2) the length of glacial cycles increases steadily the closer the chronology is to the present day, which is inconsistent with the assumption of a quasi-100,000 yr cycle; and (3) a well-developed glacial cycle occurs in the period 450–350 KYBP at a time when the astronomical theory indicates none should occur.

### 6.1.3 Devil's Hole: Global or regional data?

Questions were also raised regarding whether Devil's Hole data are representative of global or regional temperature trends. Herbert *et al.* (2001) utilized benthic $\delta^{18}O$ records to infer California coastal sea surface temperatures (SST) over the past ~500,000 years. They found that in the region now dominated by the California Current, SSTs warmed about 10,000 to 15,000 years in advance of deglaciation at each of the past five glacial maxima. However, SSTs did not rise in advance of deglaciation south of the modern California Current. They therefore concluded that warming along the California margin prior to deglaciation is a regional phenomenon, which they attributed to a weakening of the California Current during times when large ice sheets reorganized wind systems over the North Pacific. They further inferred that the Devil's Hole data would be heavily influenced by conditions prevailing along the California coast, and they concluded that the Devil's Hole (Nevada) calcite record represents regional but not global paleo-temperatures. Hence, such regional variations (it was argued) would not pose a fundamental challenge to the orbital astronomical theory of ice ages. The Herbert *et al*. (2001) paper seems overly defensive of the astronomical theory and applies tuning to that theory—which raises other questions.

Winograd (2001) responded to the paper by Herbert *et al*. (2001). He pointed out that there are data that indicate that SST warming occurred 5,000 to 15,000 years before the last deglaciation at a minimum of 28 locations in both hemispheres of the Pacific, Indian, and Atlantic Oceans. While there may well have been some regional variability to SST changes prior to deglaciations, there is ample worldwide evidence that SST temperatures tend to increase prior to deglaciation, which might provide clues as to the role of oceans in the glaciation–deglaciation cycle.

### 6.1.4 Devil's Hole data and Vostok data compared

This section is based on Landwehr and Winograd (2001). We will refer to this paper as L&W from now on.

Most ice cores, including those from Vostok, cannot be radiometrically dated, so other methods are employed to construct depth–age relationships Furthermore, because the accumulation rate is relatively low in the East Antarctic interior where the Vostok site is located, annual layer counting is not possible, even in the younger portions of the Vostok core. Consequently, many other approaches have been used to develop chronologies for the Vostok record, including ice flow modeling, orbital tuning, correspondence to SPECMAP, and some combinations of these. Despite the care put into each construction, the differences between chronologies can be significant even in critical portions of the record, thereby permitting alternative interpretations about the cause of specific paleoclimatic events.

L&W compared seven different chronologies that have been derived for the Vostok ice core relating to the critical time period in which the previous ice age came to an end, as shown in Figure 6.3.

While L&W provided reasons for Devil's Hole $\delta^{18}O$ and Vostok $\delta D$ records to be used as proxies for the same physical phenomenon, they raised the question as to whether these two paleo-temperature time series are synchronous for major climatic events such as glacial–interglacial transitions. They noted that, despite the 115° difference in latitude between the two sites and the many factors that affect the stable isotopic content of precipitation, a strong correlation exists between the data from the two sites for the period of their chronologies overlap.

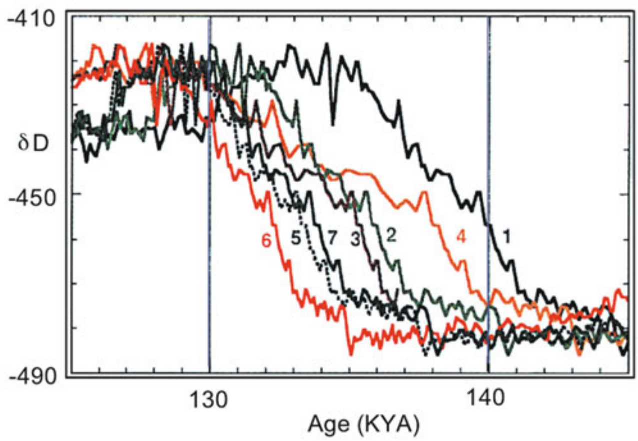



**Figure 6.3.** Vostok δD chronologies during the deglaciation of about 135,000 years ago as derived by seven different investigations (L&W).

Nevertheless, these arguments are somewhat subjective and the treatment of the two sites as synchronous must be regarded as an assumption rather than a fact. L&W also noted that differences in chronology of about 5,000 years arise at different sites at Greenland alone, so they suggested that one should consider the agreement of diverse sites to within about 5,000 years as evidence of synchronicity.

L&W developed a procedure for transferring a chronology from a well-dated paleoclimate record (in this case, Devil's Hole) to one that is not independently dated (in this case, Vostok). The underlying assumption was that both records are proxies for the same physical phenomenon and the paleoclimatic conditions forcing the two records can be considered to have occurred contemporaneously at both locations. The procedure identifies where significant state changes of comparable relative magnitude are under way in each dataset, and then utilizes a visual examination of the geometry to relate corresponding climatic excursions in the two records. Figure 6.4 shows how key points were related from the Devil's Hole age scale to the Vostok depth, and Figure 6.5 shows the resultant age vs. depth curve derived for Vostok. From this result, L&W prepared the comparison of Vostok and Devil's Hole data shown in Figure 6.6. In this figure, the black curve is the Vostok data based on the Devil's Hole chronology, and the blue curve is the Devil's Hole result. The red curve is based on extrapolating the Vostok age–depth curve to greater depths where the data are suspect because layering was disturbed by dynamic ice processes. Nevertheless, the red curve seems to be reasonable.

However Carl Wunsch has emphasized the subjectivity inherent in comparing noisy curves and cautioned that such procedures "can easily lead to unwarranted, and incorrect, inferences if simple stochastic superposition is confused with deterministic causes" (see Section 3.2.10 for further details). Nevertheless, Figure 6.6 is fairly convincing to this writer.

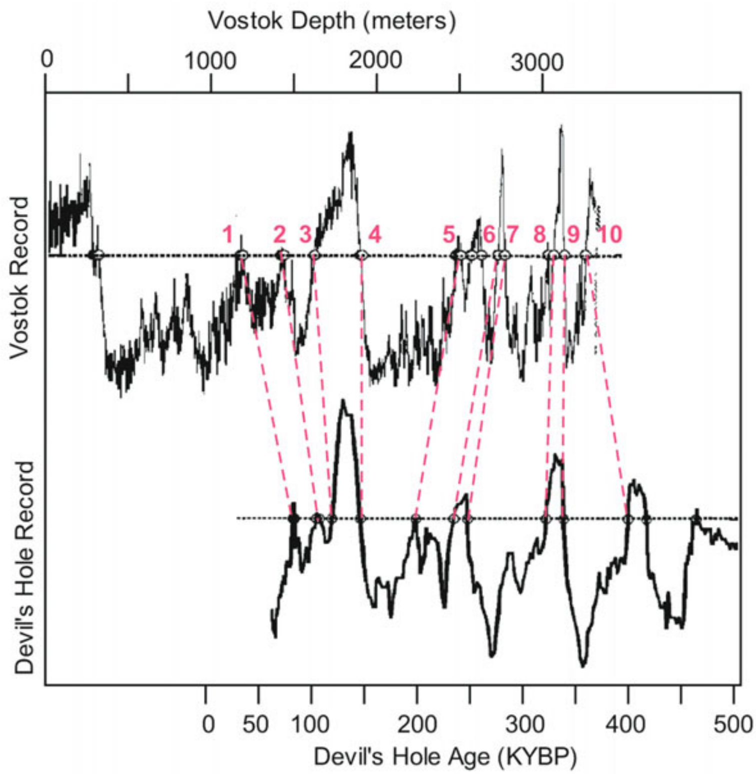



**Figure 6.4.** Alignment of Devil's Hole transition points with Vostok transition points.

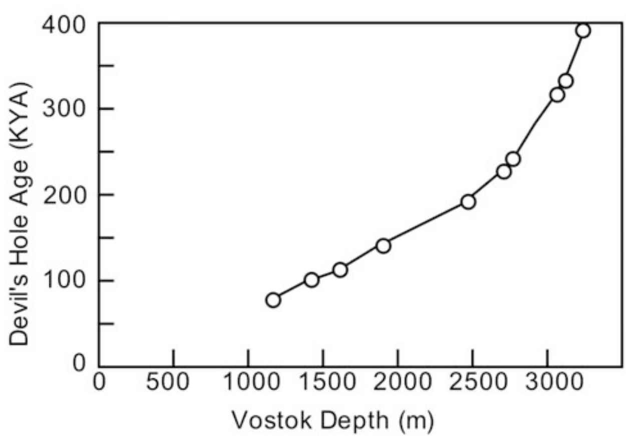



**Figure 6.5.** Vostok age vs. depth inferred from Devil's Hole.

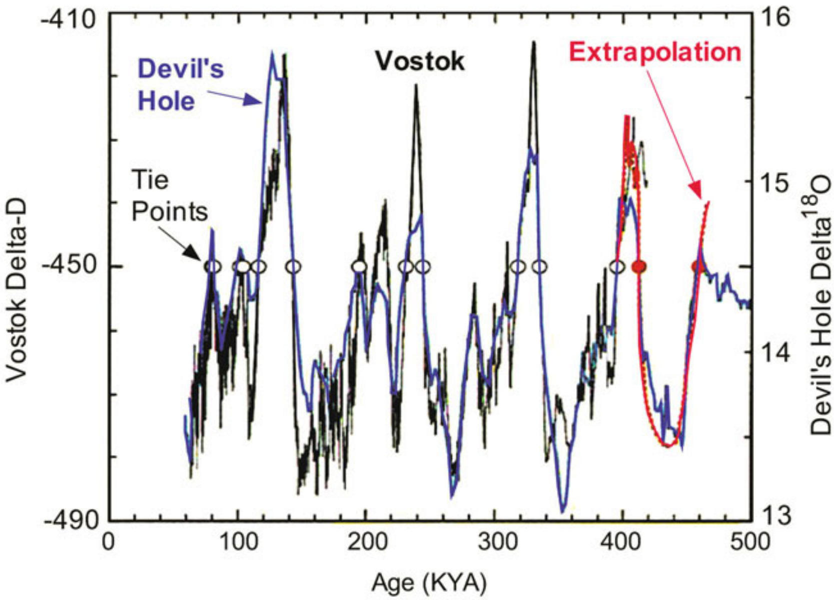



**Figure 6.6.** Relationship between Vostok data and Devil's Hole data based on Devil's Hole chronology.

## 6.2 SPELEOTHEMS IN CAVES

A speleothem is a secondary mineral deposit formed in a cave. Speleothems are typically formed in limestone or dolostone caves. Water seeping through cracks in a cave's surrounding bedrock may dissolve certain compounds, usually calcite and aragonite (both calcium carbonate), or gypsum (calcium sulfate). The rate depends on the amount of carbon dioxide held in solution, on temperature, and on other factors. When the solution reaches an air-filled cave, a discharge of carbon dioxide may alter the water's ability to hold these minerals in solution, causing its solutes to precipitate. Over time, which may span tens of thousands of years, the accumulation of these precipitates may form speleothems. One typical form of speleothem is a stalactite which is a pointed pendant hanging from the cave ceiling. Stalagmites are ground-up counterparts.

Some caves have yielded well-dated low-latitude low-elevation records that characterize atmospheric moisture earlier in its transit from source regions. An impressive cave study provided a record of Asian Monsoon precipitation, which covers most times since the penultimate glacial period, about 160,000 YBP (Yuan *et al.* 2004). This cave is located in China at 25°N latitude. Stalagmites with diameters varying between 12 and 20 cm were collected 100 m below the surface, 300 and 500 m from the entrance. Stalagmites were subjected to oxygen isotope analysis and $^{230}$Th dating by thermal ionization. The resultant time series of $\delta^{18}$O bore some similarity to the $\delta^{18}$O data from the GISP2 ice core over the past ~70,000 years.

Precipitation of $\delta^{18}O$ at this cave site is believed to be largely a measure of the fraction of water vapor removed from air masses moving between the tropical Indo-Pacific and southeastern China. Rainfall integrated between tropical sources and southeast China was found to be significantly lower during glacial times than interglacial times, perhaps related to lower relative humidity. This reduced precipitation pattern correlated to some degree with reduced temperatures during the last ice age, as measured at Greenland.

Because the cave data were dated without use of any tuning process, they provide (like Devil's Hole) an independent chronology for events around the termination of the previous ice age. They found a large sudden increase in precipitation at 129 KYBP, a fairly constant level of high precipitation from 129 to 120 KYBP, and a large sudden decrease in precipitation at 120 KYBP.

While the authors claimed that this behavior mirrored the variability of solar input (as Figure 9.9 shows), the timing of these cave variations does not match solar timing. Nor does it match the ice core data in Figure 6.3. The Devil's Hole data (expanded version of Figure 6.1) show a sharp increase in temperature from about 140 to 133 KYBP, high temperatures persisting from 133 to about 121 KYBP, and a sharp decrease in temperature from about 121 to 112 KYBP. This seems to parallel the Chinese cave data except that the Devil's Hole dates are about 10,000 years earlier.

## 6.3 MAGNETISM IN ROCKS AND LOESS

### 6.3.1 Magnetism in loess

The magnetic properties of thick (100–300 m) deposits of wind-borne dust, called loess, from China may provide a continuous record of climate variations over the last 2.6 million years. Although the loess paleoclimate records are not as detailed as those from ice cores, they are a potential source of continental paleoclimate information for non-Arctic land regions.

When sediment is deposited, magnetic particles within the sediment tend to align with the Earth's magnetic field. As they are compacted and consolidated they become immobile, preserving a record of the direction in which the magnetic field was oriented at the time of deposition. Because the Earth's field reverses polarity from time to time and the reversal chronology has been determined with good accuracy for the last 100 million years or so, sediments can be dated by comparing the alignment of magnetic particles with the established reversal history.

According to Banerjee and Jackson (1996), the thick loess deposits of central China have accumulated at an average rate of about 10 cm every thousand years, and the rate increased by a factor of 3–4 during ice ages due to stronger winds and a greater preponderance of dust in the air. During interglacial periods, soils developed on the loess surface. As the cycle of glaciation and deglaciation continued, alternating layers of loess and soil built up. The soils and loesses can generally be distinguished visually, but magnetic measurements are more quantitative: sediment ages can be determined by means of the magnetic polarity time scale, and the magnitude of climate changes can be related to the magnitude of variation in magnetic properties. Soils deposited during interglacials are about 200 times more magnetic than loess deposited during glacials. Increased magnetic susceptibility values may result (in principle) from either a higher concentration of magnetic iron-bearing minerals in interglacial wind-borne dust, or formation of such minerals from preexisting non-magnetic or magnetic materials, as a result of chemical changes during soil formation.

A number of papers have been published reporting studies of the magnetic properties of loess (e.g., Florindo *et al.*, 1999 who reported on a core representing 150,000 years). However, the data from these various studies tend to be qualitative.

### 6.3.2 Rock magnetism in lake sediments

It has been proposed that the magnetic susceptibility of rocks buried in lake sediments can provide a proxy record of past temperatures. However, the description of how it works is not very clear. There exist so-called *maar-diatreme phreatomagmatic explosion craters* which form when magma rises close to the surface and interacts explosively with groundwater. This leaves behind a crater that may fill with water, forming a lake. Such lakes store sediments that have measurable age vs. depth characteristics.

Thouveny *et al.* (1994) investigated lake sediments at two such sites in France. Cores >50 m in length were taken. It was claimed that past cold climates tended to preserve residual magnetism in the rocks in sediments, whereas warmer climates would have reduced magnetic susceptibility—although it is not clear to this writer how this occurs. Nevertheless, the authors made measurements to determine the concentrations of magnetite ($Fe_3O_4$) and titano-magnetite ($Fe_{3-x}Ti_xO_4$) vs. depth and converted this to age by independent radioisotope measurements. The results are shown in Figure 6.7. The susceptibility measurements seem to match up moderately well with Greenland ice core measurements, suggesting that the cooling during the Ice Age was widespread across the NH.

## 6.4 POLLEN RECORDS

Wilson *et al.* (2000) provide a good overview of the use of pollens as climate proxies. Pollen from flowering plants and conifers as well as spores from ferns, horsetails, and mosses provide microscopic grains that are very resistant to decay and often occur well preserved in sediments in bogs and lakes. The abundance and distribution of such pollens provides insights into regional climates at various times in the past. Figures 1.1 and 1.2 illustrate how changing climates affect the distribution of plant life across the globe. The proportion of different types of pollen and spores in sediments depends on the amounts produced by various

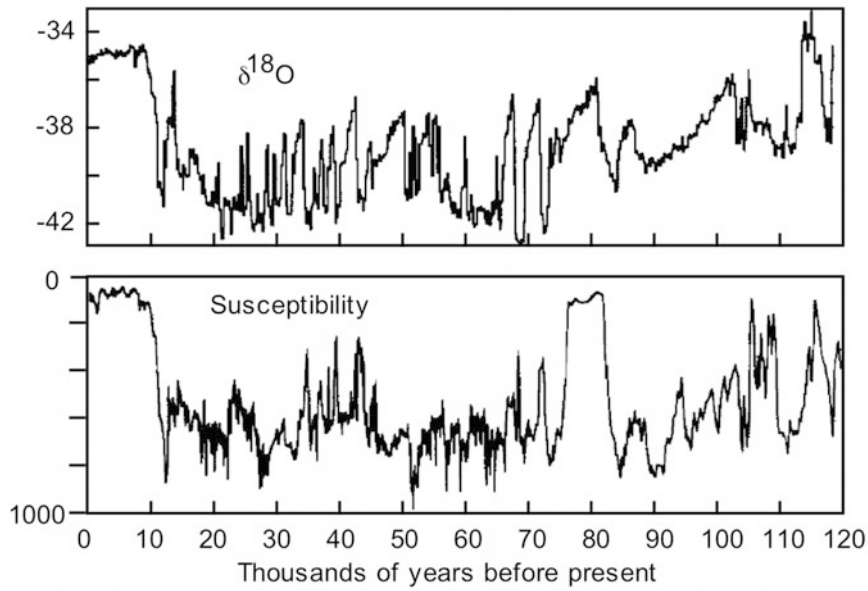



**Figure 6.7.** (Upper panel) $\delta^{18}$O from GRIP in Greenland. (Lower panel) Measured susceptibility of lake sediments in France.

plants and how easily they are transported by wind or by animals. Wilson *et al.* (2000) provided data from a site that was a former lake in the United Kingdom. A sediment core revealed that, prior to about 9,600 YBP, the only trees were birch, with few willow and juniper. Birch pollen probably indicates tundra (mostly dwarf birch). There was also sedge, grass, and herb pollen. Starting around 9,600 YBP, a series of sharp changes occurred in the pollen record. First, the number of birches increased sharply. They were subsequently replaced by Scotch pine, which were in turn replaced by hazel and bog myrtle. Soon thereafter, there was great diversification into elm, oak, and many other species of trees as the climate warmed. Even lime pollen was found:

> "Fossil pollen is especially useful in determining the number of different kinds of trees, shrubs, and other plants that grew around a pond when each layer formed. The core samples that scientists take from the bottom of these ponds capture this record in long cylinders of mud. Then scientists date each layer using radiocarbon methods and identify and count the fossilized pollen grains. Thus, the ooze at the bottom of a pond can provide the key to unlocking the ancient history of a forest. Scientists reconstructed the vegetation that grew on the Great Plains and elsewhere during the Ice Age using fossil pollen and macrofossils, or fossilized plant parts such as seeds, needles, cones, wood, and twigs. Much of this evidence comes from cores, but plant parts also accumulate in pack rat dens, glued together with their droppings into a mass called a midden.

> These middens provide valuable evidence of past vegetation because they last for thousands of years. Additional evidence comes from logs and land snails that became buried beneath the thick layers of soil that glacial winds spread across the land. Scientists know from this kind of evidence that the enormous expanse of grasslands so familiar to us did not exist on the Great Plains during the Ice Age. White spruce forests covered the plains, although grasses still grew in openings among the trees" (Bonnicksen, 2000).

Colinvaux (2007) wrote an extraordinary book detailing 50 years of research in an attempt to define the climate of the Amazon region during the past Ice Age based primarily on pollen records and plant fossils. His results suggest that rainforests continued unabated through the Ice Age but were partly infiltrated by species normally restricted to higher elevations. This is in contrast to the widely held belief that aridification converted most rainforests to savannas and that only smaller pockets of rainforest (refuges) remained through the Ice Age.

Various pollen studies have shown how the various vegetation strata on mountainsides descended to lower altitudes during ice ages (Andriessen *et al.*, 1993). In some cases, time series of terrestrial climates were extracted and compared with time series from ocean sediments (e.g., Tzedakis *et al.*, 2006). The details of these studies are beyond the scope of this book. Most pollen studies are relegated to the period since the end of the past Ice Age.

## 6.5 PHYSICAL INDICATORS

### 6.5.1 Ice sheet moraines

Moraines (i.e., debris bulldozed into place by the advancing ice sheet front) mark the perimeter of past ice extent. Marine oxygen isotope records suggest that each of the great ice ages culminated with roughly the same ice volume (Broecker, 2002). Where moraines from earlier ice maxima are preserved, they support this interpretation. However, although the location of the southern margins of the North American and Eurasian ice sheets is clearly defined by moraines, considerable uncertainty remains concerning the extent of ice along their northern perimeters. Based on the extent of moraines, computer simulations of the height and contour of past ice sheets fitted to these boundaries are only accurate to about $\pm 30\%$.

### 6.5.2 Coral terraces

Corals provide a widely used archive to investigate past variations in sea level. Because many coral species survive only in shallow water, fossil corals found above or below present reefs preserve indications of past sea levels. As Lambeck *et al.* (2002) emphasized,

> "Coral growth proliferates when the rate of sea-level rise equals or exceeds the rate of land uplift, but when sea-level rise cannot keep up only patchy and thin reef veneers develop. Important examples are from Barbados, Sumba and Papua New Guinea. Uplift at Huon Peninsula, Papua New Guinea, is as high as 4 mm/yr, resulting in a more detailed record than is available from other localities. Huon terraces of last interglacial age are now at elevations up to 400 m, whereas in tectonically stable areas such reefs occur near modern sea level."

Corals can be dated by radiocarbon for the past 40,000 years and by the formation of $^{230}$Th through the radioactive decay of uranium for the past 500,000 years. However, Henderson (2005) cautioned that: "the longer a coral sits around waiting for a passing geochemist to take it back to the lab, ... the more likely it is to be altered, causing addition or loss of uranium or thorium and making uranium–thorium ages inaccurate." Over the past million years or so, global sea level changed almost exclusively in response to the volume of water stored in the ice sheets. Therefore, by dating any remnant shorelines that formed in the past, it should be possible to directly assess the amount of water tied up in ice caps in historical times. Since the oceans are presently roughly 100 m or more higher than they were during the Last Glacial Maximum, most of the glacial age shorelines we might wish to study lie beneath the present level of the oceans. Carrying out underwater geologic studies on submerged shorelines to establish the relationship between the elevation of the sample to be dated and the elevation of the sea at the time it formed is a difficult task. In addition, the problem of assessing past ocean levels is complicated by the fact that almost all the land on Earth has changed elevation in the intervening years.

A breakthrough was made when the $^{230}$Th/$^{234}$U ages of corals from raised shorelines in many locations in the tropics revealed a prominent sea level high stand with an age of about 124,000 years. These radiometric methods were applied to corals that depend upon the presence of *Acropora palmata* which is known to grow only within the top 2 m of sea level. It is now generally accepted that these reefs formed during a time when global ice volume was slightly smaller than today's. These areas, as a result of rapid tectonic uplift, have preserved the shorelines from the last interglacial maximum and are amenable to radiometric dating. Quite a number of reports have been published based on radiometric dating of coral terraces. In this connection, a major point of interest is the timing of the peak ocean level at the termination of the last interglacial. One result is shown in Figure 6.8.

M&M discussed the results of sea level measurements from coral terraces in relation to the astronomical theory of ice ages. Figure 9.12 shows that solar input to high northern latitudes minimized around 138,000 YBP, peaked around 125,000 YBP, and minimized again around 114,000 YBP. Based on solar input alone, one would expect a time lag for maximum sea level after peak solar intensity; so, one might guess that the astronomical theory would predict a maximum sea level somewhat more recently than 125,000 YBP. Figure 9.14 shows

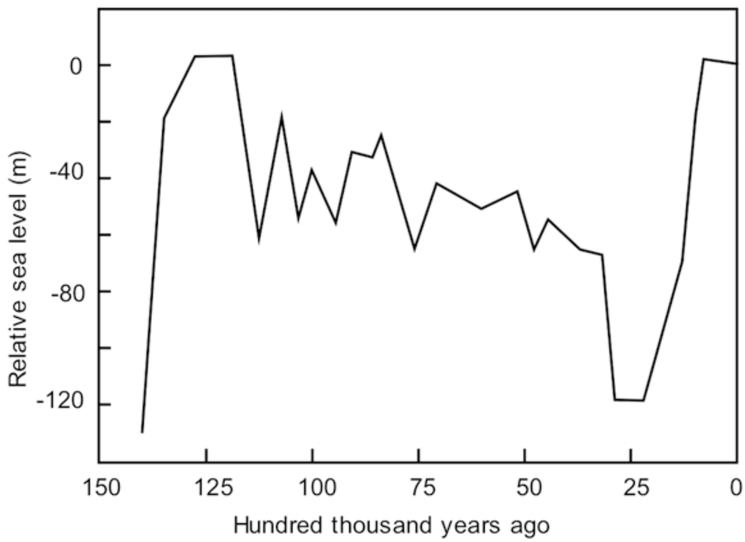



**Figure 6.8.** Estimated variation of sea level from coral terraces (Lambeck *et al.*, 2002; Lambeck, 2004).

that, according to the Imbrie model for ice volume based on the integration of solar intensity, the ice volume would have had an intermediate peak at around 137,000 YBP and would have minimized about 120,000 YBP. Thus, the astronomical theory seems to point to a high water mark at around 120,000 YBP and a significant lowering of sea level about 17,000 years prior to that date. However, data reported by a number of investigators (e.g., Henderson and Slowey, 2000) indicated that the high water mark may have been reached by 130,000 YBP and sea level began rising at around 140,000 YBP when solar intensity was low. This led M&M to conclude that there is a "causality problem" with the astronomical theory in which the timing of solar variations does not match the timing of climate changes. However, Thompson and Goldstein (2005) revised the process for dating coral terraces that corrects ages for the bias imposed by previous workers who assumed closed-system behavior for Th isotopes. This shifted the ages to more recent times as shown in Figure 6.9. With this change, the peak sea level is reached around 128 KYBP, but sea level nevertheless began rising at around 135 KYBP when the astronomical theory would have predicted a low sea level.

As Henderson (2005) commented, substantial swings in sea level appear to have occurred not all of which can be explained by orbital changes. He said:

> "Perhaps most surprising is that 185,000 years ago—at a time when orbital parameters and climate proxies indicate cold conditions—sea level was only about 20 m below its present level. This event challenges our understanding of the conditions required for ice growth. Between 130,000 and 90,000 years ago, the record provides clear evidence for sea level change at higher frequency than can be explained by orbital changes."

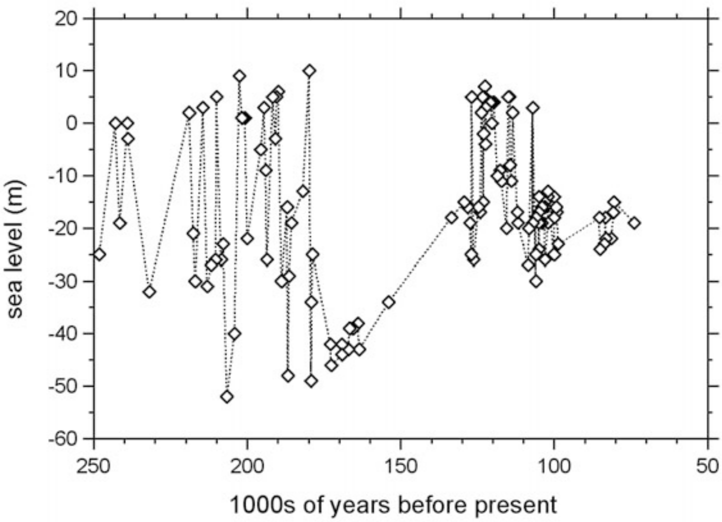



**Figure 6.9.** Estimates of sea level by Thompson and Goldstein (2005) with ages calculated from open-system equations.

### 6.5.3 Mountain glaciers

Even in the tropics, the highest mountains are capped by ice. The boundary between elevations where snowfall exceeds melting and elevations where melting exceeds snowfall corresponds roughly to the position of the mean annual 0°C isotherm (snowline). Moraines left behind by glaciers that were once more extensive than they are today are easily identified on all of the world's snow-capped mountains. Radiocarbon and cosmogenic isotope dating demonstrate that these moraines formed during the peak of the Last Glacial Maximum (LGM). Through careful mapping of these features, it has been possible to reconstruct the elevation of the snowline at the LGM. In most places, lowering was in the range $830 \pm 70$ m, after correction for the lowered sea level (Broecker, 2002). Broecker concluded that on high mountains located from 45°N to 45°S the temperature was probably more than 5°C colder than it is today. This change produced shifts in vegetation zones on mountainsides to lower elevations, as evidenced by studies of pollen grains extracted from the sediments of mountainside lakes and bogs.

Over the last three decades, ice core records have been recovered from 10 high-elevation ice fields, 9 of which are located in lower latitudes. These ice core histories provide evidence that the growth and decay of the large ice fields in lower latitudes are often asynchronous, both between hemispheres and with high-latitude glaciation. Thompson *et al.* (2005) concluded that variability of precipitation (rather than temperature change) was the primary driver of glaciation in lower latitudes.

## 6.6 RED SEA SEDIMENTS

While benthic sediments at ocean bottoms provide an indication of past glaciation, such sediments in constricted areas such as the Red Sea are distorted by the changing rate of flow into and out of the Red Sea as the ocean level changes. However, this effect can be exploited to estimate the past variability of sea level using dynamic models for the Red Sea and its interchange with the open ocean.

An estimate of past sea level variability was based on the fact that the Red Sea is extremely sensitive to sea level change, as a consequence of the narrow (18 km) and shallow (137 m) character of its only connection with the open ocean (Siddall *et al.*, 2003). During periods when sea level is lowered, the rate of exchange transport of water through the strait is reduced. This leads to an increased residence time of water within the Red Sea, enhancing the effect of the high rate of evaporation on the properties of residual water in the Red Sea. The basin thus amplifies the signals of sea level change, which are recorded in $\delta^{18}O$ values of foraminifera in Red Sea sediment cores. This amplification was previously used to calculate sea level low stands at times of maximum glaciation during the past 500 KYBP (Rohling *et al.*, 1998). To unlock the potential of Red Sea data for the development of continuous sea level records (rather than only low stands) Siddall *et al.* (2003) combined a model for flow exchange in the strait with a model of the Red Sea basin. They calculated salinity and $\delta^{18}O$ values for calcite in equilibrium with ambient water. Changes in modeled salinity and $\delta^{18}O$ values were dominated by changes in sea level. The simulated variation of $\delta^{18}O$ values with sea level change were used to translate $\delta^{18}O$ values records from sediment cores into records of past sea level change.

Strictly speaking, these sea level reconstructions pertain to the level at Bāb el Mandab (Yemen), which may deviate somewhat from truly global changes owing to uplift and isostatic effects. Uplift of the strait was estimated and corrected for. Isostatic effects were believed to be negligible. It was therefore concluded that

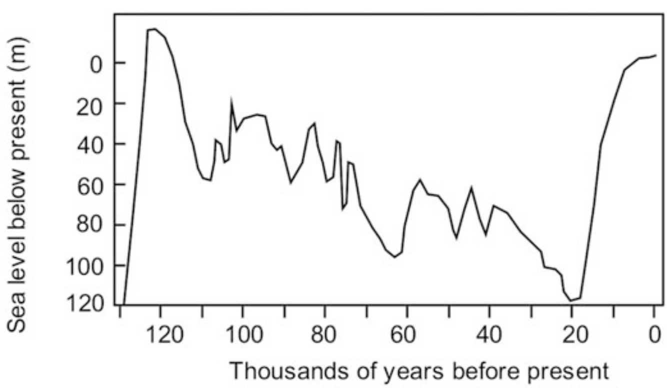



**Figure 6.10.** Smoothed data on sea level based on Red Sea sediments and coral terrace data (Siddall *et al.*, 2003).

these reconstructions provided close approximations to global sea level (and hence ice volume). Siddall *et al.* (2003) integrated a range of Red Sea sediment data and coral terrace data to prepare an estimate of sea level over the past ~125,000 years. A smoothed version of their data is given in Figure 6.10.

Almogi-Labin also made measurements of $\delta^{18}O$ values in Red Sea sediment cores. Rohling *et al.* (2008) used a combination of two independent parameters from a single central Red Sea sediment core—namely, stable oxygen isotope ratios in surface-dwelling planktic foraminifera—and bulk sediment magnetic susceptibility. The $\delta^{18}O$ measurements provide the basis for sea level reconstructions from the Red Sea but magnetic susceptibility provides a proxy for aeolian dust content in sediments.

## 6.7 INFLUENCE OF DUST AND IRON

Dust in ice cores can be detected by several means: (i) shadowing of a laser beam in a melted core, (ii) changes in the electrical impedance of a melted core, (iii) non-sea salt calcium concentration, and (iv) mass spectrometry. Research shows that the dust concentration in ice cores is up to 2 orders of magnitude higher during glacial stages than during interglacials. This is thought to be due to higher aridity and storminess during colder climates.[1] Petit *et al.* (1997) provide dust data from the Vostok ice core showing that the dust concentration reached about 1.5 ppm during the LGM, whereas it is presently essentially zero (also see Petit *et al.*, 1990). According to Martinez-Garcia *et al.* (2011), atmospheric dust has the potential to cool the global climate by reflecting incoming sunlight and "by supplying iron and other essential limiting micronutrients to the ocean. Indeed, dust supply to the Southern Ocean increases during ice ages, and 'iron fertilization' of the subantarctic zone may have contributed up to 40 ppm of the decrease (80–100 ppm) in atmospheric $CO_2$ observed during late Pleistocene glacial cycles." The stimulation of phytoplankton growth would have increased the uptake of $CO_2$ from the atmosphere. Prior to the work of Martinez-Garcia *et al.* (2011), the variability of dust had been measured in ice cores dating back 800,000 years (e.g., Petit *et al.* 1997). Martinez-Garcia *et al.* (2011) produced a high-resolution dust and iron record from the subantarctic Atlantic spanning the past 4 million years based on marine sediments from a subantarctic Atlantic site (ODP 1090). They showed that iron content and dust content varied in unison over the past 4 million years. While dust and iron levels remained moderate from about 4 to about 1.2 MYBP, dust and iron levels rose rapidly after about 1.2 MYBP. While these levels continued to oscillate with ice age–interglacial cycles, the overall amplitude of these oscillations increased considerably after 1.2 MYBP.

As we have seen from ocean sediment data (e.g., Figures 2.42 and 5.6), the pattern of ice age–interglacial cycles changed about 1.2 MYBP in which the more

[1] *http://www.awi.de/de/forschung/fachbereiche/geowissenschaften/glaziologie/palaeoclimate/dust_in_ice_cores/*

recent cycles had greater amplitude and longer cycle length (~100,000 years vs. ~41,000 years). Martinez-Garcia *et al*. (2011) suggested that increasing dust and iron levels after 1.2 MYBP contributed to this transition. Whether the transition produced additional dust and iron, which in turn provided a positive feedback, or whether additional dust and iron from some cause contributed to the transition is difficult to resolve.

# 7

# Summary of climate variations

***Cooling over the past 50 million years*** Zachos *et al*. (2001) studied oxygen isotope ratios in ancient sedimentary deposits and thereby estimated deep-sea temperatures over the past 60 million years. Hansen *et al*. (2010) modified their results to take into account the fact that isotope data represent a combination of deep-sea temperature and ice sheet volume and, during periods when there were ice sheets, the data had to be corrected for this (see Figure 2.7). Deep-sea temperature dropped by about 12°C over the past 50 million years.

Hansen *et al*. (2010) claimed that deep-sea temperature is closely related to global average temperature. They roughly estimated that changes in deep-water temperature represent two thirds of global average temperature changes, which implies that the change in global average temperature was perhaps ~12°C over the past 50 million years. That represents a huge cooling effect.

***Origin of glaciation—past 34 million years*** This topic is discussed in Section 2.5.2. About 55 MYBP, Australia began to drift northward away from Antarctica. Evidence suggests that by 34 MYBP, a circumpolar ocean current developed around Antarctica that thermally isolated it, allowing glaciation to proceed. In addition, there may have been a reduction in atmospheric $CO_2$. Mountain building may have hastened glaciation. Since about 34 MYBP, the temperature of the Earth has been on a generally downward path, permeated by significant oscillations.

***The past 3 million years*** Around 3 MYBP the Isthmus of Panama closed isolating the waters of the Atlantic and Pacific Oceans. It seems likely that this may have fundamentally changed global ocean circulation. Evaporation in the tropical Atlantic and Caribbean left those ocean waters saltier. As this salinity increased, the water transported northward in the Atlantic became warmer and saltier. As this water reached high North Atlantic latitudes, it transferred heat and moisture to the atmosphere, leaving behind cold salty dense water that sank toward the ocean floor. This water flowed at depths, southward and beneath the Gulf Stream, to the Southern Ocean. Hence, this thermohaline circulation was enhanced

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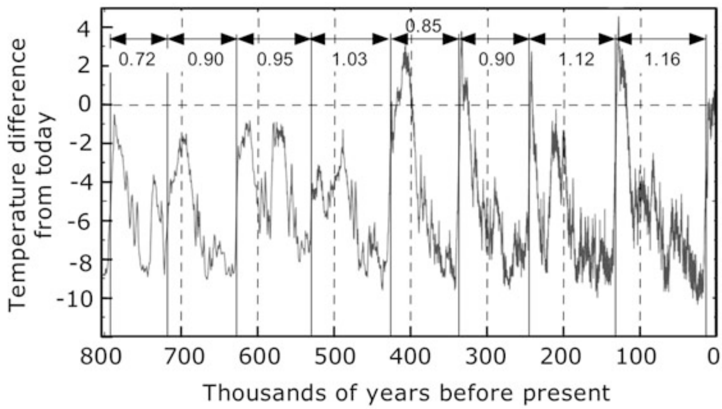


**Figure 7.1.** Copy of Figure 4.10 for Vostok ice core data showing the spacing between rapid terminations in millions of years.

by the closure of the Isthmus of Panama. It is not clear whether this event is tied to the advent of subsequent ice ages. It may well be that additional moisture was provided to higher northern latitudes, allowing ice sheets to build up in the north when other factors dictated glaciation should advance. The "other factors" are widely believed to be variable solar input to higher latitudes. This is discussed in Chapters 9 and 10.

As Figure 5.6 shows, the climate of the Earth became unstable and subject to cycles with the advent of glaciation. Initially (until about 1 MYBP) the oscillations were rapid (period ~40,000 years) and of moderate amplitude. In the past million years, the oscillation period gradually increased to about 100,000 years and the amplitude increased significantly.

***The past 800,000 years*** Over the past 800,000 years, the Earth has undergone approximately eight major cycles of glaciation and deglaciation spaced at roughly 100,000-year intervals. These cycles are shown in Figures 4.10, 4.12, 5.1, 5.2, 5.4, 5.5, 5.7, and 5.8. The trend has been for long slow accumulation of ice in northern ice sheets while the Earth cooled, followed by rather sudden warming back to interglacial conditions and a warm hiatus for several thousand years before a new cooling trend began. During each cooling period, which may have lasted 50,000 to 100,000 years, there were frequent significant short-term violent fluctuations in the climate. As Figure 7.1 shows, the spacing between cycles has been increasing over the past 800,000 years by roughly 5,000 years per cycle (with some non-uniformities). Oscillation amplitudes increased significantly over that period.

***The most recent ice age and its aftermath*** The most recent ice age and its aftermath are recorded in the Greenland ice cores (Figure 4.7). This figure shows the end of the penultimate ice age with a warming trend starting around 145 KYBP, leading to the so-called Eemian interglacial from about 135 to about 115 KYBP, followed by a buildup of ice sheets in the last ice age from about 115 to about 20 KYBP. This ice age was permeated by numerous very sharp but short-lived

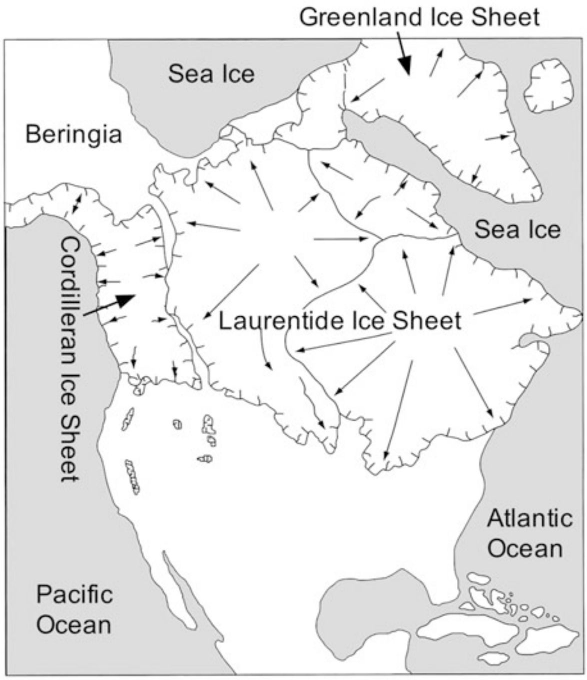


**Figure 7.2.** Extent and movement of great ice sheets during the Last Glacial Maximum (Burroughs, 2005).

fluctuations. We have been in the Holocene interglacial period for about the past 10,000 years. Figures 4.2 to 4.6 display higher resolution data for more recent time periods. As Figure 4.5 shows, a warming trend in Greenland actually began slowly about 20 KYBP when glaciation was at a maximum, went through a significant "bump" around 16 KYBP, and then rapidly accelerated to Holocene conditions around 10–11 KYBP.

An interesting aspect of the growth of northern ice sheets is the fact that the epicenters for growth of ice sheets appear to have been at latitudes of 60 to 65°N, high enough to be cold but low enough to have access to airborne moisture (see Figures 2.9 and 7.2).

Note that Wright (1896) discovered that "the glacial phenomena of Labrador all indicate that it has been a center from which the ice has moved outward in all directions."

***The last termination*** Broecker (2002) described the termination of the most recent ice age in considerable detail. This section is based on his description:

- *~18,000 years ago, peak glacial conditions prevailed*—both mountain glaciers and continental ice sheets stood at or close to their maximum extent. The oxygen isotope ratios and dust content of polar ice still had their full glacial values. The sea level stood ~110 m lower than today. The $CO_2$ and $CH_4$ content of the air remained at the low values characterizing full glacial conditions.

- *~14,500 years ago, the termination was in progress*—glaciers throughout the world began to retreat; polar temperatures began to rise; atmospheric dustiness began to diminish; $CO_2$ and $CH_4$ began to rise. In the northern Atlantic basin, this first phase of the termination manifested itself in the catastrophic breakup of the large valley glaciers that extended northward from the Alps. Within a period of a few hundred years, the valleys became ice free. However, climatic conditions remained too harsh to permit the valleys to be reforested.
- *~12,800 years ago, there occurred a sudden warming event*—a major warming event took place in the northern Atlantic region that created climatic conditions similar to those of the present. Trees replaced shrubs. The interglacial had seemingly arrived. The warm period lasted about 1,800 years but was interrupted by a short sudden cooling event around 12,000 years ago, known as the Allerød–Bolling event.
- *~11,000 years ago, glacial conditions abruptly returned*—cold prevailed for 1,200 years (this was the Younger Dryas).
- *~10,000 years ago, the cold snap abruptly ended*—since then interglacial conditions have remained uninterrupted.

According to Broecker (2002), "no equivalent of the Younger Dryas cold snap appears to punctuate earlier terminations .... It appears to be a one-time event triggered by a sudden and very large release of meltwater stored in proglacial Lake Agassiz."

Wright (1896) studied the rates of ablation of Greenland and Swiss glaciers during local summers and concluded: "During the closing stages of the glacial period, the ice sheets, both in America and Europe, may have melted away very fast. If such ablation prevailed every summer for one or two centuries, it must melt 600 to 1,200 meters of ice ...."

Most marine sediments are subject to mixing as they accumulate, so the time scale is blurred by several thousand years. Hence, unlike ice cores, marine sediments are unable to detect sudden climate changes, but they can provide a smoothed record of past climate changes. Thus, in describing the last termination and recent climate history of the past 20,000 years, we must rely mainly on Greenland ice core data (see, e.g., Figures 4.2, 4.3, and 4.4). Broecker (2002) also cited corroborating data from the sediments of Gerzensee (a small Swiss lake), the distributions of various beetle species, and the high-resolution planktic foraminifera speciation record in deep-sea sediments off the British Isles.

The sudden sharp changes in climate that occurred during the past ice age (Figure 4.5), and especially in its aftermath (Figures 4.3 and 4.4), have been the subject of many investigations and discussions. Broecker (2002) devoted 26 pages to this topic. It is theorized that the sudden cooling of the Younger Dryas was produced by a large release of stored meltwater from proglacial Lake Agassiz that gushed through the St. Lawrence lowlands into the northern Atlantic. The sudden decrease in salinity triggered a shutdown of the ocean's deep-circulation system that previously brought heat to northern latitudes via ocean circulation. At the end of the Younger Dryas, both the warming and the drop in dust content appear to have occurred over a period of a few decades. Broecker (2002) cited evidence that these climate changes, detected in Greenland ice cores, were reflected in climate changes worldwide, except that temperature records from Antarctica do not follow the Greenland pattern.

***North–south synchrony*** The relationship between climate variations in the NH and the SH can be elucidated by comparing the chronologies of the Greenland and Antarctic ice cores. This requires an accurate means of putting both ice core records on a common chronological basis. It is not necessary that the chronologies be exact on an absolute basis—only that the two chronologies must be accurately matched. The preferred means for doing this is to compare $CH_4$ time series in the Greenland and Antarctic ice cores. The results are shown in Figures 4.15 and 4.16. There appears to be a correlation between major climate changes in Greenland and Antarctica. Sudden temperature increases in Greenland were preceded by rather slow moderate temperature increases in Antarctica for a few thousand years. Each sudden rise in Greenland occurs near the end of a more protracted rise in Antarctica. If there is a causal relationship between these events, it seems likely to involve the thermohaline flow of the oceans.

***Carbon dioxide and methane*** The patterns of $CO_2$ and $CH_4$ concentration vs. time are similar to those of temperature vs. time with the concentrations of greenhouse gases rising with rising global temperature and vice versa. In particular, $CO_2$ seems to vary from about 180–190 ppm at the height of glaciation to about 280–290 ppm during interglacial periods. The $CO_2$ vs. time curve lags the temperature vs. time curve by about 1,000 years. These changes cannot simply be explained in terms of changing solubility in the oceans with temperature. Evidently, the process is far more complex.

# 8

# Overview of the various models for ice ages in the recent past (3 MYBP to present)

More than 100 years ago, G. Frederick Wright (1896) said:

> "What were the causes of the accumulation of the ice sheets of the Glacial period? Upon their areas, warm or at least temperate climates had prevailed during long foregoing geologic ages, and again at the present time they have mostly mild and temperate conditions. The Pleistocene continental glaciers of North America, Europe, and Patagonia have disappeared; and the later and principal part of their melting was very rapid, as is known by various features of the contemporaneous glacial and modified drift deposits, and by the beaches and deltas of temporary lakes that were formed by the barrier of the receding ice sheets. Can the conditions and causes be found which first amassed the thick and vastly extended sheets of land ice, and whose cessation suddenly permitted the ice to be quickly melted away?
>
> Two classes of theories have been presented in answer to these questions. In one class, ... are the explanations of the climate of the Ice Age through astronomic or cosmic causes, comprising all changes in the Earth's astronomic relationship to the heat of space and of the sun. The second class embraces terrestrial or geologic causes, as changes of areas of land and sea, of oceanic currents, and altitudes of continents, while otherwise the Earth's relations to external sources of heat are supposed to have been practically as now, or not to have entered as important factors in the problem."

Wright also described how the astronomical theory "has been alternately defended and denied." He also pointed out that it was likely that there were "two, three or more epochs of glaciation, divided by long interglacial epochs ... when the ice sheets were entirely or mainly melted away." He mentions that James Geike "distinguished no less than eleven epochs, glacial and interglacial ...."

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Today, 112 years later, Wright's observations are still appropriate. Wright (1896) went on to say:

> "It is easily seen that a glacier is the combined product of cold and moisture. A simple lowering of the temperature will not produce an Ice Age. Before an area can maintain a glacier, it must first get the clouds to drop down a sufficient amount of snow upon it. A climate that is cold and dry may not be so favorable to the production of glaciers as one which is temperate, but whose climatic conditions are such that there is a large snowfall. For example, on the steppes of Asia, and over the Rocky Mountain plateau of our Western States and Territories, the average temperature is low enough to permit the formation of extensive glaciers, but the snowfall is so light that even the short summers in high latitudes cause it all to disappear; whereas, on the southwestern coast of South America, and in southeastern Alaska, where the temperature is moderate, but the snowfall is large, great glaciers push down to the sea even in low latitudes. The circumstances, then, pre-eminently favoring the production of glaciers, are abundance of moisture in the atmosphere, and climatic conditions favorable to the precipitation of this moisture as snow rather than as rain. Heavy rains produce floods, which speedily transport the water to the ocean level; but heavy snows lock up, as it were, the capital upon dry land, where, like all other capital, it becomes conservative, and resists with great tenacity both the action of gravity and of heat. Under the action of gravity, glaciers move, indeed, but they move very slowly. Under the influence of heat ice melts, but in melting it consumes an enormous amount of heat."

In his day, Wright (1896) identified nine possible causes of ice age cycles. These included shifting of the polar axis, a former period of greater moisture in the atmosphere at higher latitudes, depletion of carbon dioxide in the atmosphere, variations in the heat radiated by the Sun, changes in the Earth's orbit, and changes in the distribution of land and water as well as changes in land elevation.

## 8.1 INTRODUCTION

A number of models have been proposed to explain the alternating cycles of glaciation and interglacial cycles. We can classify the various models for the occurrence of ice ages and interglacial periods as follows:

1. *Solar* Variability of the Sun—it has been hypothesized that variations in the innate solar intensity due to structural variations within the Sun may have provided the forcing function for glacial–interglacial cycles.
2. *Orbit* Variability of Earth's orbital parameters—quasi-periodic variations in eccentricity, obliquity, and precession of the equinoxes produce changes in the sequencing of solar intensity to higher latitudes which have been hypothesized to

provide the forcing function for glacial–interglacial cycles. Within this group of models there are those that are based on:

(a) variability of solar intensity in the NH summer;
(b) variability of solar intensity in the SH summer;
(c) variability of individual parameters such as eccentricity, obliquity, precession of the equinoxes, one at a time or in pairs.

3. *Volcanism* The occurrence or absence of high levels of volcanism cause temporary changes in the Earth's response to the Sun which may trigger the initiation of longer term glacial–interglacial cycles.
4. *Greenhouse gases* Variability of concentrations of greenhouse gases (particularly $CO_2$ and $CH_4$) induced by unspecified forcings have been conjectured to be a cause of glacial–interglacial cycles via changes in the greenhouse effect. However, the change in greenhouse gases appears to be a secondary effect of other primary geological or biological processes.
5. *The oceans* Variability in the thermohaline circulation of the oceans producing large changes in the heat delivered to higher latitudes has been hypothesized to provide the forcing function for glacial–interglacial cycles.
6. *Extraterrestrial accretion* Several models are based on the effects due to quasi-periodic accretion of extraterrestrial dust in the Earth's atmosphere as the primary forcing that induces changes in cloud cover, which in turn affects the climate.
7. *Ocean–atmosphere interactions* In this model, the primary factor that controls large-scale variations in the Earth's climate is the Earth's albedo, which in turn is controlled by the degree of cloudiness which is subject to repetitive cycles due to ocean–atmosphere interactions.

The greatest effort and attention has been addressed to the variability of Earth's orbital parameters as the forcing function for glacial–interglacial cycles, and this model is widely accepted among scientists. Thus, we devote all of Chapter 9 to this model.

## 8.2 VARIABILITY OF THE SUN

Rapp (2008) provided a lengthy and detailed review of the literature on variations in power emitted by the Sun. Total solar irradiance (TSI) above the atmosphere has only been measured since 1978, so there are no long-term measurements of solar intensity. The Sun currently passes through repeated sunspot cycles that range from solar maximum to solar minimum with a period of about 11 years. At solar maximum there are typically >100 sunspots whereas at solar minimum there are typically <10 sunspots. Total solar irradiance at solar maximum is about 0.1% higher than at solar minimum. The Sun has been the subject of visual observation since the 17th century, and it is known that the number of sunspots at solar maximum has varied widely over the years. There is evidence that sunspots essentially disappeared altogether for a ~70-year period toward the end of the 17th century. This period is known as the Maunder Minimum and may be associated with the unusually cold temperatures of the time (Rapp, 2008). In addition, the length of the solar cycle has varied from about 9 to 13 years. Thus, the appearance and activity of the Sun can be shown to pass though significant changes over a mere few hundred years. However, it is not known whether these changes in appearance are associated with changes in TSI over such time intervals.

Because past historical variation of the TSI is an important part of the science of paleoclimatology, a number of attempts have been made to estimate historical variations of TSI from approximate models. These models are described by Rapp (2008). They include models based on (1) past sunspot activity, sunspot area or sunspot cycle duration, (2) comparison with Sun-like stars, (3) models based on coronal source flux, and (4) use of cosmogenic isotope proxies. Most of these models only reach back about 100 to 300 years. A few go back as far as several thousand years. None of the models provide estimates over a sufficiently long time period to be compared with paleoclimatological data over hundreds of thousands of years. Furthermore, the models all suffer from significant imperfections and unsubstantiated approximations. Thus, it is a matter of pure conjecture whether variations in TSI over the past few million years have contributed to glacial–interglacial cycles, and there does not seem to be any way to check this hypothesis. However, there are physical models of the Sun that suggest that such variability is unlikely.

## 8.3 THE ASTRONOMICAL THEORY

The astronomical theory does not depend on any innate variability of the TSI but, rather, depends on small quasi-periodic wobbles in the Earth's orbit about the Sun which produce changes in solar input to high latitudes. Even though total solar input falling on the Earth may not change, quasi-periodic changes in the distribution of solar input to high latitudes is thought to have a controlling effect on the ability of high-latitude ice to persist through summer and, thereby, spread from year to year. It is fairly straightforward to calculate changes in the Earth's orbit over the past million years or so and, thereby, to estimate changes in solar input to high latitudes.

While the astronomical theory is based on the general hypothesis that the variability of solar input to high latitudes is the forcing function for glacial–interglacial cycles, the specifics of how this variability produces glacial–interglacial cycles are lacking. Although the simplistic notion is widely held that reduced summer solar input at high latitudes allows ice and snow to survive the summer and spread from year to year, it is not clear which distributions of ice and snow at which locations survive to what degree from any quantitative reduction in solar input above the atmosphere. The confounding effects of water vapor, cloud, precipitation, wind, changing ocean and land albedo, ocean currents, aeolian dust, ocean level, ice sheet formation, and exposure of continental shelves are not included in this simple model. The fact that paleotemperature variations derived from the Greenland ice cores have been much sharper and more sudden than slowly varying solar input indicates that solar input variability to high latitudes cannot be the sole cause of climate fluctuations. Nevertheless, when comparison is made between solar input variability to high latitudes and estimates of past glacial ice volume from ocean sediments, there are some parallels between the two sets of data. However, the translation of solar input variability to high latitudes (which can be calculated accurately) into estimated changes in glacial ice volume is far from straightforward, and only rudimentary models have been put forth up to this point. Testing of these models is obfuscated in many cases by the use of the same models to interpret the chronology of the data (tuning), thus introducing circular reasoning.

The astronomical theory is the most widely used, discussed, and accepted of theories for ice ages (it is discussed in greater detail in Chapter 9).

## 8.4 VOLCANISM

Volcanic eruptions have had a significant but not sustained effect on climate (Rapp, 2008). Various indices classify volcanoes by size. In regard to climate change induced by volcanic eruptions, the most important factor is radiative forcing which is due to the injection of sulfurous material into the stratosphere. This is not always directly related to the explosiveness of the eruption. For example, the Mt. St. Helens eruption (1980) ejected material from the side of the mountain and relatively little was injected into the stratosphere, so it had only a minor effect on global climate. The Volcano Explosivity Index (VEI) is measured in units from 1 to 8, with 8 being the most powerful. Each increase of 1 unit in the index results in an increase of about a factor of 10 in the magma volume emitted. The largest volcano in the past 250 years was Tambora (VEI $\sim$ 7) in 1815.

Volcanic eruptions can inject tens of teragrams of chemically and microphysically active gases and solid aerosol particles into the stratosphere. Large volcanic eruptions inject sulfur gases into the stratosphere which are converted to sulfate aerosols. These concentrations gradually diminish, typically dropping by a factor of about 1/3 each year. Large ash particles fall out much more quickly. The radiative and chemical effects of this aerosol cloud affect the climate system. By scattering some solar radiation back to space, the aerosols cool the surface, but by absorbing both solar and terrestrial radiation the aerosol layer tends to heat the stratosphere. Because sulfate aerosol particles have an effective radius of about the wavelength of visible light, they interact more strongly with shortwave incident solar radiation than the longwave radiation emitted by the surface and atmosphere. Some incident sunlight is back-scattered and reflected to space, cooling the planet. Some is forward-scattered, depleting direct beam downward radiation, but increasing downward diffuse radiation. Figure 8.1 shows the impact of two recent volcanic eruptions on direct and diffuse irradiance at Mauna Loa, Hawaii a considerable distance from the volcanoes. The major impact on solar irradiance occurs in the first year, extending somewhat through the second year. The increase

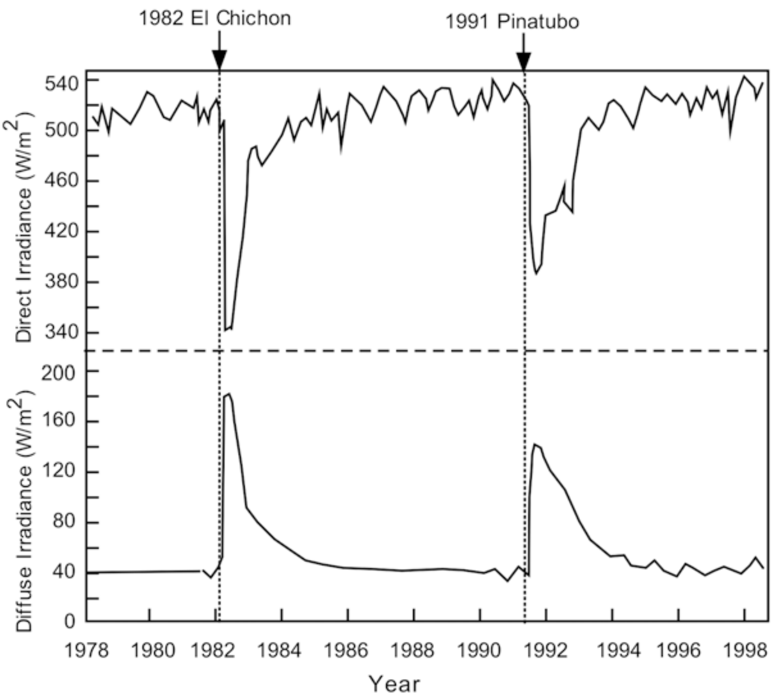


**Figure 8.1.** Direct and diffuse solar irradiance measured at Mauna Loa following volcanic eruptions at a solar zenith angle of 60° corresponding to the passage of sunlight through the two Earth air masses (adapted from Robock, 2000).

in diffuse irradiance is roughly 70% of the decrease in direct irradiance, producing a maximum deficit in TSI of about 40 W/m$^2$ for both El Chichón and Pinatubo. This produces global cooling. Although the Pinatubo eruption's input to the stratosphere was greater, the center of the El Chichón cloud passed directly over Hawaii, while only the side of the Pinatubo cloud was observed there (Rapp, 2008).

The reduction in net TSI (and surface temperature) produced by a major eruption is huge and produces a very strong reduction in solar forcing. If the reduction in TSI (and surface temperature) observed during the first year after an eruption persisted for many years, the Earth would almost certainly enter an ice age. Fortunately, the heat capacity of the Earth is great enough that the reduction in global temperature produced by a Pinatubo-like eruption (VEI = 6) is only about 0.3°C. However, regional temperature reductions can be greater. The Tambora eruption of 1815 led to the year without a summer (1816) in the NH.

The greatest known eruption of the past 100,000 years was the Toba eruption of about 71,000 years ago on the island of Sumatra. While the principal effects of Pinatubo lasted only about two years, it is probable that the effects of Toba may have lasted for about six years. Individual large eruptions certainly produce global or hemispheric cooling for a few years.

As Figure 8.1 shows, the Earth typically returns to normal behavior about three years after a fairly major volcanic eruption. However, Robock (2000) raised the question whether longer term climate changes could be induced or enhanced by either (a) the impact of an extremely large volcano (e.g., Toba at VEI $\sim 8$) or (b) the cumulative effect of a series of large volcanoes (VEI $> 5$ to 6) over some extended time period. Figures 4.6 and 4.7 show that after the Eemian interglacial from about 135 to 115 KYBP, there was a period from 115 to 74 KYBP of meandering Greenland temperature that tended downward, but this ~40-year period lacked the wild oscillations that followed from about 74 to 20 KYBP. Two very high amplitude oscillations occurred around 74 and 70 KYBP in which the Greenland temperature varied by about 20°C in about a millennium. These are also evident in Figures 4.16, 5.2, 5.4, and 5.5. The ice core records suggest that the two wild climatic oscillations from 74,000 to 70,000 YBP provided a pivotal turning point when the climate went from a mild phase to a full glacial world.

Could the eruption of Toba be implicated in this transition? Burroughs (2005) discussed this possibility. Toba was the greatest known volcanic eruption in the past million years. Rampino and Self (1992, 1993) presented model calculations to investigate the possible climatic effects of the cloud that lofted more than $10^{12}$ kg of material to heights of over 30 km. We actually know a good deal more about the Tambora eruption in 1816 than we do about the Toba eruption. Tambora produced about one fifth as much aerosol material as Toba, and it is estimated that this led to a decrease of about 0.7°C decrease in average Northern Hemisphere temperature. Using linear scaling they estimated that volcanic dust and aerosols from Toba may have produced a hemispheric temperature decrease of up to 3–5°C for several years, which could have "accelerated the shift to glacial conditions that was already underway, by inducing snow cover and increased sea ice extent at sensitive northern latitudes." But the effect of Tambora was amplified at high northern latitudes. Tree ring data from northern Quebec suggest that mean summer temperatures after Tambora were lowered by ~3.5°C, indicating a fivefold amplification of NH average temperature decrease. Thus, summer temperature decreases produced by Toba at high northern latitudes could have been as high as 15°C adjacent to regions already covered by snow and ice. The Toba eruption was dated by a number of investigators to be $74{,}000 \pm 3{,}000$ YBP. While the effect of an individual volcano is not long-lasting, it is conceivable that the impact of a very large volcano or series of large volcanoes could trigger a nonlinear climate response.

Robock *et al.* (2009) revisited the question of whether the Toba eruption might have contributed to the budding Ice Age 74,000 years ago. They investigated how the Toba eruption may have affected the Earth's climate by using a climate model. Robock *et al.* (2009) were not certain how much $SO_2$ was injected into the stratosphere so they parameterized this quantity as a multiple of the known amount emitted by Pinatubo, a much smaller volcano. Pinatubo released approximately 0.02 Gt of $SO_2$. Robock *et al.* (2009) considered the possibility that Toba emitted 33, 100, 300, and 900 times this amount without interactive chemistry and 300 times with interactive chemistry.

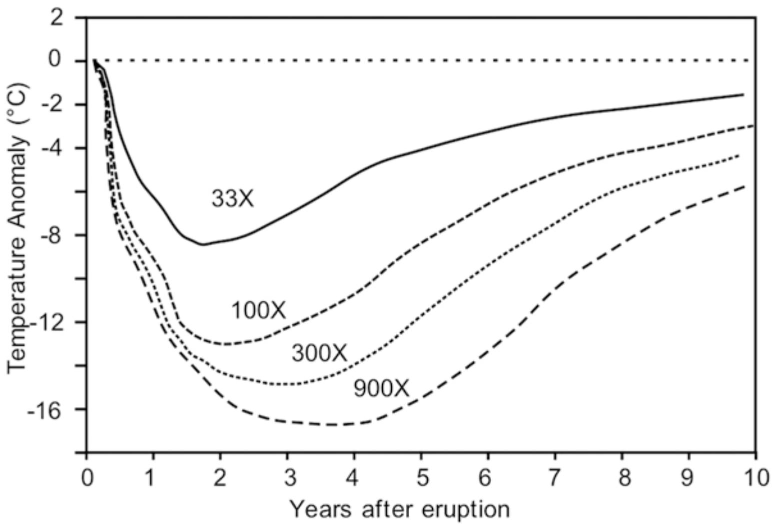


**Figure 8.2.** Global temperature change after the Toba eruption (smoothed) for various magnitudes times Pinatubo (adapted from Robock *et al.*, 2009).

Using a model that did not include full interactive atmospheric chemistry, they found that a Toba-size eruption produces a severe impact on global climate with huge amounts of global cooling (up to ~15°C for 300× Pinatubo) and reduced precipitation (up to 45% reduction). However, these effects only lasted for a limited time and diminished after about a decade (as shown in Figure 8.2). Irrespective of the amount of $SO_2$ assumed, there was no evidence for ice age initiation. Although snow persisted for several summers in the mid-latitudes of the Northern Hemisphere, it melted as aerosols left the atmosphere and full insolation returned. When they used a model with full atmospheric chemistry for 300× Pinatubo, they found a larger (~18°C temperature anomaly) and longer lasting response (more than 20 years), but still no evidence of ice age initiation. They then answered the question of whether a Toba-like eruption could produce an ice age today, and the answer was in the negative. Nevertheless, they pointed out that a "volcanic winter following a supervolcano eruption of the size of Toba today would have devastating consequences for humanity and global ecosystems."

What Robock *et al.* did not answer was whether an Earth leaning toward glaciation might have been driven toward further glaciation by an eruption of such a large volcano. As they put it:

> "Clearly, a volcanic eruption is not required to produce a glaciation, so it is obvious that if the climate system was poised to cool dramatically anyway, a slight nudge could have sped it along. With lower $CO_2$ concentrations, different solar activity, or even different vegetation patterns producing a different planetary albedo, the sensitivity of the climate system to massive radiative forcing might have been higher and maybe more prone to switch."

They indicated that further studies by them would be aimed in this direction.

Dawson (1992) provided references to a number of major volcanic eruptions of significance. In addition to Toba, he mentions four major volcanic eruptions in Mexico and Guatemala; the three Mexican eruptions had ages of 100, 65, and 35 KYBP. The age of the Guatemalan eruption was inferred to be about 84–90 KYBP. There were Antarctic eruptions between 30 and 16 KYBP. Major North Atlantic ash deposits (possibly from Iceland) have been identified with an age around 58 KYBP.

A study of sulfates in the Greenland ice cores provided data on volcanic eruptions (VEI $> 4$) over the past 9,000 years (Zielinski *et al.*, 1994). During this period, 69 major volcanic events were identified. Nevertheless, it remains unclear whether this volcanic activity had more than temporary impacts on climate.

## 8.5 GREENHOUSE GASES

It is difficult to support the proposition that changes in greenhouse gases cause ice age–interglacial cycles, because one would then have to explain why the changes in greenhouse gas concentrations occur in the first place. As discussed in Section 4.5 (see references therein), the general consensus is that changes in greenhouse gas concentrations are primarily effects (rather than causes) of climate change in regard to ice age cycles. However, it is possible that changes in greenhouse gas concentrations provide positive feedback to climate trends established from other causes. While principal attention has been addressed to $CO_2$—and, to a lesser extent, $CH_4$—water vapor is the most potent greenhouse gas and the presence of a lowered global temperature and huge ice sheets acting as cold traps would likely have lowered global atmospheric water vapor content, thus amplifying any cooling trend once started. Conversely, the exponential dependence of water vapor pressure on temperature could lead to rapid increases in water vapor content during warming trends, thus providing positive feedback to warming trends.

Clearly, changes in greenhouse gas concentrations between glacial and interglacial conditions are significant. However, it seems unlikely that these changes can be construed as innate causes of such cycles.

## 8.6 ROLE OF THE OCEANS

In many aspects of climate change, the scientific community often coalesces on a consensus view based on limited data. The thirst for accepted models seems to outrun the accumulation of data and true understanding. As a result, hypotheses tend to become rigidified into accepted explanations and acquire the weight of fact, while herd behavior induces many scientists to go along with the flow like weather vanes adapting to prevailing winds (see Section 11.1.2). Such is the case regarding the role of oceans in climate change; not that there is no role but, rather, that the actual role is more subtle than the consensus would have you believe.

### 8.6.1 Glacial–interglacial cycles: the consensus view

We begin discussion of the role of the oceans in climate change with the consensus viewpoint. This viewpoint was originated by WB in the 1980s and 1990s (see Broecker, 2002 and Alley, 2007).

Gerhard and Harrison (2001) discussed the role of the oceans in determining long-term climate change. According to them:

> "Oceans are the single greatest influence on the distribution of heat over the surface of the earth, by virtue of their volume, ferality, and the specific heat of water. The world's oceans serve as a means to absorb, transport, and release large quantities of thermal energy, and this flux exerts a major control on global climate. The Atlantic Ocean serves as an example of the phenomenon .... The oceans are effective in absorbing and transporting extremely large quantities of thermal energy (heat) and thereby exerting a major control on global climatic patterns."[1]

Ocean currents now form large gyres in each of the world oceans. These gyres move equatorial waters to the poles. Although glaciation requires cold temperatures that permit ice and snow to remain over summer seasons, it also requires massive moisture in order to provide the snow and ice necessary for maintenance of such conditions. Some authors claimed that the flow of atmospheric moisture to polar regions is enhanced by the oceanic circulation system that brings enough warm moist air to the polar region to generate Northern Hemisphere snowfall.[2] A continental landmass at one polar position might be a necessary condition for establishment of continental glaciation and icehouse conditions.

In the consensus view, the world's thermohaline circulation system is claimed to be driven by density contrasts that result from temperature and salinity differences. The pole-to-pole deepwater component of today's thermohaline circulation pattern is possible because of the current locations of continental landmasses.[3] If the positions of the landmasses change, as is known to have occurred in the geologic past, it is logical that thermohaline-controlled heat flux will be

[1] Actually, as Figure 8.5 shows, the atmosphere transports a great deal more heat than the oceans, particularly at higher latitudes. Thus, the claim that "Oceans are the single greatest influence on the distribution of heat over the surface of the earth" is simply wrong.

[2] However, according to C. Wunsch (pers. commun., December 2008), "the ocean circulation does not provide warm moist air—the atmosphere does."

[3] However, according to C. Wunsch (pers. commun., December 2008), "The sinking of high latitude water does *not* sustain the Gulf Stream. The Stream is a wind-driven feature and a result of the torque exerted on the ocean by the wind. It would exist even in a constant density fluid with zero convection."

different. This heat flux will result in changes in weather patterns and climatic conditions.

The consensus view of the role of the oceans in controlling and contributing to climate change was discussed at length by Rahmstorf (2002). As a result of their heat capacity and circulation, the oceans store and redistribute large amounts of heat before releasing it to the atmosphere (via latent heat in the form of water vapor) or radiating it back into space. The northern North Atlantic, the Ross Sea, and the Weddell Sea were identified as key areas for the thermohaline circulation of the world oceans in which surface waters reach a critical density and sink after releasing heat to the atmosphere.

In addition to their heat storage and transport effects, the oceans influence the Earth's heat budget through sea ice cover, which alters planetary albedo. Sea ice also acts as an effective thermal blanket, insulating the ocean from the overlying atmosphere. According to Rahmstorf (2002):

> "This is so effective that in a typical ice-covered sea more than half of the air–sea heat exchange occurs through patches of open water (leads) that make up around 10% of the surface area."

The oceans also affect the climate system by participating in biogeochemical cycles and exchanging gases with the atmosphere, thus influencing its greenhouse gas content:

> "The oceans contain about fifty times more carbon than the atmosphere, and theories seeking to explain the lower concentrations of atmospheric carbon dioxide that prevailed during glacial times invariably invoke changes in the oceanic carbon sink, either through physical or biological mechanisms (the so-called 'biological pump')."

Rahmstorf (2002) focused on the role of ocean circulation changes in major climate changes during the past 120,000 years, since the Eemian interglacial. However, he perhaps over-modestly cautioned that "controversies remain over many issues, and the interpretation I have attempted here is subjective and will probably turn out to be partly wrong."

Rahmstorf (2002) described ocean circulation (see Figure 8.3). He suggested that three distinct circulation modes prevailed in the Atlantic Ocean at different times, depending on the mode of formation of North Atlantic Deep Water (NADW). These are labeled as the interstadial (warm), stadial (cold), and Heinrich (off) modes. They are illustrated schematically in Figure 8.4. In the interstadial mode, near-surface ocean currents persist up to higher latitudes and, as they cool and their salinity increases, NADW is formed in the Nordic seas and drops to great depths for return to the south. In the stadial mode, NADW is formed in the subpolar open North Atlantic (i.e., south of Iceland) and does not achieve the density of the interstadial mode, so the return flow is not as deep. In the Heinrich mode, NADW formation all but ceases and waters of Antarctic

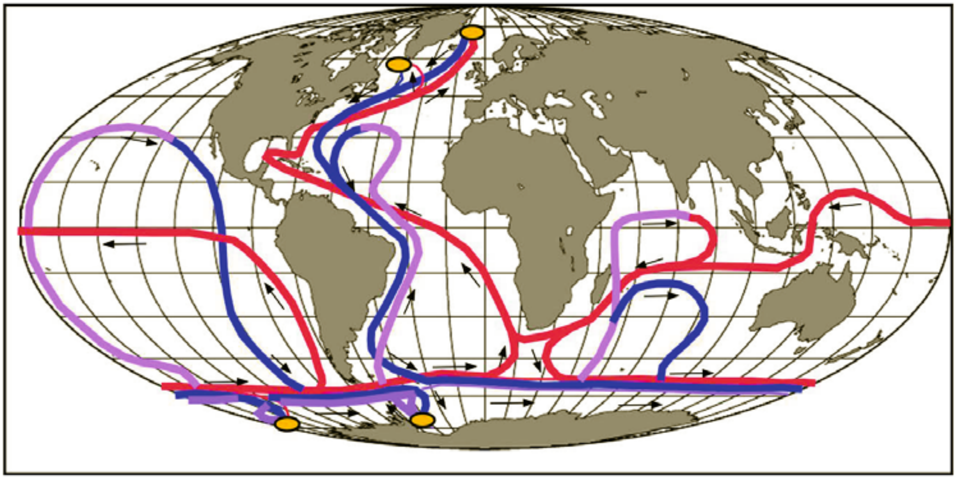

**Figure 8.3.** Near-surface waters (red lines) flow towards four main deepwater formation regions (yellow ovals)—in the northern North Atlantic, the Ross Sea, and the Weddell Sea—and recirculate at depth (deep currents shown in blue, bottom currents in purple) (#Rahmstorf, 2002#).[4]

origin fill the deep Atlantic basin. While these groupings are somewhat arbitrary and not necessarily discontinuous, they describe the essential range of variability of NADW. There is also firm evidence for links between these changes in ocean circulation and changes in surface climate.

Rahmstorf (2002) was concerned with the onset of the most recent ice age, which began about 115,000 years ago based on Greenland data (see Figure 4.7), about 135,000 years ago based on Antarctica data (see Figure 4.9), and at varying times according to ocean sediment data (see Figures 5.4 and 5.5). As Figure 9.8 shows, there was a steep minimum in solar input around 115,000 YBP, although it quickly increased after that. Rahmstorf quoted Paillard's model as evidence. This model is described in Section 9.6.1, but it appears to contain several flaws. Rahmstorf then raised the question: "Does a weakening in Atlantic Ocean circulation have a role in glacial inception?" He partly answered his own question by saying: "there are no palaeoclimatic data showing that NADW formation slowed at this time." He claimed that model simulations achieve glacial inception with only minor changes in ocean circulation. However, the validity of such models is difficult to confirm. Rahmstorf also criticized the reverse theory—that a warm North Atlantic could have induced ice sheet growth by enhanced moisture supply—saying that this "goes against our knowledge of glacier mass balance: glaciers grow when climate is cold, not warm and moist." Actually, that is not

[4] According to Carl Wunsch, Figure 8.2 is a "memorable graphic". However, he argues that it provides some misleading inferences, but it is so visually appealing that his students tend to remember the graphic—not his objections to it (pers. commun. from C. Wunsch, December 2008).

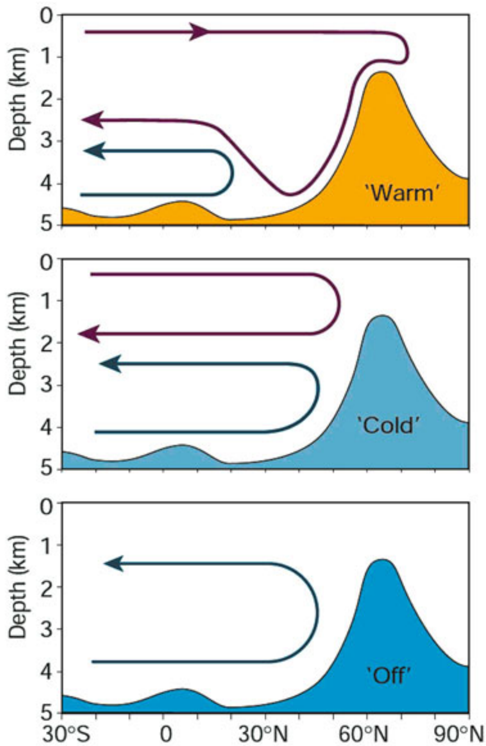


**Figure 8.4.** Schematic of the three modes of ocean circulation that prevailed during different times of the last glacial period. A section along the Atlantic is shown. The rise in bottom topography symbolizes the shallow sill between Greenland and Scotland. North Atlantic overturning is shown by the solid line, and Antarctic bottom water by the dashed line (Rahmstorf, 2002).

necessarily true. Glaciers grow when the rate of precipitation exceeds the rate of evaporation and sublimation. An ample source of moisture must be an ingredient of glacier formation.

Bischof (2000) has suggested that an alternative to the astronomical theory of solar-driven ice ages

> "... can be achieved by physically moving excessive amounts of ice from the polar regions to lower latitudes. If, for example, the air pressure distribution over the Arctic Ocean were such that winds blew from the Bering Strait across the Pole towards Fram Strait, then massive amounts of pack ice would be moved into the Norwegian Greenland Sea and push the polar front southward. In the winter, this process would continuously produce additional sea ice in the open leads created by the offshore winds in the Bering Strait region, setting in motion a veritable 'ice machine'. The regional extent of ice and snow cover in the Norwegian Greenland Sea would increase, cooling the region, and the high

albedo would reflect more of the incoming solar radiation, further amplifying the cooling. Depending on the strength and duration, this process could lead to an episode of relatively cold climate over the North Atlantic region, perhaps lasting from a few years up to decades. But if it were sufficiently strong and durable, it could set the stage for the global climate to return to full glacial conditions.''

### 8.6.2 Sudden climate change: the consensus view

In Section 4.6 we showed that the Earth's climate is subject to rapid extreme climate change, particularly during glacial periods. In the aftermath of a glacial period, when the great ice sheets are breaking up, abrupt climate changes also take place. In addition, there is some evidence that rapid climate changes may have occurred during the previous (Eemian) interglacial period. Many studies have focused on these rapid gyrations in the Earth's climate, and the literature in this field is extensive. Two important review articles provide overviews of this work (Adams *et al*., 1999; Alley, 2007). This section relies heavily on these articles and the classic book by Broecker (2002).

Two impressive aspects of abrupt climate change are (1) they can occur in short time periods (centuries to decades) and (2) the changes in temperature can be a significant fraction of the long-term secular change in temperature observed in the ~70,000-year evolution of an ice age. The impact of such violent climate changes on primitive humans was undoubtedly significant.

Various mechanisms—involving changes in ocean circulation and biotic productivity, changes in atmospheric concentrations of greenhouse gases and haze particles, and changes in snow and ice cover—have been proposed to explain sudden climate change. Some changes such as the Younger Dryas and Heinrich events might only occur during glacial periods when large ice sheets and more extensive sea ice cover are prevalent.

Adams *et al*. (1999) discussed several sources of evidence that significant rapid climate changes occurred during the previous (Eemian) interglacial period. They concluded:

> ''The combined sources of evidence suggest that there was a cold and dry event near the middle of the Eemian, at about 122 KYBP, which was characterized by a change in circulation of the North Atlantic, a several-degree decline in the Nordic seas and Atlantic sea-surface temperatures, and an opening up of the west European forests to a mixture of steppe and trees.''

As the most recent ice age settled in over the past ~100,000 years, numerous sudden climate changes took place (as shown in Figure 4.26 and discussed in Section 4.6).

In the mid-1980s, Wally Broecker developed a concept that the Earth's climate may have two or more stable modes and may shift almost discontinuously between them. Broecker (2002) emphasized that the concentrations of continental dust and sea salt in Greenland ice were more than an order of magnitude higher during the coldest parts of the last glacial period than during the Holocene. Dust and sea salt also underwent abrupt threefold jumps during Dansgaard–Oeschger cycles. Thus, it is clear that the atmosphere was far dustier and salt laden during glacial times. The high sea salt content in glacial ice from both Antarctica and Greenland points to storminess as the key cause. Broecker (2002) also emphasized the suddenness of climate changes that may have taken place in less than a decade. He eliminated changes in glacial extent, sea level, and atmospheric $CO_2$ content as candidates because they are incapable of such rapid climate changes. While water vapor, snow cover, and cloudiness can change with sufficient rapidity, he argued that they do not seem to have the required property of being able to be turned on and off. Only the ocean's thermohaline circulation appears to fulfill the requirements. Broecker also emphasized that each of the major glacial periods over the last million years ended abruptly. The climate typically switched from full glacial to full interglacial in fewer than 5,000 years.

According to Adams *et al.* (1999), the circulation of the North Atlantic Ocean probably plays a major role in either triggering or amplifying rapid climate changes in the historical and recent geological record. The North Atlantic has a peculiar circulation pattern: the northeast-trending Gulf Stream carries warm and relatively salty surface water from the Gulf of Mexico up to the seas between Greenland, Iceland, and Norway. Upon reaching these regions, the surface waters cool and (with the combination of becoming cooler and relatively saltier) become dense enough to sink into the deep ocean. The pull exerted by this dense sinking water is thought to help maintain the strength of the warm Gulf Stream, ensuring a current of warm tropical water into the North Atlantic that sends mild air masses across to the European continent. If the sinking process in the North Atlantic were to diminish or cease, sea ice would form more readily in the North Atlantic. This would reinforce a much colder regional climate:

> "The trigger for a sudden 'switching off' or a strong decrease in deep water formation in the North Atlantic must be found in a decrease in density of surface waters in the areas of sinking in the northern Atlantic Ocean. Such a decrease in density would result from changes in salinity (addition of fresh water from rivers, precipitation, or melt water), and/or increased temperatures .... During glacial phases, the trigger for a shut-off or a decrease in deep water formation could be the sudden emptying into the northern seas of a lake formed along the edge of a large ice sheet on land (for instance, the very large ice-dammed lake that existed in western Siberia), or a diversion of a melt-water stream from the North American Laurentide ice sheet through the Gulf of St. Lawrence, as seems to have occurred as part of the trigger for the Younger Dryas cold. A pulse of fresh water would dilute the dense, salty Gulf Stream and float on top, forming a temporary lid that stopped the sinking of water that helps drive the Gulf Stream. The Gulf Stream could weaken and its northern end could switch off altogether, breaking the 'conveyer belt' and allowing an extensive sea ice cap to form across the North Atlantic, preventing the ocean current from starting up again at its previous strength. Theoretically, the whole process could occur very rapidly, in

the space of just a few decades or even several years. The result could be a very sudden climate change to colder conditions, as has happened many times in the area around the North Atlantic during the last 100,000 years.

The sudden switch could also occur in the opposite direction, for example if warmer summers caused the sea ice to melt back to a critical point where the sea ice lid vanished and the Gulf Stream was able to start up again. Indeed, following an initial cooling event the evaporation of water vapor in the tropical Atlantic could result in an 'oscillator' whereby the salinity of Atlantic Ocean surface water (unable to sink into the north Atlantic because of the lid of sea ice) built up to a point where strong sinking began to occur anyway at the edges of the sea ice zone. The onset of sinking could result in a renewed northward flux of warm water and air to the north Atlantic, giving a sudden switch to warmer climates, as is observed many times within the record of the last 130,000 years or so."

The process of switching off or greatly diminishing the flow of the Gulf Stream would not affect Europe alone. Antarctica would be even colder than it is now, because much of the heat that it receives now ultimately comes from Gulf Stream water that sinks in the North Atlantic, travels down the western side of the deep Atlantic Basin, and then partially resurfaces just off the bays of the Antarctic coastline.

The role of ocean circulation and variations in salinity as a cause for the sudden changes in glaciation has been discussed by many authors (e.g., Lehman and Keigwin, 1992; Schmidt *et al.*, 2006; Fleitmann *et al.*, 2008).

Dokken and Jansen (1999) analyzed the sudden climate changes over the past 60,000 years based on ice core and ocean sediment data. They assumed that Pacific sediment data reflected global mean glacial–interglacial transitions while high-resolution sediment data from the Nordic seas represented regional variations in that area superimposed on global trends. By subtracting the Pacific trends they obtained residual differences between the deep Nordic seas and the deep global ocean. These residual differences in $\delta^{18}O$ were so large that very large temperature changes in the deep ocean would be needed to explain these isotope shifts if temperature changes were the cause. They asserted that such large temperature changes were impossible, so they concluded that the cause must have been the vertical transport of $^{18}O$-depleted waters from the surface to the deep. This ran counter to the usual theory that convective vertical transport is impeded during glacial periods due to the buoyancy of meltwater, and so another mechanism was required. They suggested it was due to the higher density of brine as a result of increased salinity as great masses of sea ice formed.

Thus, Dokken and Jansen (1999) concluded:

"Deep water was generated more or less continuously in the Nordic Seas during the latter part of the last glacial period (60 to 10 thousand years ago), but by two different mechanisms. The deep-water formation occurred by convection in the open ocean during warmer periods (interstadials). But during colder phases (stadials), a freshening of the surface ocean reduced or stopped open-ocean convection, and deep-water formation was instead driven by brine-release during sea-ice freezing. These shifting magnitudes and modes nested within the overall continuity of deep-water formation were probably important for the structuring and rapidity of the prevailing climate changes.

We conclude that common to all stadial–interstadial cycles (D–O and Heinrich-events) is a shift in the mode of overturning in the Nordic Seas, with normal deep-water formation (similar to the modern form, although less vigorous) in the warmer phases of the glacial, interrupted by a shift to deep-water formation dominated by brine-release during the cold phases with meltwater injection.''

These dramatic climate changes observed in the North Atlantic are heavily muted or absent in Antarctica. For example, Figure 4.15 shows no evidence of the Younger Dryas in the Antarctic ice core.

$CO_2$ variability does not appear to be involved as a cause of rapid climate change because changes in $CO_2$ concentration occur too slowly.

Adams *et al.* (1999) pointed out that another potential factor in rapid regional or global climate change may be shifts in the albedo of the land surface that result from changes in vegetation or algal cover on desert and polar desert surfaces. Increased dust levels occur during cold periods, but it is unclear whether this is a cause or an effect.

### 8.6.3 Wunsch's objections

The field of climatology seems to be permeated by studies that draw a dollar's worth of conclusions from a penny's worth of data. While there is nothing fundamentally wrong with conjecturing what might be, there is an unfortunate tendency for such contemplations to become hardened in the annals of climatology as fact. This can (and does) happen in other fields as well.[5] Carl Wunsch of MIT has pointed out the frailty of some of these conjectural arguments in several instances. For example, in Sections 3.2.10, 4.3, 5.2, and 6.1.4 we referred to his criticism of the way in which curves are compared visually, in which he concluded: ''*Sometimes there is no alternative to uncertainty except to await the arrival of more and better data*'' (emphasis added). This writer strongly endorses this viewpoint.

[5] I am reminded of an event that occurred in the 1970s. At that time, there was some controversy regarding the altitude at which the Earth's ionosphere transitioned from mainly $O^+$ to $H^+$. This was dependent on the rate of the reaction $O^+ + H \Rightarrow O + H^+$. On the first day of a national meeting, a leading expert, Alec Dalgarno, made a presentation on this topic. At the end of his talk, someone asked him what the rate of the charge exchange reaction was. He said he didn't know. They pressed him to make a guess. So, he guessed. Three days later at the meeting wrap-up, Dalgarno was asked to present a summary. In doing this, he used the aforesaid reaction rate. Someone asked him where he obtained that figure. He replied: ''I don't know. Someone provided it on the first day of the meeting!''

Wunsch (2003) claimed that there is little concrete evidence that abrupt climate changes recorded in the Greenland ice cores are more than a regional Greenland phenomenon. He suggested that D-O events are a consequence of interactions of the wind field with continental ice sheets and that better understanding of the wind field in glacial periods is needed. He emphasized that wind fields are capable of great volatility and very rapid global-scale teleconnections, and they are efficient generators of oceanic circulation changes and (more speculatively) of multiple states relative to great ice sheets.

Huber *et al.* (2004) provided a response to Wunsch's criticism in a short note. Wunsch had said: "A serious question concerns the extent to which the Greenland cores reflect tracer concentration change without corresponding abrupt climate change. The large, abrupt shifts in ice $\delta^{18}O$ can be rationalized as owing to wind trajectory shifts, perhaps of rather modest size." Huber *et al.* (2004) argued: "this hypothesis is no longer tenable in light of new data on the nitrogen and argon isotopic composition of gases trapped in the Greenland ice cores." These data indicate that abrupt $\delta^{18}O$ shifts are accompanied by gas isotope anomalies, and the magnitudes of these anomalies demonstrate that warmings and coolings were large, typically greater than 10°C. In addition, abrupt shifts in atmospheric methane concentration were observed to occur at the same time as the Greenland temperature shifts. Such changes are presumed to indicate worldwide climate changes as long as $CH_4$ sources are widely dispersed. Huber *et al.* (2004) therefore concluded that the abrupt climate shifts in Greenland were not merely local phenomena because methane sources are widely distributed over the globe. However, the argument that warmings and coolings were large does not preclude them from being local or regional. The connection to methane was rebutted by Wunsch (see discussion in the following paragraphs).

Wunsch (2006) published a later paper in which he pointed out that there is a very large literature on the interpretation of abrupt climate shifts, which depends on several assumptions, assertions, and inferences including

(1) The $\delta^{18}O$ variations appearing in the Greenland ice core records are a proxy for local temperature changes. (*Wunsch*: "in part true.")
(2) Fluctuations appearing in the Greenland ice core data reflect climate changes on a hemispheric and, probably, global basis. (*Wunsch*: "little evidence exists other than a plausibility argument.")
(3) The cause of the sudden (e.g., D-O) events can be traced back to major changes (extending to shutdown) of the North Atlantic meridional overturning circulation (MOC) and perhaps even failure of the Gulf Stream. (*Wunsch*: "unlikely to be correct.")
(4) Apparent detection of a D-O event signature at a remote location in a proxy implies its local climatic importance. (*Wunsch paraphrase*: the issue is complicated.)

Regarding whether Greenland ice core records are a proxy for local temperature changes, Wunsch (2006) concluded that the relation of $\delta^{18}O$

variations to temperature is strong, but apparently not as simple as is usually portrayed (e.g., see Chapter 3 of this book).

The issue regarding the global implications of fluctuations appearing in the Greenland ice core data partly comes down to the degree to which the patterns observed at Greenland are also observed at other sites around the world. In this connection, Wunsch raised a theme that he has presented previously, namely "the major problem in tuning or wiggle-matching is that of 'false-positives'—the visual similarity between records that are in truth unrelated." He presented several examples of time series that appear to the human eye to be related but, when a proper statistical analysis is made of the underlying data, there is no statistical confirmation of a relationship.

As we observed in Section 4.3, there appears to be a causal relationship between temperature patterns at Antarctica and Greenland. The data in Figure 4.16 suggest that each sudden increase in temperature at Greenland was preceded by a rather slow moderate temperature rise in Antarctica for a few thousand years. However, this provides no information on how these temperature changes at Greenland influenced the global climate.

Wunsch (2006) asserted that there is little direct support for the hypothesis that abrupt changes in Greenland also appear in other distant records. However, he did admit that some D-O events correlate with changes in global methane concentration:

> "Glacial-period methane sources are supposedly controlled largely by tropical wetlands, and to the extent that those regions are showing strong correlation with D–O events in Greenland, one infers that there is at least a hemispheric reach. There are two issues here: (1) Whether methane sources (and sinks) are definitively tropical, and, (2) the actual correlation in Greenland of methane and $\delta^{18}$O."

Regarding the first point, Wunsch quoted studies that claim that most modern wetlands occur at high latitudes and most were at low latitudes during the Last Glacial Maximum. How wetlands would have behaved during regional warm events lasting $\sim$1,000 years is not clear, and wetlands, though dominant, are not the only source of methane. Regarding the second point, Wunsch said:

> "Some of the D–O events are indeed correlated with methane emissions, but the evidence that it results from a strong, remote, tropical response remains unquantified. Nonetheless, the methane $\delta^{18}$O correlation is the strongest evidence that the D–O events reach to low latitudes, albeit the inference depends upon the scanty knowledge of the methane sources and sinks during these times."

He concluded that the putative large scale of D-O events is "possible but not demonstrated".

Wunsch (2006) provided some counterarguments to the widespread belief that the cause of the sudden (e.g., D-O) events can be traced back to major changes

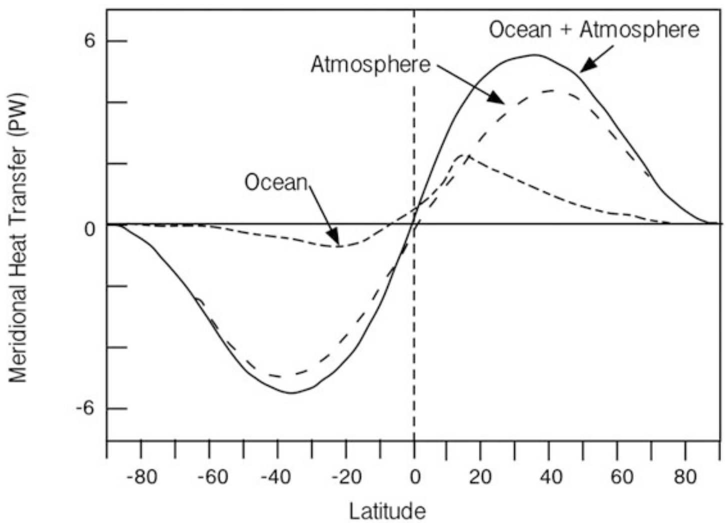


**Figure 8.5.** Total meridional heat flux of the combined ocean–atmosphere system estimated from Earth Radiation Budget Experiment (ERBE) satellites, direct ocean measurements, and atmospheric contribution as a residual (1 PW = $10^{15}$ watts) (Wunsch, 2005, 2006).

(extending to shutdown) of the North Atlantic MOC and perhaps even failure of the Gulf Stream. Wunsch emphasized that generally one must distinguish between climate phenomena whose (a) trigger regions, (b) foci of strongest signal, and (c) regions where a signal is detectable may each be radically different. Regarding the trigger, he presented Figure 8.5 showing the contributions made by the atmosphere and the oceans to meridional heat flux toward the poles. Contrary to widely held perceptions, the oceans only deliver a modest fraction of the heat flux to high northern latitudes and heat transport by the atmosphere outweighs that by the oceans 7:1 at the 50°N latitude.

The assumption that the prime mover of abrupt climate change is fractional change in the comparatively minor contribution of ocean currents to global heat flux may not hold up under this scrutiny. Wunsch (2006) discussed how atmospheric heat transport might be affected if there were a shutdown of the oceanic heat flux and suggested that it could produce "a warmer (and/or wetter) Northern Hemisphere atmosphere rather than a colder one." The disparity between oceanic and atmospheric poleward heat fluxes is enough to raise doubts that the MOC is the major source of abrupt climate change. But Wunsch amplified this argument by questioning how such overturning might occur. Inevitably, the theory requires an injection of fresh water, probably from a strong decrease in surface salinity from melting glacial ice. Wunsch provided several reasons to doubt this hypothesis and finally suggested that the most effective way to change ocean circulation is via a change in wind fields.

On the other hand, as Wunsch (2005) said:

> "It may well be that the ocean is carrying as little as 10% of the net poleward heat transport at the mid-latitudes. But 10% of 5 PW is 0.5 PW whose redistribution or change would correspond to a large climate shift. The area of the Earth's surface poleward of 40° is $5.6 \times 10^{13}\ \mathrm{m}^2$. A shift in the oceanic heat transport, removing 0.5 PW, would correspond to an atmospheric radiative forcing change of about $9\ \mathrm{W/m}^2$, larger than what is expected from doubled atmospheric $CO_2$."

Thus, the fact that the oceans carry a comparatively small *percentage* of the total heat flux does not imply that this is not a large *absolute* quantity. Furthermore, the reason that the atmosphere carries such a high heat flux is because it transports water vapor that provides the high heat needed by condensation for it to precipitate. However, the oceans provide a supply of water vapor and, therefore, as Wunsch (2005) said: "... much of the heat flux commonly assigned to the atmosphere is actually in a combined mode of both systems."

Wunsch (2006) emphasized the difference between the placid Holocene and the violently variable period that preceded it. The main difference between the two eras was the presence of gigantic ice sheets in the earlier period. He therefore suggested that it was the disappearance of the Laurentide and Fennoscandian ice sheets that brought the era of D-O events to an end. During the glacial period, changes in the wind field were suggested as the prime mover in abrupt climate change.

The most recent paper on abrupt climate change is the very long review written by Alley (2007). In some respects this is a polemic in favor of the widespread belief that the cause of the sudden (e.g., D-O) events can be traced back to major changes (extending to shutdown) of the North Atlantic MOC and perhaps even failure of the Gulf Stream (as previously mentioned). In other respects it is a tribute to Wally Broecker, who championed this concept in the mid-1980s.

Alley (2007) mentioned that:

> "... scientific skeptics do still remain (most notably Wunsch), providing important impetus for additional research, but Broecker's North Atlantic/conveyor paradigm has gained widespread acceptance. For example, the Broecker papers listed above have been cited more than 2000 times as indexed by ISI, and a brief perusal indicates that at least most of those citations are in general agreement."

But good science is not a matter of voting, and there are many examples of scientific beliefs that are widely accepted (e.g., the so-called "hockey stick" model of Earth temperatures over the past 2,000 years) that are clearly wrong (Rapp, 2008). Amazingly, despite the length of Alley's article (34 pages and many references) he did not respond directly to some of Wunsch's major points, nor does "ERBE" appear in his document. While it is true that Wally Broecker is a giant amongst paleoclimatologists, Alley's unbounded reverence for WB may possibly have affected his objectivity.

Alley (2007) asserted at the beginning of his review:

> "Abrupt climate changes happened, their large geographical extent is confirmed by Greenland ice-core data and by geographically widespread records, the pattern closely matches that modeled for North Atlantic causes, and models and data agree on the involvement of the meridional overturning circulation (MOC)."

Alley (2007) emphasized "of particular importance are the Greenland records of methane ($CH_4$)" citing his Supplemental Figure 1. However, this figure merely shows limited data for two short time periods from 7 to 9 KYBP and from 10 to 16 KYBP. In both time periods, the comparison between variable $CH_4$ concentration and $\Delta T$ shows some similarity but is far from convincing to this writer. Like beauty, perhaps comparison lies in the eye of the beholder. Figure 8.6 shows a comparison of Greenland temperatures with $CH_4$ concentrations measured at Vostok, Antarctica over 100,000 years. While there is some similarity, it can hardly be construed as proof of worldwide climate variations in sync with Greenland temperature variability.

Alley (2007) asserted that $CH_4$ is globally mixed, with widely distributed sources and no dominant localized sources. Changes in the atmospheric concentration of methane of up to 50% require involvement of gas sources across large regions of the globe. Even Wunsch admitted that this was a point in favor of the global character of the abrupt climate changes observed in Greenland. Alley (2007) provided extensive further discussion that is beyond the scope of this book. Nevertheless, the claim made by Alley (2007): "Greenland ice-core data show the existence of abrupt climate changes *affecting broad regions, has been confirmed very strongly*" (emphasis added) seems perhaps too emphatic for the foundation it rests upon. Alley (2007) may well be right, but a little less certainty in his conclusions would be welcome.

Regardless of whether one accepts the consensus view or Wunsch's view of the role of ocean circulation in climate change, Wunsch (pers. commun., December, 2008) asserts that the role of ocean circulation in glacial–interglacial cycles is unknown since there are essentially no data on past circulation rates.

## 8.7 MODELS BASED ON CLOUDS

Cloud cover is an important factor that controls the way radiation is absorbed and reflected by the Earth. Increases in cloudiness enhance global albedo thus cooling the surface, but increased cloudiness also traps thermal radiation leading to warming. Overall, the cooling effect is believed to be dominant, but this is a function of cloud height and type with thin high clouds causing net warming. Any factor tending to modify cloud cover will thus have an impact on climate so that it

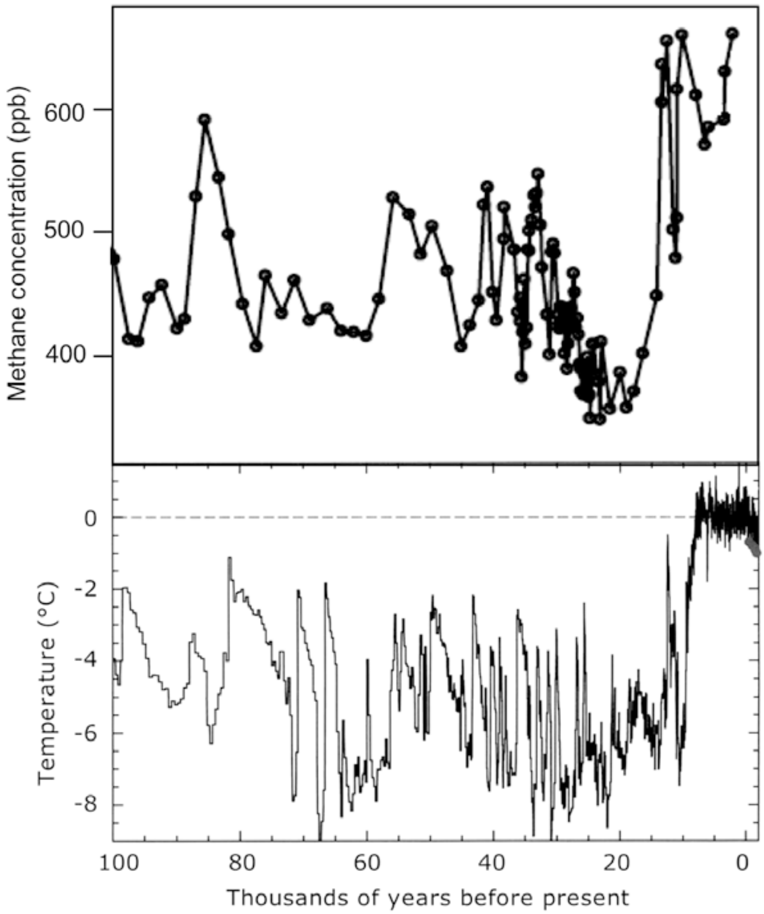


**Figure 8.6.** Comparison of the Greenland temperature profile (from Figure 4.6) with the methane profile at Vostok, Antarctica (Petit *et al.*, 1999).

is important to understand natural variability in cloud climate forcing (Kernthaler *et al.*, 1999).

Cloud cover has a strong effect on the Earth's climate by reflecting incident sunlight and absorbing outgoing IR emitted by the Earth. With an average solar input to Earth of 342 W/m$^2$, even a change of only 1% in the Earth's average albedo generates a climate forcing of 3.4 W/m$^2$. The effect is even greater in the equatorial zone. Cloud formation provides a strong positive feedback mechanism that can amplify other climatological variations that change the distribution of clouds. However, the effects of clouds are complex. Some clouds predominantly reflect incident sunlight, causing cooling. Other clouds predominantly absorb and re-emit IR radiation and, thereby, produce a heating effect. M&M provided the summary given in Table 8.1, based on estimates from the Earth Radiation Budget Experiment (ERBE).

**Table 8.1.** Heating and cooling effects of clouds.

| *Parameter* | *High clouds* | | *Middle clouds* | | *All low clouds* | *Total* |
|---|---|---|---|---|---|---|
| | *Thin* | *Thick* | *Thin* | *Thick* | | |
| Global fraction (%) | 10.1 | 8.6 | 10.7 | 7.3 | 26.6 | 63 |
| *Forcing relative to clear sky* (W/m$^2$) | | | | | | |
| Albedo (visible) | −4.1 | −15.6 | −3.7 | −9.9 | −20.2 | −53.5 |
| Outgoing IR | +6.5 | +8.6 | +4.8 | +2.4 | +3.5 | +25.8 |
| Net forcing | +2.4 | −7.0 | +1.1 | −7.5 | −16.7 | −27.7 |

The overall effect of cloudiness is production of a net cooling effect. As M&M pointed out, even if these values are only approximate, they show that changes in cloud cover can affect climate significantly.

If there are forces acting on the Earth that produce quasi-periodic changes in cloud cover, these forces could produce periods of glaciation interspersed by deglaciation periods. Three such models are discussed briefly in the following sections. One model has to do with interplanetary dust affecting stratospheric conductivity and, thereby, affecting cloud formation via a complex process. Another is based on quasi-periodic changes in cosmic ray penetration of the Earth's atmosphere affecting cloud formation. A third model is based on time lags in the interaction between the ocean and the atmosphere, leading to quasi-periodic changes in cloud cover. None of these models are very convincing to this writer, but as M&M said: "The atmosphere, especially the upper atmosphere, is not a well understood system, so even the craziest ideas may prove to be right—and maybe even important."

### 8.7.1 Extraterrestrial dust accretion

M&M provided an extensive discussion of interplanetary dust centered on the ecliptic plane of planets' orbits. This dust is probably the result of collisions between asteroids. The main bulk of the dust lies within ±5° of the ecliptic but can reach ±15° from the ecliptic plane. The distribution of dust around the Earth is highly non-uniform. As the Earth traverses through space, its orbital parameters vary, the tilt of the Earth's orbital plane wobbles relative to the ecliptic, and the Earth intercepts varying amounts of this interplanetary dust. Calculation of this variability is complex. M&M claim that it follows a cycle with a period of 100,000 years. Dust particles that impinge on the Earth's atmosphere tend to vaporize and recondense as very tiny particles called "smoke."

M&M estimated the reduction in solar intensity reaching the Earth due to reflection from high-altitude dust. They found that the density levels were too low to produce any significant variation in solar intensity reaching the Earth, so changes in solar intensity due to variable dust cannot directly account for glacial–interglacial cycles.

There is a theory that smoke particles affect stratospheric conductivity and, by means of processes somewhat obscure to this writer, affect cloud formation above the Earth. This, in turn, affects the Earth's climate. M&M seem to be enthusiastic about this model. Variability of the inclination of the Earth's orbital plane modulates the accretion of interplanetary dust. The dust, in turn, is claimed to affect climate through its effect on cloud cover and ozone.

### 8.7.2 Clouds induced by cosmic rays

Benestad (2005) provides an extended discussion of a theory that cosmic rays, controlled by the Sun's magnetic field, produce changes in cloud formation which affect the Earth's climate. He provides many references. Only a brief report is given here.

The theory postulates that, as variations in solar activity take place, the solar wind changes, and the solar wind controls the number of galactic cosmic rays from deep space that enter our solar system and penetrate the Earth's atmosphere. The solar wind thus acts like the control grid on an old-fashioned triode vacuum tube where cosmic rays provide the "current to the anode". The theory then claims that cosmic rays enhance cloud formation by producing charged atmospheric aerosols that act as nuclei for cloud formation. Thus, according to this model, an increased flux of cosmic rays due to lower solar activity produces a cooling effect on the Earth. So, it is claimed that the putative correlation of solar activity with climate is an indicator of solar wind effects that in turn affect cosmic ray penetration, which affects cloud formation, which in turn produces cooling. Several versions of this concept have been proposed.

Patterson (2007) asserted all of this as if it were self-evident and a proven fact.

Svensmark and Friis-Christensen (1997) compared the variation in low- to mid-latitude total cloudiness between 1984 and 1990 with cosmic ray flux (which is inversely dependent on solar activity). During the period of minimum solar activity in 1986 total cloudiness was 3–4% higher than near solar maximum in 1990. From this they suggested that cosmic rays might enhance cloudiness possibly through a mechanism involving an increase in atmospheric ionization and formation of cloud condensation nuclei. Such an increase in cloudiness would produce a cooling effect. Over a sunspot cycle, the authors found cosmic rays varied by 15–20% and this correlated strongly with a 3% (absolute) variation in cloud cover over that same period. Since total cloud cover is about 63% (see Table 8.1), this is about a 5% relative change in cloud cover. A 5% relative change in cloud cover would result in a variation in the radiation budget equivalent to about 1 W/m$^2$ (M&M).

Kernthaler *et al.* (1999) disputed the results of Svensmark and Friis-Christensen (1997) on the grounds that the correlation between cosmic rays and cloudiness is weakened if higher latitude data are included. A greater concern, however, is that the short period involved in the study is statistically inadequate to draw firm conclusions.

Svensmark (2000) extended previous work. He showed that the production of radiocarbon-14 in the Earth's atmosphere was inversely related to the pattern of Earth temperature over the past 1,000 years, with low production of $^{14}C$ during the MWP and high production during the LIA. The production of $^{14}C$ decreased sharply in the 20th century along with global warming. All of this is compatible with Figures 11.10 and 11.11. Svensmark said:

> "In 1900 the cosmic rays were generally more intense than now and most of the warming during the 20th Century can be explained by a reduction in low cloud cover. Going back to 1700 and the even higher intensities of cosmic rays, the world must have seemed quite gloomy as well as chilly, with all the extra low-level clouds."

Lockwood and Fröhlich (2007) published a rebuttal to Svensmark's theory. They admitted that over the 20th century the trend in $^{10}Be$ has been downward and the temperature trend upward, which supports Svensmark's theory. However, they claimed:

> "Over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures."

Svensmark and Friis-Christensen (2007) responded to Lockwood and Fröhlich (2007) by pointing out that the use of running means of global temperature data over about 10 years obfuscated the fact that temperatures stopped rising after 1998. In addition, discrepancies between tropospheric temperature trends and surface temperature trends led to different conclusions on temperature variations over the past few decades. Using tropospheric temperatures without averaging and allowing for the effects of El Niños and volcanic eruptions, Svensmark and Friis-Christensen (2007) found a good anti-correlation between cosmic ray levels and global temperatures over the past few decades. It is also noteworthy that the bias of observers toward (or against) the alarmist position on global warming produced by $CO_2$ may have crept into the arguments. Lockwood and Fröhlich (2007) proclaimed the alarmist position with apparent satisfaction:

> "Our results show that the observed rapid rise in global mean temperatures seen after 1985 cannot be ascribed to solar variability, whichever of the mechanisms is invoked and no matter how much the solar variation is amplified."

Svensmark and Friis-Christensen (2007) took the opposite position:

> "The continuing rapid increase in carbon dioxide concentrations during the

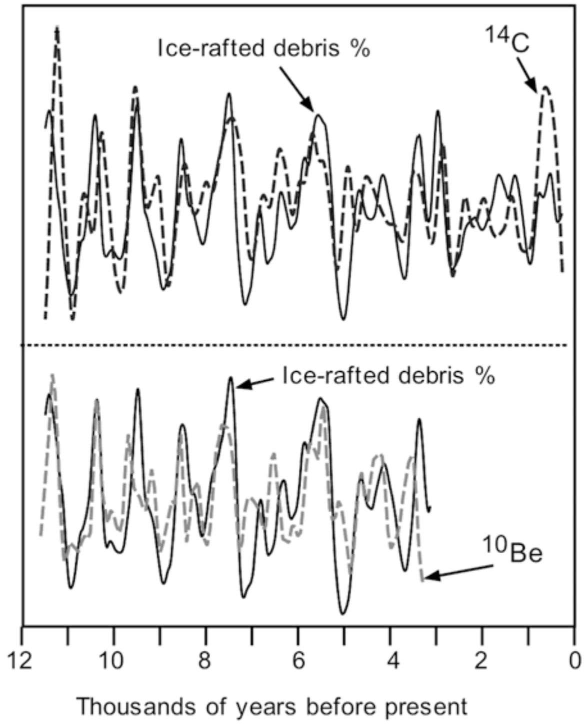


**Figure 8.7.** Comparison of radionuclide fluxes with relative amount of ice-rafted debris over the past 12,000 years (Bond *et al.*, 2001).

> past 10–15 years has apparently been unable to overrule the flattening of the temperature trend as a result of the Sun settling at a high, but no longer increasing, level of magnetic activity. Contrary to the argument of Lockwood and Fröhlich, the Sun still appears to be the main forcing agent in global climate change.''

Kniveton and Todd (2001) found a close correspondence between cosmic ray flux and global precipitation efficiency.

Bond *et al.* (2001) found close correlations between the extent of ice-rafted debris in the North Atlantic and fluxes of nuclides produced by galactic cosmic rays over the past 12,000 years. Figure 8.7 illustrates their results. Higher levels of ice-rafted debris are expected to reflect warmer temperatures and these correlate with higher nuclide production and, therefore, presumably greater cloud formation.

Unfortunately, there does not seem to be much in the way of analysis over time spans of several hundred thousand years. However, Kirkby *et al.* (2004) analyzed the level of $^{10}$Be over the past 220,000 years using ocean sediments in which the chronology was set by tuning. They found that during the past 220,000 years, the rate of $^{10}Be$ production was predominantly higher than today, although there were four periods when the $^{10}Be$ rate was as low as the current rate. These periods included 230–190, 135–110, 85–75, and 50–43 KYBP. Comparison with Figure 4.10 shows that 230–190 KYBP was associated with a moderate interglacial period, 135–110 KYBP was associated with a major deglaciation, 85–75 KYBP was associated with a short-term spike in temperature, and the period 50–43 KYBP was associated with climatic instability. Thus, there are at least some indications that the level of cosmic ray flux may affect climate over time spans of hundreds of thousands of years. Kirkby *et al.* (2004) actually proposed "a new model for the glacial cycles in which the forcing mechanism is due to galactic cosmic rays, probably through their effect on clouds." They based this on "the accumulated experimental evidence of the last few years as well as new results presented here on a 220,000-year record of GCR flux obtained in deep-ocean sediments." They concluded that the evidence was "sufficient to propose the GCR model for the glacial cycles, [but] clearly insufficient to establish it."

Kirkby (2008) reviewed the status of the cosmic ray theory over several time periods from the past few thousand years to hundreds of millions of years. While he concluded that "numerous paleoclimatic observations, covering a wide range of time scales, suggest that galactic cosmic ray variability is associated with climate change," he also admitted that there is considerable uncertainty in the mechanisms and the significance of the effect.

This topic should alert us to the possibility that complex processes may be at work in the Earth's climate that depend on factors seemingly unrelated to our climate. Most recently, Agee *et al.* (2011) reviewed the proposed hypothesis that "galactic cosmic rays (GCRs) are positively correlated with lower troposphere global cloudiness." They emphasized that Marsh and Svensmark (2000) and Svensmark (2007) utilized "lower troposphere cloud cover" rather than total cloud cover, and this appears to be more appropriate to the theory. However, several published papers have questioned the validity of the cloud data. Agee *et al.* (2011) examined the recent period between solar cycles 23 and 24 during which solar activity was very low, leading to "record high levels of GCRs" by correlating data on GCR levels with measurements of lower-troposphere cloud cover. Figure 8.8 shows a very poor correlation between cosmic rays and clouds, which seems to cast doubt on the GCR theory.

### 8.7.3 Ocean–atmosphere model

Bell and Eng (2007) published a small book in which they expounded their theory on the origin of ice ages and interglacial cycles as an alternative to the astronomical theory. Orbital variations have been around for many millions of years, but ice ages have only been around for about 3 million years—which suggests that the origin of ice ages does not lie in orbital variations.

Instead, they believe that the solar energy actually absorbed by the Earth is what matters—not the small changes in solar input above the atmosphere. In their

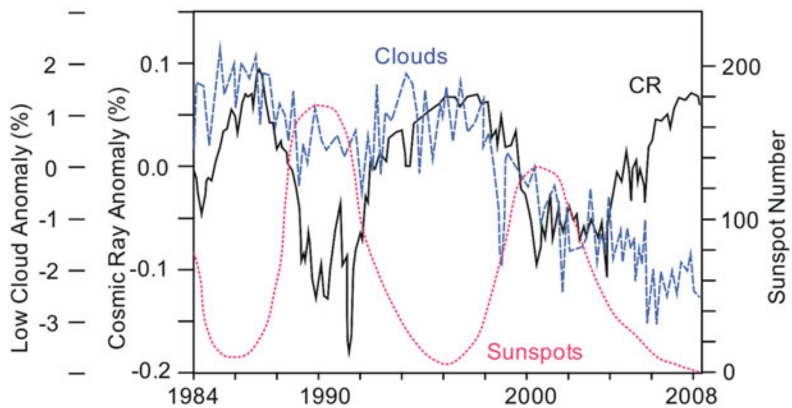


**Figure 8.8.** Comparison of the lower-troposphere cloud cover anomaly with the cosmic ray anomaly over the past two sunspot cycles (adapted from Agee *et al.*, 2011).

model, the primary factor that controls large-scale variations in the Earth's climate is the albedo of the Earth, which in turn is controlled to a considerable degree by the amount of cloudiness. Cloudiness affects the Earth's albedo and, since average solar input to the Earth is about 342 W/m$^2$, a change of only 1 or 2% in overall albedo can produce an effective forcing of 3.4 to 6.8 W/m$^2$, which would have a significant impact on the climate. Actually, solar input to the tropics is considerably higher, and variability of cloudiness in the tropics could have a dramatic effect on net solar input to the Earth.

Consider a cold glacial period. With the Earth colder than average, cloudiness is assumed to be below normal because the vapor pressure of water is reduced. As a result, solar penetration of the Earth increases above normal, instigating a warming trend in the atmosphere. Gradually, this heat is transferred to the oceans, but that may require many thousands of years. As the Earth warms up and enters an interglacial period, the oceans warm up but do so slowly over a considerable time lag. By the time that the Earth is well into the interglacial period, the oceans have warmed up enough to significantly increase world cloudiness by evaporation. This process reduces net solar input to the Earth, instigating a cooling trend. Now the process reverses. High levels of cloudiness cool the atmosphere quickly and the oceans follow slowly. By the time the Earth enters a new glacial state, the oceans have not lost all their excess heat. As the glacial state persists, the oceans eventually cool off, reducing cloudiness. Now, the warming cycle begins all over again.

While the formation of large ice sheets is a slowly evolving process, the decay of ice sheets can be accelerated by the formation of moulins that produce a liquid layer below the ice sheet that enhances slippage and calving. Thus, the glaciation–deglaciation cycle is asymmetric in time with a slow buildup of ice sheets and comparatively rapid decay.

The cycle proposed by Bell and Eng (2007) is affected by the rise and fall of $CO_2$ concentrations in interglacial–glacial cycles. At the beginning of a new glacial cycle, the oceans remain warm and $CO_2$ is therefore high, providing greenhouse resistance to further cooling. This lengthens the period over which glaciation occurs. At the beginning of a new interglacial period, the oceans remain cold and low $CO_2$ inhibits the warming process. Hence, $CO_2$ acts as an inertial force to resist climate change in these cycles.

The theory of Bell and Eng has some attractive features. A cyclic climate history naturally falls out from the fact that oceanic warming or cooling lags the warming or cooling of the surface, and warming produces clouds that, in turn, produce cooling via increased albedo. However, Bell and Eng did not seem to include the greenhouse effect of water vapor, which is likely to be very significant in opposing the putative cloud effect. Furthermore, when one traces out multiple cycles of surface temperature, ocean temperature, cloud formation, and ice formation, it is difficult to obtain a result with long glacial periods and comparatively short interglacials.

## 8.8 MODELS BASED ON THE SOUTHERN HEMISPHERE

Because the great ice sheets that formed during past ice ages were in the NH, almost all models based on variable solar intensity have concentrated on solar input to the NH. However, by comparing the synchrony of climatic changes in the NH with the SH, Blunier *et al.* (1998) and Blunier and Brook (2001) found that, despite the qualitatively different temperature time series between Greenland and Antarctica, there appears to be a correlation between major discontinuities in Greenland and slope changes in Antarctica. This is discussed in Section 4.3 (see Figures 4.15 and 4.16). The data suggest that each sudden increase in temperature in Greenland was preceded by a rather slow moderate temperature rise in Antarctica lasting a few thousand years. In addition, the EPICA Community compared data over 125,000 years from three Antarctic sites with NGRIP data from Greenland and the results were similar to those shown in Figures 4.15 and 4.16. As shown in Figures 4.15 and 4.16, the occasional sharp rises in Greenland data also appear to be preceded by slower more gradual rises in Antarctica (EPICA, 2006).

It has been proposed that there is a correlation between temperature patterns in Antarctica and Greenland due to a connection between them by means of heat transport via ocean currents known as the *bipolar seesaw* (Barker and Knorr, 2007). In this model, increasing solar input to the SH produces an increase in local temperatures. This stimulates the thermohaline circulation of warm currents to the NH. When some nonlinear threshold is exceeded, the NH undergoes rather sudden and decisive heating. As this process proceeds, heat is drawn away from Antarctica and starts to cool. This reduces the flow of heat to the NH. In addition, meltwater in the Greenland area interferes with North Atlantic Deep Water (NADW) formation, reducing thermohaline circulation. Thus, the NH begins to cool. Meanwhile, circulation away from Antarctica is impeded so it begins to slowly warm again.[6]

Stott *et al.* (2007) found that the onset of deglacial warming throughout the Southern Hemisphere occurred long before deglacial warming began in the tropical surface ocean. In a second paper (Timmermann *et al.*, 2009) this group modeled the likely cause of initiation of deglaciation after 20 KYBP as being the increase in insolation coupled with the sea ice–albedo feedback as sea ice went into retreat. As the $CO_2$ concentration rose, this added another warming feedback. They also showed[7] that each of the last four major ice age terminations were associated with increases in solar input to the far SH. Solar input to the far SH during the austral spring period when the ice pack is at a maximum appears to be a major factor in initiating deglaciation.

[6] However, note that Wunsch (2002) insisted (correctly) "The upper layers of the ocean are clearly wind-driven, involving such major features as the Gulf Stream and the Circumpolar Current. A large body of observational, theoretical, and modeling literature supports the inference that the mass fluxes in the top several hundred meters of the ocean are directly controlled by the wind stress."
[7] Lowell Stott, pers. commun., November 2008.

# 9

# Variability of the Earth's orbit: The astronomical theory

## 9.1 INTRODUCTION

A history of the origination and evolution of the astronomical theory (often called the "Milankovitch theory") was first provided by Imbrie and Imbrie (1979). Bol'shakov (2008) provided an interesting and valuable review of the various contributors to the astronomical theory of ice ages, emphasizing the early innovative ideas of James Croll who realized that orbital variations did not change total solar input to the Earth very much, but rather changed the distribution of solar energy by latitude. In addition, as Bol'shakov said: "Croll was the first to introduce Earth positive feedbacks that enhance insolation variations as a climatic influence."

It is well established that the Earth has undergone a long series of ice ages interspersed with interglacial warm periods over the past 3 million years. The ice ages were not continuous and were heavily interpolated by rather sudden large swings in temperature, up and down. Nevertheless, aside from short-term fluctuations, the data display quasi-periodic variations that span many tens of thousands of years.

Quasi-periodic variations in Earth's orbital parameters change peak solar intensity in summer at higher latitudes with periods of many tens of thousands of years. The fact that peak solar input in summer to high latitudes and data on past climate variations both show quasi-periodic variations with comparable time spans suggests that the two may be inherently coupled. Spectral analysis (see Section 10.3) supports this viewpoint to some extent. It has been widely presumed that this variability has a significant effect on the ability of surface ice and sea ice at higher northern latitudes to withstand the onslaught of summer heat. It has been theorized that during time periods when peak solar intensity in summer at higher northern latitudes is lower than average, the lower solar input may trigger feedback processes that lead to the spreading of ice cover and the start of ice


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ages. Conversely, time periods with peak solar intensity at higher northern latitudes may trigger feedback processes that cause melting, leading to deglaciation. Thus, it is generally accepted that the variability of the Earth's orbit about the Sun is a primary factor in determining the timing of ice age–interglacial cycles.

M&M asserted that there are several persuasive reasons to think that astronomy is responsible (at least to some extent) for the glacial–interglacial variations observed. One is the coincidence of astronomical frequencies with those found in ice age data. In their spectral analysis of sediment data, M&M found that the strongest frequencies that showed up typically had periods of 100,000, 41,000, and 23,000 years, which are readily identified with periods corresponding to eccentricity, obliquity, and precession. A second reason pointed out by M&M is that over long periods ($\sim$800,000 years), these oscillations remain coherent (i.e., they maintain a relatively constant phase). However, as Figure 7.1 shows, the coherence is only approximate and there has been a systematic increase in the spacing of ice ages over the past 800,000 years. Even more important is the fact that coherence is even worse over a 2.7-million-year period. M&M further argued that the narrowness of spectral peaks implies that glacial cycles are driven by an astronomical force regardless of the details of the driving mechanism. The reason given by M&M for this is that natural processes in astronomy virtually always give rise to narrow spectral peaks, while natural processes in geology and climate do not. Narrow peaks are characteristic of processes that have low loss of energy. That implies a shortage of mechanisms capable of draining energy away. In simpler terms, the regularity of the patterns of glaciation and deglaciation would seem to suggest some astronomical pacemaker driving the process, rather than random interactions between the atmosphere and oceans. For example, if the glaciation–deglaciation patterns were caused by changes in thermohaline circulation, why wouldn't the spectrum of data be broader? This seems to be a strong point in favor of an astronomical factor being the cause of glaciation–deglaciation cycles.

It is not immediately obvious which measure of solar intensity is of greatest relevance in the astronomical theory. There is some reason to believe that ice ages originate at high latitudes in the Northern Hemisphere (NH) because geological evidence shows a great expansion of ice sheets in that region during ice ages and because land (rather than water) occurs at high northerly latitudes, providing a base for ice sheet formation. It also seems reasonable to guess that the onset of widespread glaciation at high northern latitudes would be enhanced if a greater preponderance of ice could survive the effects of higher solar irradiance in the summer. Hence, most investigators have utilized midsummer solar irradiance in the NH as a measure of solar variability from year to year. Alternatively, it has been theorized that the key site for solar-induced climate change might be in the SH causing variations in the oceanic transport of heat linking the NH to the SH, but with a time delay. In particular, there is evidence that terminations of ice ages might originate in the SH.

Aside from the question of north vs. south as the region of interest for solar variability, there is also the question of which measure to use for solar input to any latitude. We could use peak insolation using total daily insolation (or, almost equivalently, solar intensity at noon) reached in midsummer as our measure for any year. Alternatively, we could use the integral of insolation over the summer season (nearly equal to the yearly integral for high latitudes). Because the Earth's orbit is elliptical, these two measures are somewhat different. When the Earth is farthest from the Sun, the peak insolation reached in midsummer is lower, but the summer lasts longer. When the Earth is nearest to the Sun, the peak insolation reached in midsummer is higher, but the summer does not last as long. Thus, over many years, the extremes of variability of integrated insolation are much smaller than those of peak insolation in summer.

In the following sections, we derive the variability of peak solar intensity over the past few hundred thousand years. The next question that arises is how should one compare the historical variability of solar intensity with isotope records of the past climate? There is no immediately obvious connection between the time sequences of solar variability and isotope variability. The simplest version of the astronomical theory suggests that solar variability is the forcing function that causes glaciation–deglaciation cycles. However, the astronomical theory (in its simple form) does not predict the timing and intensity of such cycles based on the solar variability record. Some isotope records are believed to mainly represent ice volume in ice sheets, while others are believed to represent temperatures prevailing at the region where samples were taken. Temperature records show wide variability vs. time whereas ice volume measurements show a more gradual variability. It is also widely believed that the time constant for the buildup of major ice sheets is greater than 10,000 years. Therefore, if solar variability is the main factor producing glaciation–deglaciation cycles, the ice volume curve is likely to lag behind the solar irradiance curve significantly. Testing the astronomical theory by comparing historical solar variability with isotope variability is far from straightforward. While several investigators have claimed to have done this and, thereby, proclaimed validation of the astronomical theory, closer examination raises some doubts as to the veracity of such comparisons. This topic is discussed further in the following sections.

While almost all discussions of the astronomical theory in the literature deal mainly with the initiation and termination of ice ages via variable solar input to high latitudes, it should be borne in mind that an ice age is a global phenomenon, and a full explanation of an ice age (or a termination) requires a global description that goes well beyond solar input to high latitudes. While solar input to high latitudes may well be the trigger that initiates an ice age, the increased albedo of growing ice sheets and sea ice, changes in vegetation over widening areas, lowered oceans and expanded coastlines, ocean currents circulating between high latitudes and the tropics, dust in the atmosphere, and changes in greenhouse gas concentrations all contribute to ice age–interglacial cycles. Nevertheless, it is widely believed that all these other factors are like orchestra musicians waiting for the conductor (solar input to high latitudes) to ascend the podium before they play their roles.

## 9.2 VARIABILITY OF THE EARTH'S ORBIT

### 9.2.1 Variability within the orbital plane

The orbit of the Earth about the Sun is illustrated in Figure 9.1.

The Earth's orbit has three characteristic parameters that are relevant to the variability of solar energy input to higher latitudes.

The Earth spins on its axis, and that axis is

(a) fixed in space during the course of a year; and
(b) tilted with respect to the plane of the orbit at an angle designated the *obliquity*.

The obliquity is presently 23.45° but has slowly varied over many thousands of years typically between about 22° and 24.5° with a ~41,000-year period.

The Earth's orbit is not quite circular and possesses a small *eccentricity*, which is dependent on the distance between the center of an ellipse and the position of a focus. In simplistic terms, it is a measure of how elongated one axis is compared with the other. Eccentricity varies with a period of roughly 100,000 years but the amplitude of these variations is highly variable.

The summer solstice (June 21) occurs in the Northern Hemisphere when the spin axis of the Earth points exactly toward the Sun, and winter solstice (December 21) occurs in the Northern Hemisphere when the spin axis points directly away from the Sun. This is illustrated for the present case in Figure 9.1.

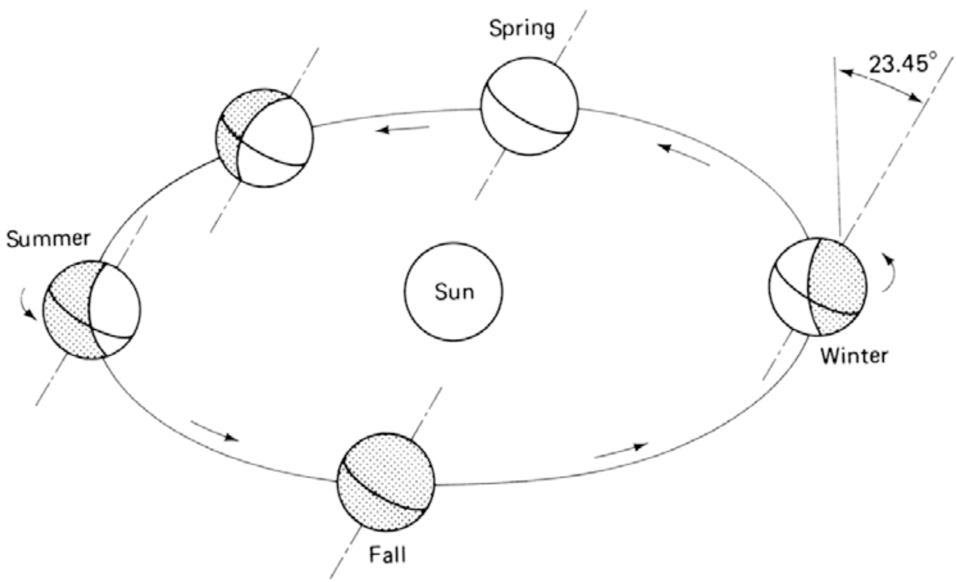


**Figure 9.1.** Motion of Earth about the Sun. Seasons are for the Northern Hemisphere. The current obliquity is 23.45°.

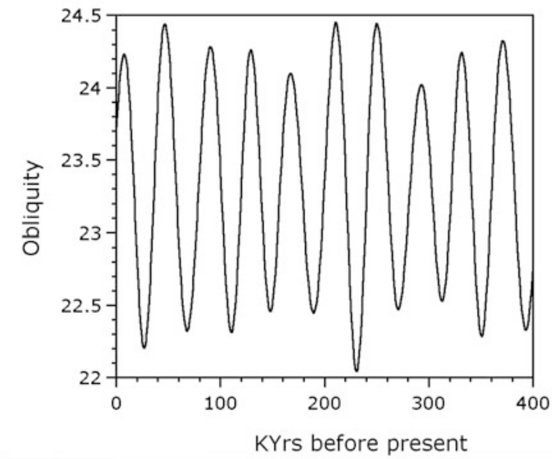


**Figure 9.2.** Variation of obliquity over the past 400,000 years.

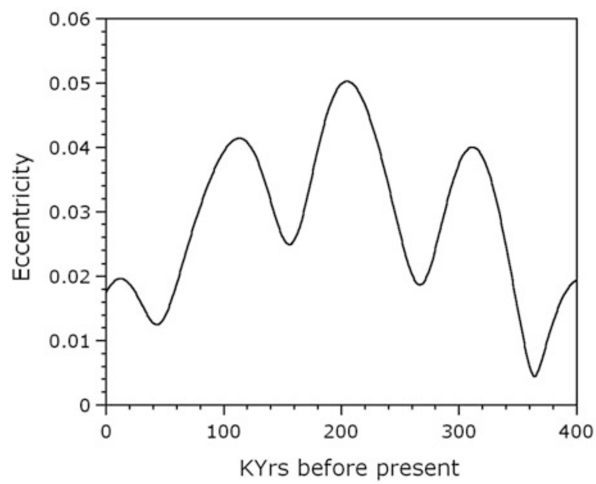


**Figure 9.3.** Variation of eccentricity over the past 400,000 years.

Solstices in the Southern Hemisphere are reversed. Solstices may occur anywhere along the elliptical orbit of the Earth. The third parameter is the so-called *longitude of perihelion*. The longitude of perihelion is the angle measured counter-clockwise in Figure 9.1 from northern spring to the point on the Earth's orbit where the minimum distance separating the Earth from the Sun occurs.

How these parameters varied over the past 400,000 years is shown in Figures 9.2, 9.3, and 9.4.

The position of the longitude of perihelion varies with a ~22,000-year period. Over this 22,000-year period, its position along the Earth's orbit varies fairly

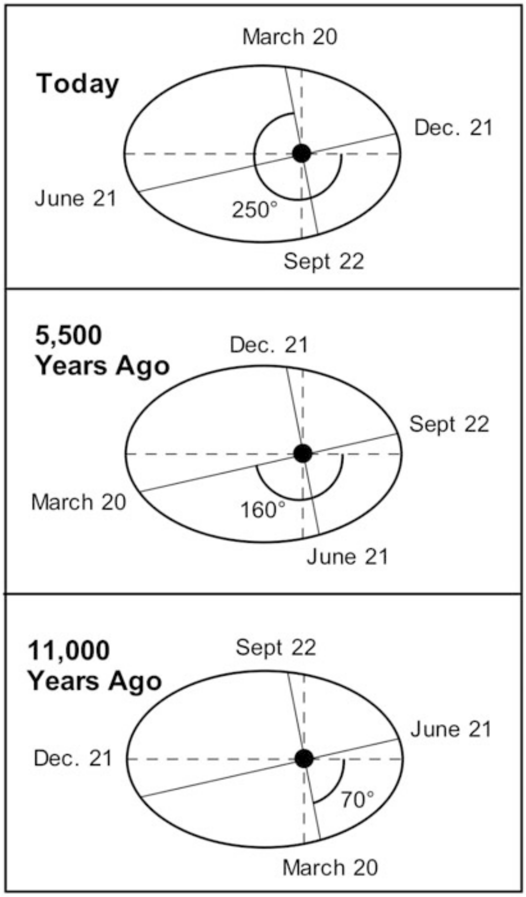


**Figure 9.4.** Variation of the longitude of perihelion over the past 400,000 years.

uniformly. When the longitude of perihelion occurs near 90° the Earth is closest to the Sun in northern summer, and when the longitude of perihelion occurs near 270° the Earth is closest to the Sun in northern winter. Since ice age formation or interglacial period formation are influenced by peak solar input to higher northern latitudes in summer, one might expect that a longitude of perihelion near 90° is conducive to interglacial conditions while a longitude of perihelion near 270° may contribute to glacial conditions. However, if peak solar input to higher southern latitudes were more important, the conditions for glacial and interglacial conditions would be just the opposite. At present, the longitude of perihelion is about 250°, so that the perihelion of the Earth's orbit occurs near the winter solstice in the north. This is illustrated in the upper figure in Figure 9.4. The angle measured counterclockwise from where the Earth is on March 20 to the position of the

Earth's orbit when it is closest to the Sun is the longitude of perihelion (presently about 250°). About 5,500 years ago, the seasons rotated 90° and the longitude of perihelion was about 160°. About 11,000 years ago, the longitude of perihelion was about 70°.

### 9.2.2 Variability of the orbital plane

M&M pointed out that, although the orbit of the Earth lies in a plane called the "ecliptic", this is not a good reference plane for paleoclimate because it changes with time. It is perturbed by torques from Jupiter, Venus, and Saturn. When we refer to the orbital plane, we must state the year that we are referring to. It requires two angles to specify the inclination of the Earth's orbital plane relative to a reference plane fixed in space. One is the angle between the orbital plane and the reference plane and the other specifies the direction of the tilted orbital plane. These angles were given by M&M as shown in Figure 9.5. Over the past 600,000 years, the inclination of the Earth's orbital plane in space has wobbled by about ±0.5° with a period that varied from about 50,000 to 100,000 years.

As M&M pointed out, little attention was paid to this variation because NH insolation does not depend directly on this parameter and, according to the standard astronomical theory, such insolation is the only physical parameter that affects climate. M&M speculated that this variation could play a role in ice age cycles.

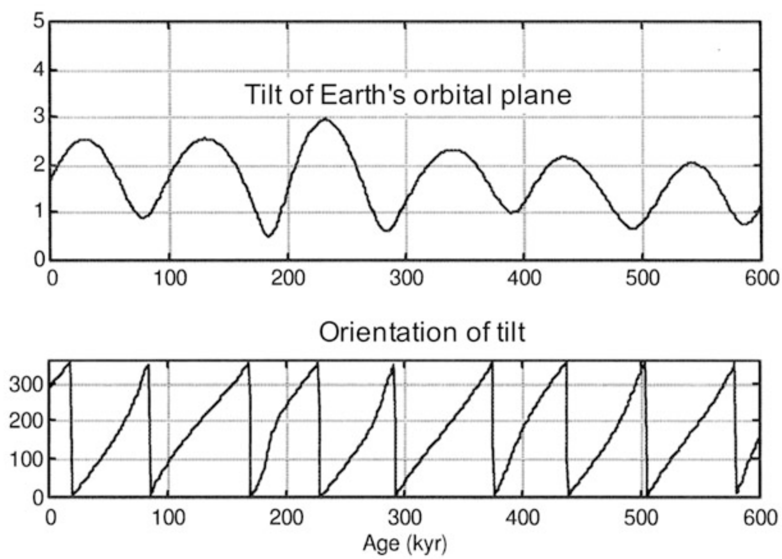


**Figure 9.5.** Variability of the tilt of the Earth's orbital plane.

## 9.3 CALCULATION OF SOLAR INTENSITIES

We are concerned with the evolution and decay of ice ages, and the potential effect of variable solar intensity at higher latitudes. Actual solar input to the Earth depends on the degree of cloudiness, moisture in the atmosphere, and the albedo of the terrain below. Our calculations are limited to estimates of solar intensity falling on a hypothetical horizontal surface above the atmosphere at some latitude. Two measures of solar intensity[1] that might be used in the astronomical theory are:

(1) Peak solar intensity at 65°N on a horizontal surface at noon on June 21 in any year.
(2) The yearly integral of solar intensity for any year.

Declination ($d$) depends on obliquity ($q$) and $L_s$, the longitude of the Sun that varies from 0 to 360° during the course of a year (being 90° at the winter solstice and 270° at the summer solstice in the Northern Hemisphere).

Declination can be calculated from the formula:

$$\sin d = \sin q * \cos(L_s - 90^\circ)$$

On June 21, $L_s = 270^\circ$, so

$$\sin d = \sin q$$

Direct normal solar intensity on any day of the year (defined by $L_s$) is given by:

$$S_N = 1{,}367\{[1 + e\cos(L_s - L_p)]\}^2/(1 - e^2) \quad (\text{W/m}^2)$$

where $e$ is eccentricity, and $L_p$ is the value of $L_s$ at perihelion. Solar intensity on a horizontal surface is:

$$S_H = S_N * \cos Z$$

where $Z$ is the angle that the Sun's rays make with the vertical. At solar noon,

$$\cos Z = \sin d \sin L + \cos d \cos L$$

where $L$ is latitude. On June 21, $\sin d = \sin q$ so:

$$\cos Z = \sin q \sin L + \cos q \cos L$$

Peak solar intensity at 65°N on a horizontal surface at noon on June 21 depends on latitude, eccentricity, obliquity, and the longitude of perihelion.

On December 21, $\sin d = -\sin q$ so

$$\cos Z = -\sin q \sin L + \cos q \cos L$$

Figure 9.6 illustrates how daily total solar irradiance varies with day of the year for various latitudes. At latitudes greater than 66.55°N (for the current obliquity) there is a period of no solar irradiance centered on December 21. For

[1] For details, see *Solar Energy* by Donald Rapp, Prentice-Hall, 1981.

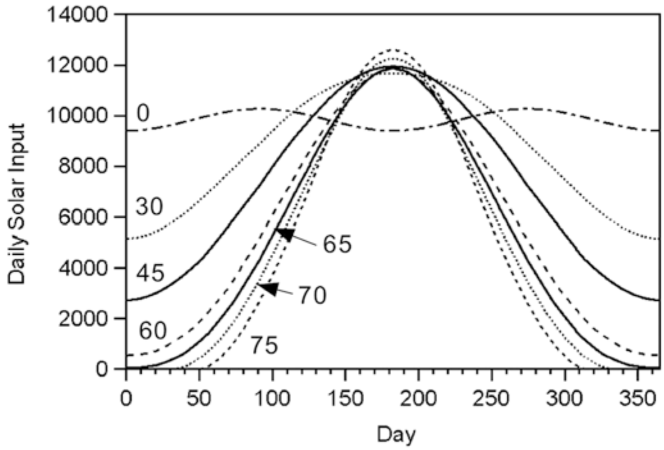


**Figure 9.6.** Variation of daily total solar irradiance (W-h/m$^2$) with day of the solar year (December 21 = day 1) for several northern latitudes.

high latitudes, solar input during summer is of primary concern because that is when it mostly takes place.

Yearly average solar intensity was evaluated by Ward (1974). The result is:

$$\langle S_H \rangle = [1{,}367/(2\pi^2)][1 - e^2]^{-1/2} \int [1 - (\sin L \cos\theta - \cos L \sin\theta \sin\varphi)^2]^{1/2}\, d\varphi$$

where the integral is taken from $\varphi = 0$ to $2\pi$. For any latitude and obliquity one must perform the integral numerically. Note that although $\langle S_H \rangle$ depends significantly on obliquity ($\theta$) it also depends very weakly on eccentricity ($e$). The reason for this is that the Earth is sometimes closer to the Sun and sometimes farther from the Sun during the course of a year. When it is closer to the Sun it is moving faster in its orbit, and when it is farther from the Sun it is moving slower in its orbit, so the effect of eccentricity is diminished.

## 9.4 IMPORTANCE OF EACH ORBITAL PARAMETER

Each of the orbital parameters has an effect on the distribution variability of solar input to the Earth.

Eccentricity varies with a period of roughly 100,000 years but the amplitude of these variations is highly variable. Eccentricities as high as 0.05, and as low as 0.01, have occurred over the past 800,000 years.

Eccentricity determines the degree of elongation of the Earth's elliptical orbit. The more eccentric the orbit, the greater the variation of solar input to the Earth during the course of a year.

Note that the distance of the Earth from the Sun is given by:

$$R = \frac{A(1 - e^2)}{1 + e \cos L_s}$$

where $A$ is the half-length of the major axis of the Earth's orbit. If we integrate this over $dL_s$ from 0 to $2\pi$, and divide by $2\pi$, we obtain the average value of $r$:

$$r = A(1 - e^2)^{1/2}$$

Since total annual solar input to the Earth is proportional to the inverse square of $r$, it follows that total annual solar input to the Earth is proportional to

$$(1 - e^2)^{-1/2}$$

Thus, total annual solar input to the Earth depends slightly on eccentricity—not on obliquity or the longitude of precession. As we showed in Figure 9.3, the full range of variability of $e$ over hundreds of thousands of years is from about 0.01 to about 0.05. Over this range of eccentricity, the variation of total annual solar input to the Earth is 0.24%. Since the average value of solar intensity impinging on a square meter of Earth is 342 W, the variability of solar input to the Earth over long time periods due to variations in eccentricity is about $0.0024 \times 342 = 0.8\ \mathrm{W/m^2}$ of forcing. This is not large enough to be the cause of ice ages.

The longitude of perihelion varies with a period of ~22,000 years. It is actually more complicated than that but this simple model is sufficient for our purposes. The effect of a change in the longitude of perihelion is to change the season that prevails when the Earth is closest to the Sun. If the longitude of perihelion ($L_p$) occurs near 90°, perihelion will occur at the NH summer solstice (June 21) and, thus, solar irradiance will be a maximum in northern summer (southern winter). If the longitude of perihelion occurs near $L_p = 270°$, perihelion will occur at the NH winter solstice (December 21) and, thus, solar irradiance will be a maximum in northern winter (southern summer). Clearly, when $L_p$ is near 90°, solar input to high northern latitudes will be near a maximum in summer if there is significant eccentricity in the Earth's orbit. Today, with the longitude of perihelion occurring near $L_p = 250°$, solar input to high northern latitudes is near a maximum in northern winter and a minimum in northern summer.

The combination of slowly changing eccentricity and rapidly changing longitude of perihelion has a significant effect on the variability of peak solar intensity at higher latitudes in summer and determines the positions of peaks and valleys of solar intensity with time at higher latitudes in summer. Slowly changing eccentricity acts as an amplitude envelope for the more rapidly varying longitude of perihelion. Eccentricity affects peak solar intensity in summer when the Earth is closest to the Sun, and the longitude of perihelion determines the season during which closest approach occurs.

In order to show the dependence of peak solar intensity in summer at high latitudes on the combination of high eccentricity and the longitude of perihelion coinciding with local summer in the Northern Hemisphere, the following parameter can be defined:

$$P = \frac{1{,}000e}{1 + |90 - L_p|}$$

This parameter maximizes when $L_p \sim 90^\circ$ (northern midsummer) and the maximum is proportional to $e$. Figure 9.7 compares this parameter with solar input to 65°N over 400,000 years.

The effect of increasing obliquity is to increase relative solar input to higher latitudes at the expense of lower solar input to equatorial latitudes. The height of any peak in solar irradiance (such as shown in Figure 9.7) will be enhanced further if obliquity is high at that time.

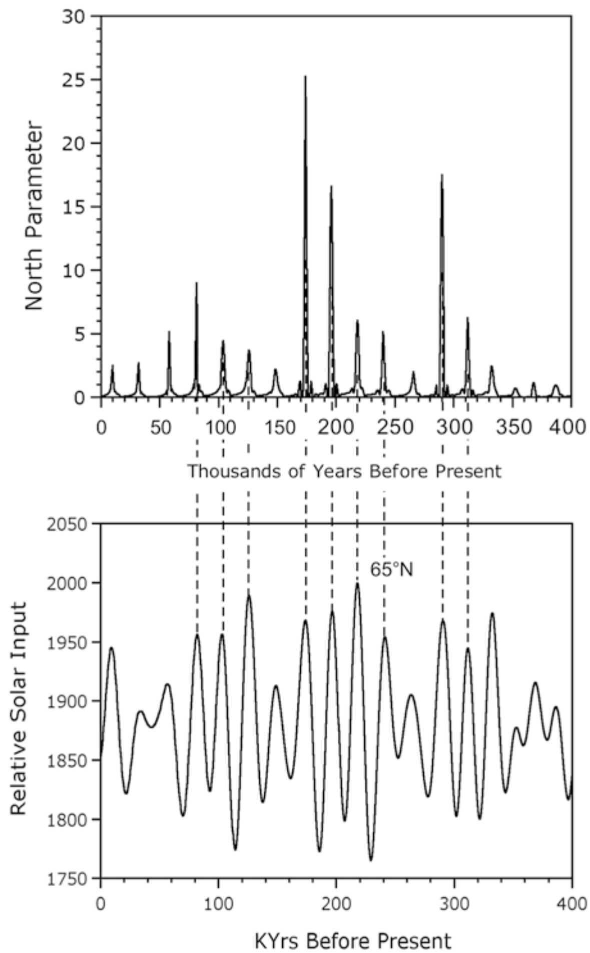


**Figure 9.7.** Peaks in solar input to Earth match peaks in parameter $P$.

Thus, we see that peak solar intensity in summer at higher latitudes (north or south) will be a maximum when (a) the longitude of perihelion occurs near local midsummer (north or south), (b) eccentricity is high at such a maximum, and (c) obliquity is high at such a maximum. The combined effect of high eccentricity and the longitude of perihelion coinciding with local midsummer (north or south) assures that peak solar intensity at the local high latitude will occur in summer (when high latitudes receive almost all their solar input anyway). The effect of obliquity is general: higher obliquity shifts more solar irradiance from low latitudes to high latitudes. As obliquity approaches 45°, there is little difference between the equator and the poles. When obliquity exceeds about 54°, there is greater solar intensity at the poles than at the equator. As these parameters evolve with time, peak solar intensity in summer at higher latitudes undergoes quasi-periodic variations and will tend to maximize either in the north or south when local conditions (a), (b), and (c) are satisfied.

While variations in obliquity change the distribution of solar input between high and low latitudes, and changes in the longitude of perihelion change the season of closest approach to the Sun, neither of these parameters affect total yearly solar input to the Earth. However, increases in eccentricity slightly increase total yearly solar input to the Earth because, when the Earth is closer to the Sun, the $1/r^2$ law causes the increase in solar intensity at closest approach to be greater than the decrease in solar intensity when the Earth is farthest from the Sun.

If the appropriate measure of solar input to high latitudes is not peak solar intensity in summer, but yearly total solar intensity, then the formula given previously should be used. In this case, eccentricity has only a minor influence and, indeed, total solar input over a year hardly varies from year to year. This does not seem to lead to a viable theory for ice ages.

A great deal of research has used spectral analysis applied to ice age isotope data and to modeled solar variability. Unfortunately, some of these researchers compared the astronomical theory with isotope data as if each of the factors—eccentricity, longitude of perihelion, and obliquity—acted independently in contributing to changes in climate. If the forcing function from the astronomical theory is peak solar intensity in summer, which is dependent on all three factors in the manner previously described, no single factor acts alone. On the other hand, one must consider the possibility that changes in the Earth's orbit might not only change peak solar intensity in summer, but also other relevant global parameters. The buildup of budding ice sheets depends not only on the rate at which solar input can deplete ice sheets in summer at high latitudes, but also on the amount of precipitation (primarily in winter) at high latitudes to replenish budding ice sheets. If precipitation is primarily affected by a single Earth orbital parameter, it may skew the dependence of ice age cycles on other Earth orbital parameters. Lee and Poulsen (2009) used a climate model to examine how precipitation in Arctic areas depends on the Earth's orbital parameters. Unfortunately, their model was not very representative. Aside from the generic inadequacies of climate models regarding clouds, aerosols, humidity, and other feedback processes, for reasons that seem inexplicable they used greenhouse gas concentrations corresponding to the 20th century (e.g., $CO_2 = 355$ ppm) whereas concentrations during ice ages ranged from 190 to 280 ppm. Furthermore, their results were presented in a manner that makes it difficult to decipher. Nevertheless, they did find that lower obliquities led to greater snowfall at higher latitudes in the NH, which could possibly lead to the greater dependence of ice ages on obliquity than other orbital parameters. This begs the question why this occurred prior to about 1 MYBP and not after. Jackson and Brocolli (2003) also used a climate model to investigate the past 165,000 years. They reported "prominent decreases in ice melt and increases in snowfall are simulated during three time intervals near 26, 73, and 117 thousand years ago when aphelion was in late spring and obliquity was low." However, these variations were less than ±10%.

## 9.5 HISTORICAL SOLAR IRRADIANCE AT HIGHER LATITUDES

In almost all descriptions of solar irradiance variability at high latitudes, an offset zero is used to emphasize the variability. However, when plotted in the normal way with zero as the base of the vertical scale, peak solar intensity in summer and yearly average solar intensity at 65°N is calculated as shown in Figure 9.8. This figure shows that the actual magnitude of these variations is small compared with the average level. Yet, according to the astronomical theory, it is these small variations in solar intensity that drive glacial–interglacial cycles.

Yearly solar irradiance at several high northern latitudes calculated for the past 400,000 years is shown in Figure 9.9. Similar graphs for latitude 65°N over 400,000 years and 800,000 years are shown in Figures 9.10 and 9.11 with expanded vertical scales. It can be seen that the patterns for several latitudes are

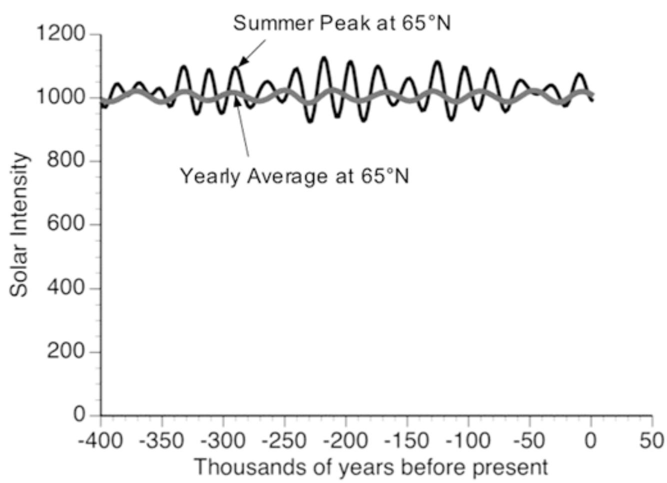


**Figure 9.8.** Calculated peak solar intensity in summer and yearly average solar intensity at 65°N.

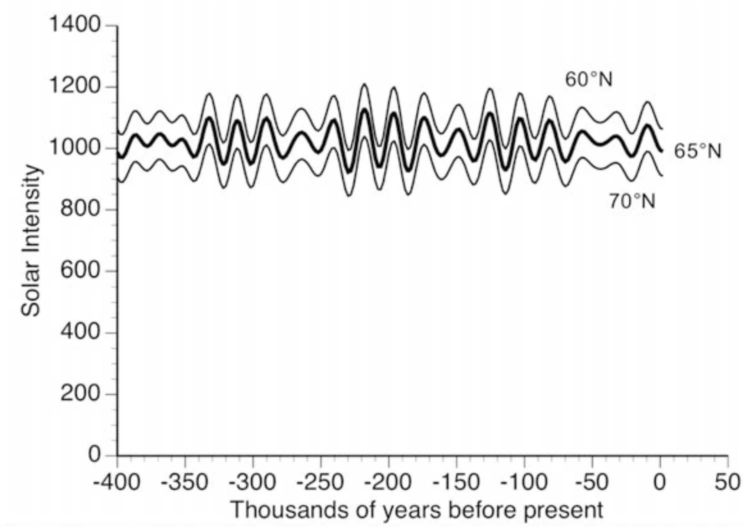


**Figure 9.9.** Calculated peak solar intensity in summer at 65°N at three northern latitudes over the past 400,000 years.

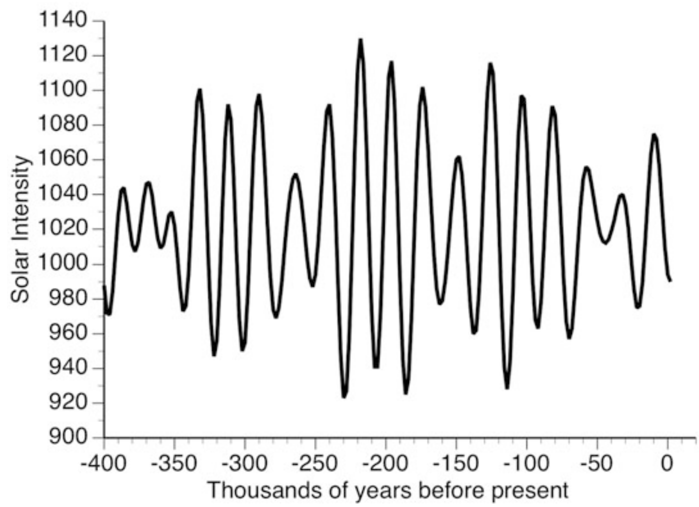


**Figure 9.10.** Relative peak solar intensity in summer at 65°N over 400,000 years.

very similar, although yearly peak irradiance decreases as latitude increases. The magnitude of variability of solar irradiance over 800,000 years about the mean is about ±5% at 60°N and increases to about ±7% at 75°N.

The pattern of variability of peak solar intensity in Figure 9.10 may be regarded as a rapidly varying (~22,000-year period) contribution due to precession of the equinoxes, with an envelope whose amplitude depends on the more slowly

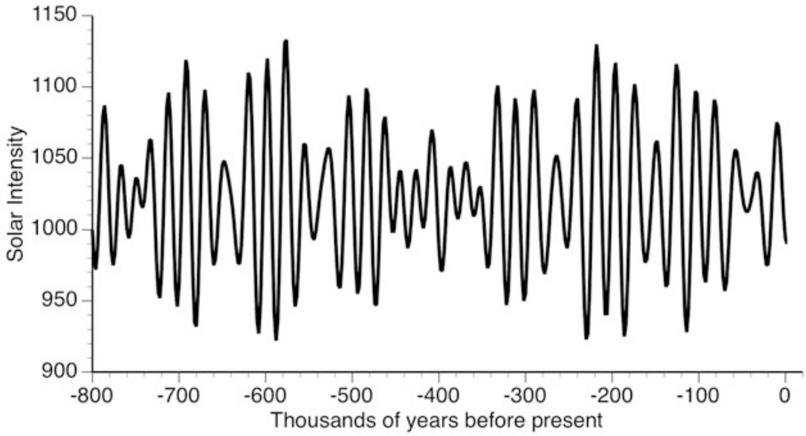


**Figure 9.11.** Relative peak solar intensity in summer at 65°N over 800,000 years.

varying obliquity and eccentricity. In a sense, this is like an amplitude-modulated radiowave where a high-power carrier wave is modulated in amplitude by the signal of interest. As we shall see in Chapter 10, there is some evidence that the amplitude of peak solar input in Figure 9.10 may be important in contributing to changes in the Earth's climate whereas the fact that solar input oscillates with a 22,000-year period may not be so important.

Solar input to high northern latitudes is maximized when the Earth is closest to the Sun in northern summer. However, the seasons of the Earth are reversed in the two hemispheres. If the Earth is closest to the Sun during northern summer, this implies that the Earth will be farthest from the Sun in southern summer. Hence, peak solar intensity in summer at high latitudes in the two hemispheres will be anti-phased (as shown in Figure 9.12).

## 9.6 CONNECTION BETWEEN SOLAR VARIABILITY AND GLACIATION–DEGLACIATION CYCLES ACCORDING TO THE ASTRONOMICAL THEORY

The astronomical theory of ice ages postulates that the distribution variability of peak solar input in summer to the Earth caused by quasi-periodic variations in the Earth's orbit about the Sun is a major contributing factor to the sequences of glaciation and deglaciation that have occurred over the past 3 million years. However, the mechanism by which this variability affects the climate is obscure. A prevalent belief is that the magnitude of solar input to higher northern latitudes during local summer determines the amount of ice that can survive the summer. According to this concept, ice will spread at high northern latitudes during years with low summer solar input and retract when summer solar input is high. The question arises as to which measure to use for solar intensity. As Figure 9.8

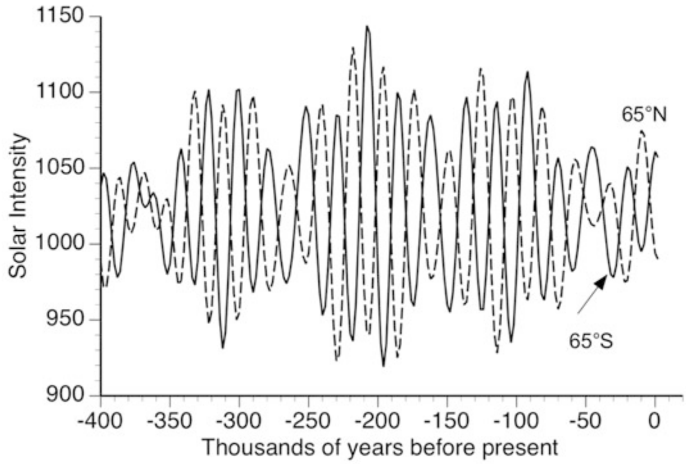


**Figure 9.12.** Comparison of peak solar intensity in summer with a horizontal surface above the atmosphere at 65°N and 65°S over 400,000 years.

clearly shows, total annual solar input hardly varies from year to year. Hence, peak solar intensity in summer seems to be a much more likely candidate. A few have claimed that it is the variability of solar input in local winter that is most important, but that makes no sense because there is hardly any solar input to high latitudes in winter. How could the variability of a small amount have any effect? Bluemele *et al.* (2001) pointed out that a 50-year glacier mass balance study in Sweden showed that it was the summer temperature that determined the extent of the glacier. Some believe that it is solar input to the south affecting ocean currents that produce climate change in the north. In addition, there are theories that climate change emanates from changes in the tropics.

Despite the extensive literature on the astronomical theory, there is an appalling lack of modeling the specifics of how solar variations produce extreme climate change. Perhaps that can be excused to some extent because of the extreme complexity of the issue. However, if this is the case, how can so many scientists reach firm conclusions as to the veracity of the astronomical theory? The astronomical theory is actually little more than a high-level belief that solar variations affect climate. Exactly how these variations affect climate remains uncertain. A few models have been developed but none of these are very satisfying—at least to this writer.

While credible mechanisms for the processes by which solar variability affects climate are not available, one may hope to gain an understanding of them by comparing the curves of peak solar intensity in summer (from the previous sections) with isotope data from ice cores and ocean sediments. The situation here is somewhat akin to that of a detective trying to solve a crime by examining clues. Two approaches have been taken.

In one approach, solar variability and isotope data are both analyzed spectrally and, to the extent that both have important frequency components that agree, there is an implication that they are coupled. That belongs to the realm of "circumstantial evidence" (e.g., the suspect was known to be in the vicinity where the crime was committed) but it does not lead to direct cause–effect conclusions.

The second approach involves comparing the detailed time series of isotope data with solar data from hundreds of thousands (or even millions) of years to determine whether there is any consonance between trends in the two datasets. However, there is a difficulty here because it is obvious that solar variability due to precession of the equinoxes involves more rapid variations than the long-term trends in global ice volume.

Assuming that the astronomical theory is fundamentally sound, it seems likely that the buildup and decay of gigantic ice sheets is a slow process that depends on the integral of solar variations over long periods—perhaps tens of thousands of years. Therefore, an integrative model is needed to estimate the slow buildup and decay of ice sheet volume as a function of more rapidly varying solar input. One can then compare either the rate of change of ice volume with solar variations, or an integral of solar variations with the measured time series for ice volume vs. time. There does not seem to be a single *a priori* model based entirely on physics with no adjustable parameters that allows unequivocal comparison of theory with data. Unfortunately, all models developed to date have been limited by their simplicity and the obvious bias of many scientists determined to validate the astronomical theory via curve fitting. The combination of fixing the chronology of isotope data by tuning to the astronomical theory and using adjustable parameters to fit simplistic models to tuned data raises the question of circular reasoning. However, it could be argued that the models provide a framework for connecting theory with data, and the curve-fitting process fills in quantitative parameters that are too difficult to estimate from fundamental principles in the real world. But the degree of elasticity in the models creates doubt as to where such procedures fit between the extremes of determining physical parameters and mere mathematical curve fitting.

The bottom line seems to be that the astronomical theory may well be correct to some extent in principle (i.e., there may be solar influence in glacial–interglacial cycles), but translating this into a detailed quantitative comparison of theory and experiment remains a difficult and elusive challenge.

### 9.6.1 Models for ice volume

Measurements of benthic $\delta^{18}O$ in foraminifera from ocean sediments are believed to mainly represent ice volume, whereas planktic foraminifera may be more sensitive to ocean temperature. Measurements of $\delta^{18}O$ and $\delta D$ in ice cores are believed to represent mainly local temperature at the core site.

In attempting to compare solar variability with isotope data representing ice volume, one must formulate a model for how solar variations lead to changes in local temperature and, ultimately, changes in ice sheet volume. Without such a model, it would not be clear how solar variations should be compared with isotope ratios even if the astronomical theory was obeyed perfectly.

Most of the models developed so far have dealt with the variability of ice volume resulting from solar variability in the NH. Calculated peak solar intensity in the NH year by year is used as a forcing function. However, none of the models yet developed seem to be completely *a priori*. The models utilize a certain amount of physical logic to set up mathematical expressions for the rate of change of ice volume as a function of solar intensity and ice volume, but the models contain parameters that are adjusted to obtain a best fit between the model and the time dependence of ice volume inferred from isotope measurements. If the chronology of the data was initially inferred by tuning to the astronomical theory, implicit circular reasoning may be involved. The significance of such comparisons is arguable. A skeptic might claim that the entire exercise is merely curve fitting to find a mathematical representation of the isotope data that is connected to solar data via mathematical artifices. However, the proponents of these models would argue that the models have a physical basis and adjustment of the parameters merely sets the details—not the underlying form of the result. The truth probably lies somewhere between these extremes.

A number of models were developed as early as the late 1960s. Some models dealt with the question of whether known variability of solar intensity was great enough to cause climate shifts leading to ice ages. Later studies attempted to model the effects of variability of solar intensity on the time evolution of ice sheet formation and decay. The goal of such models was to produce an estimate of ice sheet volume vs. time that could be compared with the variation of isotope ratios with time, as a test of the astronomical theory.

An early paper estimated the change in temperature produced by changing solar intensity, but it used current atmospheric and surface properties and did not account for changes in albedo due to ice sheet growth or other secondary factors. The temperature changes calculated appeared to be too small to suggest ice sheet formation (Shaw and Donn, 1968). Several other papers reached similar conclusions in the 1970s. North (1975) developed an energy balance climate model that predicted larger temperature changes due to variability of solar intensity, although ice sheets were not included in this model. This paper is difficult to follow and makes many assumptions. Pollard (1978) attempted to incorporate the feedback effect due to the albedo of ice sheets into such models. Unlike North, he produced specific curves of climate variability over the past 300,000 years. However, his model included a dozen adjustable parameters and it seems likely that he could have produced almost any result by choosing them appropriately.

Calder (1974) compared variations in the oxygen isotope ratio of marine sediments with calculated solar irradiance at 50°N. He made an issue of choosing 50°N, which does not make much sense to this writer, but as it turns out it doesn't matter much whether one chooses 50°N or 65°N since all solar variations at different latitudes have similar shapes (see Figure 9.9, for example). He made a few vital assumptions without providing justification. He assumed that the rate of decrease (or increase) in ice volume is proportional to the amount by which solar intensity exceeds (or is less than) some threshold level. Thus, according to this formulation:

$$dV/dt = -C_1(S - S_0) \quad \text{if } S > S_0$$
$$dV/dt = -C_2(S - S_0) \quad \text{if } S < S_0$$

where $V$ is the ice volume, $S$ is solar intensity, $S_0$ is the threshold solar intensity, $t$ is time, and $C_1$ and $C_2$ are (different) constants. These equations were integrated over 1,000-year time steps, and the accumulation of ice volume vs. time was tabulated. He added the constraint that $dV/dt$ cannot be negative when $V \sim 0$. Calder (1974) admitted that his assumptions "were almost frivolous", which raises the question of what he meant by "almost". Calder (1974) apparently adjusted the constants in the above equations to fit long-term oxygen isotope data over 800,000 years, although he was not very clear about exactly what he did or what constants he used. Nor is it clear what starting values he used for the integration. It is known empirically that ice ages seem to require several tens of thousands of years to build up, but deglaciation can take place in only a few thousand years. Hence, it seems likely that one must choose $C_2 \ll C_1$ to get a best fit to the data. However, Calder did not divulge the necessary details.

Weertman (1976) developed a model to estimate whether solar variations over many thousands of years are sufficient to produce large variations in the size of ice age ice sheets. He set up a model of an ice sheet and derived equations for the rate of change of its volume (or dimensions). He considered a two-dimensional ice sheet that rests on a land surface that was flat before the ice sheet formed on it. Figure 9.13 shows the ice sheet in profile.

The lower ice surface is, of course, not flat because of isostatic depression of the land surface. The northern edge of Weertman's ice sheet borders at the Arctic Ocean and the southern edge is on land. The total width of the ice sheet is $L$. Weertman (1976) hypothesized a snow line such that accumulation takes place wherever the height of the ice sheet locally exceeds the snow line, whereas ablation occurs wherever the snow line is higher than the ice sheet. Based on his rough

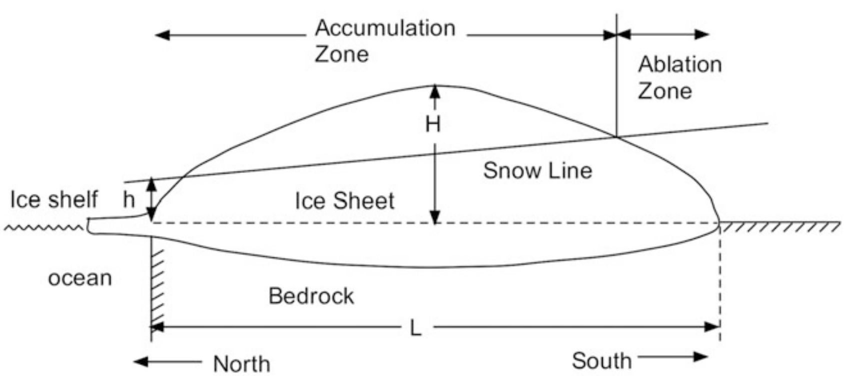


**Figure 9.13.** Weertman's ice sheet model.

estimates of the properties of ice and bedrock, as well as some additional guesses, he estimated that $h$ (the height of the snow line at the northern edge of the ice sheet) would have to be between 0 and 540 m to enable a stable ice sheet to persist. In his model, when $h \Rightarrow 0$, $L \Rightarrow \sim 2{,}500$ km. When $h$ rises to 540 m, the ice sheet becomes unstable and ablates away. He derived an expression for the rate of change of ice volume with time that depends on $h$. He made the connection to solar variations by assuming that $h$ is proportional to the variation in solar intensity at some latitude (he chose 50°N). As Weertman put it: "We assume that in this naive way the solar radiation variations can be related to changes in the elevation of the snowline." The proportionality constant was selected somewhat arbitrarily. He was then able to derive a result for ice volume in the ice sheet vs. time over the past 500,000 years. It is difficult to ascertain the degree of rigor in his various assumptions. He seems to have encountered a rather extreme sensitivity to the ratio between the rates of accumulation and ablation. A change in this ratio from 2.745 to 2.750 seems to have produced dramatic changes in the results. For example, depending on this choice (2.745 or 2.750) his result for the future either predicts no ice age in the next 120,000 years or an ice age should be starting right now.

He concluded that variations in solar irradiance were large enough to have produced ice ages. However, to reach this conclusion, it was necessary to assume that accumulation and ablation rates were substantially higher than those that occur today in Greenland and Antarctica. He also found a significant sensitivity of the possibility of ice ages to the location of northern landmasses. His results suggest that if Greenland were moved 500 km north (or south) we would either be in a perpetual ice age or forever free from ice ages. Weertman's study provided some valuable insights into ice sheet formation, but his model clearly needs refinement.

Imbrie and Imbrie (1980) reviewed the status of various models for ice volume variability and concluded: "As described above, Pollard and Weertman have made considerable progress in this direction—yet results fall short of an adequate simulation." The Imbries advocated the use of simple models because, as they put it, "even if a complex model yields a successful simulation, it may be difficult to understand what features of the model are the basis of its success." However, after advocating this fundamental wisdom, they went on to say:

> "Tuning a model to the climatic record is an essential feature of our strategy for developing a simple class of differential models. To see how drastically one's ability to tune a model is affected by complexity, define the complexity ($C$) to be the total number of adjustable parameters. We include in this total any parameter that can be adjusted within the constraints of physical plausibility to make significant changes in the system function. Some of these parameters may vary over a large range and make large changes in the system function, while others may be relatively restricted. For purposes of comparison, however, we count all of them equally. Some of the parameters ($C_F$) will occur in the system function ... while others ($C_I$) will occur in the input, so that $C = C_F + C_I$. In previous

models, $C$ ranges from 4 to 12. If each parameter is adjusted over only three levels, then $3C$ [calculations] are necessary [to tune the model]. Such a search procedure for Calder's model (81 [calculations]) is relatively easy, but for Pollard's it would require more than 500,000 [calculations].''

From the point of view of the Imbries, the task at hand was to adjust parameters in a model (i.e., to tune the model) to seek maximum agreement with isotope data. In their view, there was no doubt at all *a priori* that the astronomical theory was correct in principle, even though it was not clear how the variability of solar intensity led to variability in isotope time series. The belief was that by tuning the model one would identify the quantitative connection between solar variability and climate change, and there was no underlying doubt that such a connection existed. The second point was that if too many parameters are included in the model the number of possibilities increased rapidly, making the process of identifying the best fit cumbersome and arbitrary. Of course, there is no guarantee that there is only one unique answer.

The Imbries discussed the number of parameters involved in input (solar intensity). For a high-resolution global model that includes solar input to all latitudes there are no parameters. Solar input to any latitude is uniquely determined by the three orbital parameters: $e =$ eccentricity, $q =$ obliquity, and $w =$ longitude of precession. These parameters can be calculated by methods given previously (see Sections 9.2 to 9.5). As the Imbries pointed out, in most models a more limited approach is used involving ''linear combinations of irradiation curves at various latitudes and seasons.'' However (as Figure 9.9 suggests), the irradiation curve at any high latitude in midsummer is likely to be adequate. At this point, the Imbries embarked on a discussion of the orbital parameters that control solar irradiance which seems illogical to this writer. They discussed the effect of the three orbital parameters as if each acts independently on climate and they attempted to attribute changes in climate to one or other orbital parameter and, in some cases, more than one. But these orbital parameters do not act separately. They act in concert to determine solar irradiance, and solar irradiance is the forcing function of interest in the astronomical theory. The only two parameters in such calculations should be season and latitude. In fact, if one takes summer as the season and utilizes any latitude at, say, 50° or greater the results are essentially the same. Once they are chosen, solar irradiance is essentially uniquely determined and the Imbries actually showed this in their Figure 3. Thus, there should really be only one parameter of interest regarding input, and that is whether the latitude for solar input is chosen in the south or the far north.

The Imbries then went on to discuss how the system functions. They pointed out that the simplest system they could imagine was the one described by the equation:

$$\frac{dy}{dt} = -\frac{1}{T}(x + y)$$

In this equation, $y$ is a variable that characterizes the climate (in their case, ice sheet volume), $x$ is a parameter that characterizes variations in solar input (in their case, solar intensity in midsummer at some high northern latitude), and $T$ is a time constant that produces a lag between change in solar input and resultant change in climate. Unfortunately, the Imbries do not seem to have defined the units of $x$ and $y$ or their ranges. Since $x$ is a measure of solar intensity and $y$ is a measure of ice volume, it is not immediately clear how they are related. Although never defined, it seems likely that the quantity $x$ is the deviation of solar irradiance from some long-term average value; thus, it can either be positive or negative. The Imbries wrote this equation without a minus sign in front of $x$, but that does not make sense to this writer. When solar irradiance is lower than average ($x < 0$) ice volume increases, so the relationship between $dy/dt$ and $x$ must contain a minus sign and I have arbitrarily inserted one. It is not clear why the $y$ term was included on the right-hand side of the equation. Under average solar conditions ($x \sim 0$) the presence of the $y$ term forces the ice volume to shrink with time, so this equation has a bias toward interglacial conditions and only sustained values of $x < y$ can build up an ice sheet. This might have been based on the assumption that reduced humidity could slow down the growth of the ice sheet when it gets large, so that $dy/dt$ must diminish as $y$ builds up. As it turned out, the Imbries found the above equation did not correlate well with long-term isotope data no matter how they varied $T$.

Having failed with the simplest model, the Imbries added an embellishment to it. As mentioned previously, there is considerable evidence in isotope profiles that suggest that ice ages build up slowly but decay relatively rapidly. Therefore, the Imbries modified the model by choosing the effective time constant to be greater during ice buildup—it takes longer to add ice when $(x + y) < 0$ than it does to remove ice when $(x + y) > 0$. However, as before, in reporting their model I changed $(x)$ to $(-x)$ because increasing $x$ should reduce the ice volume. Thus, their modified model can be written (with my change):

$$\frac{dy}{dt} = -\frac{1+B}{T}(x+y) \quad \text{if } (x+y) > 0$$
$$\frac{dy}{dt} = -\frac{1-B}{T}(x+y) \quad \text{if } (x+y) < 0$$

Insertion of the constant $B$ assures that ice buildup will take place more slowly than ice sheet decay. Note that as $B$ varies from 1/3 to 2/3 the ratio of effective time constants varies from 2 to 5.

It is not immediately clear why ice volume should enter this equation on the right-hand side. Previous modelers always inserted a $-y$ term on the right-hand side to reduce the rate of ice volume growth as ice sheet volume increased, but no explanations for this were offered. The growth of ice sheets requires a source of moisture and evidence suggests that as an ice sheet grows such sources become more distant; therefore, with constant solar intensity the rate of ice sheet growth should be lower as ice sheet volume grows. That might justify inclusion of $-y$ on the right-hand side, although the argument is rather subjective.

The Imbries reported arriving at "optimum model values" by tuning this model to the (tuned) geological record of the past 150,000 years. They found a best fit with $B = 0.6$ and $T = 17{,}000$ years, so that the time constants for buildup and decay of ice sheets were claimed to be 42,500 years and 10,600 years, respectively (ice sheet decay is four times faster than ice sheet buildup when $B = 0.6$). Their solar intensity was taken at 65°N at noon on July 21 (it would have made little difference had they chosen 50°N). The Imbries claimed: "This simple model's simulation of the past 150,000 years of climate is reasonably good—in fact, somewhat better than that achieved by the more complex but untuned models." However, it is arguable whether tuning a mathematical expression to (tuned) data validates the astronomical theory or merely defines the best fit to this model assuming the astronomical theory is correct. It is well known that geological data tend to show slow buildups and rapid decays of ice volume with time, and the use of the constant $B$ in the above equations assures that the model will produce this kind of sawtooth behavior.

Paillard (1998) sought to model the time evolution of ice volume over the past 2 million years in order to validate the astronomical theory. He emphasized the "100 kyr problem" and pointed out that previous investigators suggested that nonlinear responses of ice sheet dynamics to forcing were probably responsible. He claimed: "although some of these models compare well with the geological record in the spectral domain, all of them fail to reproduce the correct amplitude and phase of each glacial–interglacial cycle."

Paillard (1998) presented a simple model which he claimed reproduces reasonably well the succession of glacial–interglacial cycles over the Late Pleistocene. He utilized daily insolation at 65°N at the summer solstice as his forcing function, thereby assuming (as most have done) "that summer insolation at high northern latitudes controls the ice-sheet volume, and hence the global climate."

He assumed that, depending on insolation forcing and ice volume, the climate system could enter three different regimes—$i$ (interglacial), $g$ (mild glacial), and $G$ (full glacial)—and that transitions between them are regulated by a set of rules as follows.

$i \Rightarrow g$ transitions occur when insolation falls below $i_0$

$g \Rightarrow G$ transitions occur when the ice volume exceeds a threshold $v_{\max}$ although this parameter need not be specified in this model

It is assumed that an ice sheet needs some minimal time $t_g$ in order to grow to the point where volume exceeds $v_{\max}$ and that the insolation maxima preceding the $g \Rightarrow G$ transition must remain below the level $i_3$. The $g \Rightarrow G$ transition then can occur at the next insolation decrease when it falls below $i_2$. Apparently (it is difficult to follow exactly what was done), if the system remains in the $g$ state for a time $t_g$, during which the peaks in insolation remain below $i_3$ and the average insolation lies below $i_2$, the system will make a sudden transition to state $G$.

$G \Rightarrow i$ transitions occur when insolation increases above $i_1$

Since it turns out that the best fit occurs for $i_1 = i_2$, both the $g \Rightarrow G$ transition and the $G \Rightarrow i$ transition are however controlled by essentially the same parameter. These transitions are assumed to be one way.

$g \Rightarrow i$ transitions are assumed to be impossible

The assumption here is that it would take a very high value of insolation to go from mild glacial to interglacial. However, it is difficult to comprehend why that should be so on physical grounds.

It was assumed that $G \Rightarrow g$ and $i \Rightarrow G$ transitions are forbidden. In this model, once deglaciation takes place from the $G$ state, it always goes all the way to $i$ and does not pass through $g$. Conversely, starting from the $i$ state, the system must pass through $g$ on the way to $G$. Again, it is difficult to comprehend why that should be so on physical grounds.

While several different sets of the parameters $i_0$, $i_1$, $i_2$, and $i_3$ were utilized, it appears that in the end Paillard (1998) chose $i_0 < i_1 \sim i_2 < i_3$. That $i_0$ should be the lowest makes sense because low insolation logically would initiate an $i \Rightarrow g$ transition. But, it is not clear to this writer why the $g \Rightarrow G$ transition should depend on insolation maxima being less than $i_3$ and the insolation remaining below $i_2$. The implication here is that the $g \Rightarrow G$ transition does not depend on very low insolation, which seems very strange indeed. Paillard varied the parameters to try to get them to fit ocean sediment data over 900,000 years and was able to find fairly good consonance between the peaks in his curve and the peaks in the isotope data with $i_0 = -0.75$, $i_1 = i_2 = 0$, $i_3 = 1$, and $t_g = 33{,}000$ years. The physical significance of this is uncertain. Paillard concluded:

> "These results highlight the fact that the interglacial stages defined in the isotope records are not directly associated with the largest maxima in the insolation curve. On the contrary, they systematically occur after the small ones. Indeed, these small maxima eventually trigger a full glacial stage, then followed by an interglacial."

This result is in consonance with the finding in Section 10.2.1 that, as solar input to high latitudes oscillates with a ~22,000-year period due to precession of the equinoxes, time periods in which these oscillations have lower amplitudes tend to produce ice ages whereas periods with higher amplitudes tend to produce interglacials.

Paillard then constructed a differential version of the previous model and compared it with isotope data over 2 million years. This second model still had the same three regimes, but ice volume was allowed to change continuously. The criteria for the $i \Rightarrow g$ and the $G \Rightarrow i$ transitions were the same as before with the same threshold values. The $g \Rightarrow G$ transition now occurs when ice volume exceeds the value $v_{\max}$ irrespective of insolation. The model is, except for the thresholds, a simple linear one:

$$dv/dt = (v_R - v)/t_R - F/t_F$$

where $v$ is ice volume, $R$ is the current climate regime ($R = I$, $g$, or $G$), $v_R$ are reference ice volumes for different regimes, $F$ is insolation forcing, and $t_R$ and $t_F$ are time constants. This model implies that the rate of addition of new ice decreases as ice volume builds up. Physically, one might expect the rate of new ice formation to increase at first as ice volume increases due to the cold trap for moisture that is created but, eventually, the amount of prevalent moisture for large ice volumes would presumably decrease and the rate of accumulation would diminish with ice volume.

Paillard normalized ice volume to unity: $v_g = v_G = v_{\max} = 1$, $v_i = 0$. The forcing $F$ is mathematically manipulated by a procedure that this writer was unable to follow. $F$ was said to depend on $f$, which in turn depended on $x$ and $a$, but neither $x$ nor $a$ were defined in the paper. Nor is it clear to this writer how the above differential equation was integrated with time or how transitions between regimes occurred within the model. Moreover, as in the case of the simpler model, it is not clear to what extent this curve-fitting procedure has a physical basis. Models that integrate periods of low insolation over time to produce ice formation with some threshold and high insolation over a shorter period to produce deglaciation seem to produce impressive results. While I do not begrudge Dr. Paillard's self-satisfaction with his results, his conclusion

> "In any case, and in contrast to recent claims, this conceptual model clearly demonstrates that the geological record can easily be explained in the framework of the classical astronomical theory"

seems a bit overly enthusiastic.

An interesting aspect of Paillard's results is that he finds very different ice volume patterns vs. time for the first million years and the second million years, despite the seemingly repetitive morphology of the insolation vs. time curve over 2 million years. How this comes about remains a mystery to this writer.

It does not seem necessary to define the three regimes of the climate system. Paillard's equation for the rate of ice volume growth is actually very similar to that used by the Imbries 18 years earlier. Unfortunately, like all the other models, it is difficult to resurrect the model and explore it further because no units are given.

### 9.6.2 Review of the Imbrie model

In attempting to check the Imbries' results and examine the model further, one encounters the problem of making the units of $x$ and $y$ compatible. The description given by the Imbries is sparse. It seems likely that they may have used the following procedure. Over any interval of time, the values of $x$ (solar insolation) are tabulated at regular intervals. The average value of $x$ and the standard deviation over the interval are calculated. The values of $x$ are measured from the average in units of multiples of the standard deviation ($x$ could be positive or negative). The average value and standard deviation of noon solar intensity at

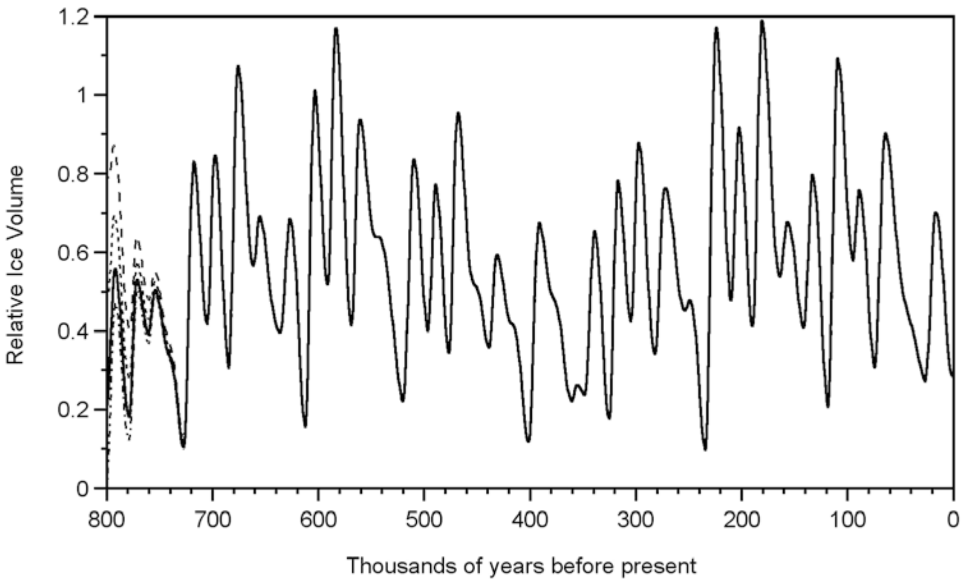


**Figure 9.14.** Dependence of the Imbries' integration on starting values for relative ice volume. The dashed lines are for starting values of 0.0, 0.2, and 0.8, while the solid line is for 0.5.

65°N over the past 800,000 years was obtained from Figure 9.11. The values of $x$ are then measured from the average in units of the standard deviation.

The resultant values of $y$ obtained by stepwise integration[2] are measured in units of the standard deviation of $x$. There remains the question of which starting value to use for $y$ to begin the integration but, as it turns out, the result is not sensitive to this choice (see Figure 9.14). Regardless of the starting value (0.0, 0.2, 0.5, or 0.8) all the curves approach a common result after about 50,000 years.

The dependence of the modeled ice volume history on the two parameters ($B$ and $T$) is illustrated in Figures 9.15 and 9.16. Regardless of the values of these parameters, the maxima and minima in modeled ice volume occur in the same time periods. Only the magnitudes of the peaks and valleys change with the parameters. Shorter time periods produce wider ranges of variation. Larger values of $B$ raise the ice volume curve and lower values of $B$ lower it. What is important here is that the locations of peaks and valleys in the ice volume curve vs. time are independent of the choice of parameters and, furthermore, the dynamic range of the peaks and valleys is not extremely sensitive to the choice of parameters. Physical arguments can be made to support the belief that $T$ should be in the general range of 10,000 to 20,000 years, and $B$ ought to be somewhere in the range 0.4 to 0.8. Hence, there is no need to keep an eye on SPECMAP data when applying the Imbrie model. The model, to the extent that $T$ and $B$ are predictable,

[2] These calculations were carried out by the present author in 2008.

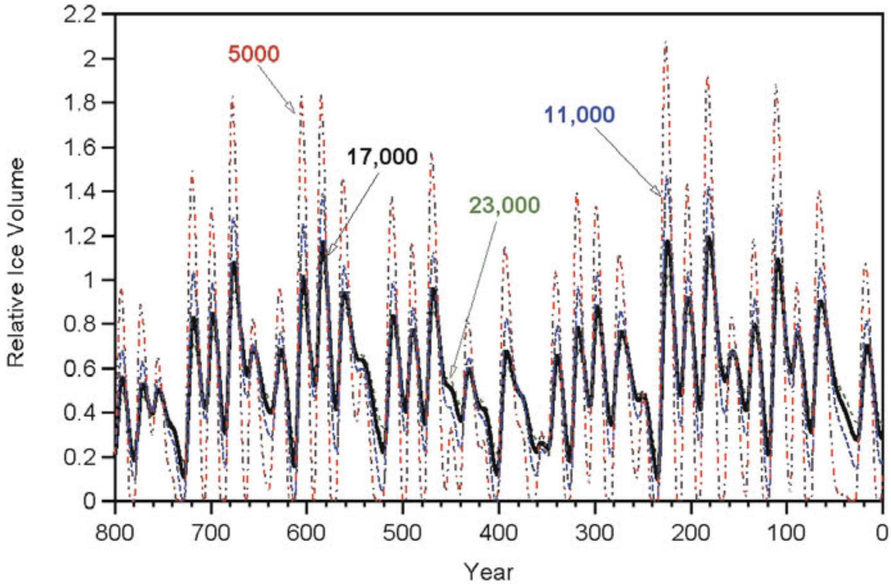


**Figure 9.15.** Dependence of the Imbries' integration on $T$. The starting value was 0.2 and $B = 0.6$.

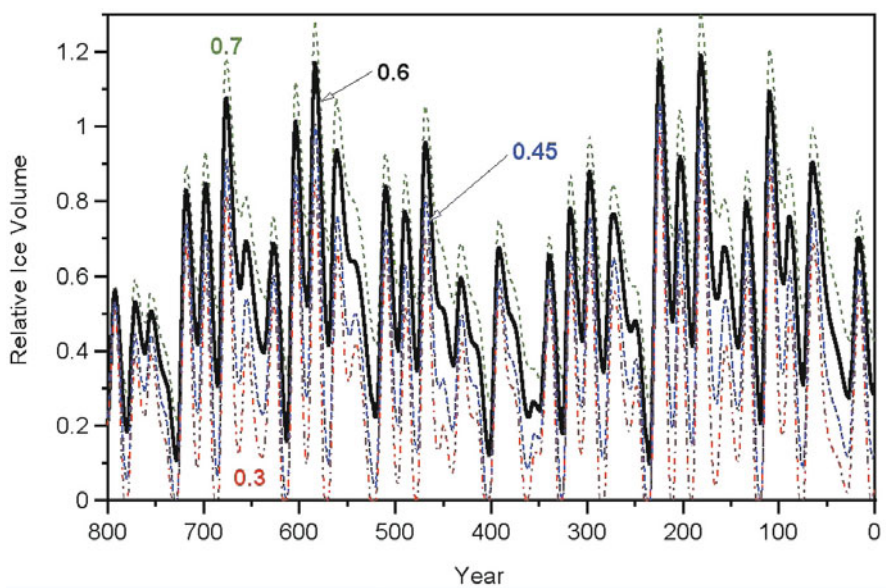


**Figure 9.16.** Dependence of the Imbries' integration on $B$. The starting value was 0.2 and $T = 17{,}000$.

can be construed to be an *a priori* model that can be compared with data without fudging.

Another approach would be to use the function $1 + B\tanh(K[x + y])$ in place of $(1 \pm B)$. Note that this function goes smoothly to $(1 + B)$ when $(x + y)$ is large-positive and to $(1 - B)$ when $(x + y)$ is large-negative. It also provides a smooth continuous equation to replace the abrupt discontinuous Imbrie model. As $K \Rightarrow \infty$, the tanh function approaches the step function used by the Imbries. A reasonable value for $K$ might perhaps be about 3.

Pisias and Shackleton (1984) embellished the Imbrie model by adding a term to represent the effect of greenhouse forcing due to variable $CO_2$ content in the atmosphere during glacial–interglacial cycles. However, they did not reveal how they did this, so it is difficult to reproduce their results. Furthermore, in the process of adding a term for $CO_2$ forcing, they seem to have fitted the model to ocean sediment data, thus producing a kind of self-confirming curve that fits the data. Nevertheless, adding a term to the Imbries' differential equation to provide for $CO_2$ forcing may be a good thing to do if done judiciously and independently of sediment data.

### 9.6.3 Memory model

Berger (1999) developed a model that dealt with the change in ice volume as a function of solar variations, a model that seems to be highly contrived. His function was:

$$\frac{dx}{dt} = K - xy^A m^C$$

in which, as before, $x$ is ice volume, $y$ is insolation (0 to 1 scale), and $m$ is a so-called memory function representing the average value of $x$ for the previous 57 years. The powers $A$ and $C$ are about 4. While he was able to find good agreement with SPECMAP data, data tuning and model artifices leave this writer with the impression that this was little more than imaginative curve fitting.

## 9.7 MODELS BASED ON ECCENTRICITY OR OBLIQUITY

### 9.7.1 A model based on eccentricity

Bol'shakov (2008) raised a number of objections to the conventional astronomical theory of ice ages. One objection was based on his claim that glaciations appear to occur in both hemispheres in synchrony, whereas the peaks and valleys in solar input are completely out of phase in the north and the south. Furthermore, he was critical of the conventional version of the astronomical theory that is based on the belief: "... a glaciation can only develop if the summer high northern latitudes are cold enough to prevent the winter snow from melting, thereby allowing a positive annual balance of snow and ice." He asserted that this:

> "... cannot be considered to be actually correct. Such an interpretation is incomplete for it considers just a half of the precession forcing, 'cold summer', whereas, one should account for an actually functioning full annual insolation cycle, i.e. long cool summer and short mild winter or long cold winter and short hot summer. It is the full annual insolation cycle for which the specific mechanism of precession climatic forcing should be found."

However, he was treating summer and winter as equal partners in high-latitude climates, when in fact they are grossly unequal. At higher latitudes, winter insolation is negligible and, at latitudes greater than 66.55°, there is actually little direct winter insolation. Almost all direct insolation occurs in summer, so his argument does not make sense.

Convinced that the conventional astronomical theory has fatal flaws (and he may be right for the wrong reasons), he was led to believe that we should seek an effect that changes total solar input to Earth (rather than seasonal variations at high latitudes within a constant total input to Earth). In this regard, he focused on eccentricity. He quoted Croll who said:

> "... the glacial epoch could not result directly from an increase of eccentricity, it might nevertheless do so indirectly. Although an increase of eccentricity could have no direct tendency to lower the temperature and cover our country with ice, yet it might bring into operation physical agents which would produce this effect."

Bol'shakov emphasized the role of feedback mechanisms in amplifying the small signals from variable solar input due to eccentricity changes. He mentioned positive feedback associated with albedo change—due to snow and ice volume and vegetation cover change—and with changes in greenhouse gas concentration. He also described enhancement of atmospheric circulation due to glaciation (the higher temperature gradient from the equator to the poles increases the flow of warm air toward the poles, reducing the temperature gradient) as a negative feedback. However, this moist air can supply moisture to the growing ice sheets and can therefore act as a positive feedback as well.

Bol'shakov claimed that the various feedbacks might not respond in equal measure to the several orbital parameters. He said:

> "The positive indirect relation caused by albedo change in mainly high latitudes of the Earth is likely to enhance strongly the insolation signal associated with variations of Earth axis inclination angle whose highest variations do also occur in high latitudes. Atmospheric circulation speed changes, caused by change of temperature gradients between pole and equator, are most likely first of all to influence the same orbital signal."

Bol'shakov argued that the three orbital parameters could operate independently on the Earth's climate system, rather than acting in concert to change solar input to higher latitudes. Thus he claimed that, prior to about one million years ago,

> "... ice volume wasn't sufficiently high and Earth surface temperature was[n't] sufficiently low to provide the extent of ice comparable to those of the Pleistocene ice sheets. The change of glaciations mainly grouped at high latitudes ... in this situation was caused by rather short-period forcing of axial tilt according to empirically found 41-kyr periodicity of these changes."

In other words, he claims that obliquity alone affected the Earth's climate prior to a million years ago, but this has no technical basis.

Although Bol'shakov admitted, "All those conclusions ... are perfectly legitimate so far as the direct effects of the eccentricity are concerned, and it was quite natural, and, in fact, proper to conclude that there was nothing in the mere increase of eccentricity that could produce a glacial epoch," the essence of his proposal is that sometime around a million years ago, the "Earth surface temperature and glacier mass at high latitudes reached critical values" so that the effect of global insolation change resulting from eccentricity variation "was sufficient to prevent melting of glaciers." In other words, he believes that the climate was driven by obliquity changes prior to a million years ago, but in the last million years it was driven by changes in eccentricity. When the global ice budget reached a certain point, the Earth became sensitized to greater positive feedbacks as a result of albedo and greenhouse gas per unit change in insolation. Thus, he concluded:

> "... for the last million years the development of global glaciations [has been] mainly determined by the simultaneous forcing of eccentricity and obliquity variations enhanced by positive feedbacks effect against the background of the global cooling."

According to this model, glacial–interglacial transitions are primarily controlled by changes in eccentricity, which alters overall solar input to the Earth, modulated somewhat by changes in obliquity. Higher eccentricity produces a warmer climate due to the $1/r^2$ law for solar irradiance. Thus, one can compare the time series of eccentricity with that of climate. If one compares that with measures of ice volume, a time lag would likely be involved.

His arguments do not make sense to this writer. Had he presented them as suggestions of a possibility, they would be received more kindly; however, his bombastic insistence that he has the answers belies the fragility of his arguments.

### 9.7.2 The Mid-Pleistocene Transition

As Figures 2.4 and 5.6 reveal, the fundamental character of ice age–interglacial cycles changed during the past 2.7 million years. Whereas prior to roughly

1 million years ago, climate oscillations had moderate amplitudes and periods near 41,000 years, in more recent times the amplitude of cycles increased considerably and the dominant period extended to roughly 100,000 years. This transition is known as the "Mid-Pleistocene Transition" (MPT) (Clark *et al.*, 2006). Since variations in the Earth's orbit did not change character over the 2.7-million-year time period, the astronomical theory does not predict the MPT. Thus, the MPT poses a challenge to the astronomical theory, and a number of attempts have been made to resolve this without much success.

There are a fair few journal articles that seek the separate effects of orbital parameters (precession, obliquity, and eccentricity) one at a time on historical climates. This makes no sense because the Earth does not react to these orbital parameters directly, at least according to the astronomical theory. The Earth reacts to solar insolation—not to orbital parameters. Because there appears to have been a transition from ~41,000-year cycles before a million years ago or so to ~100,000-year cycles for the past million years or so, some scientists have referred to the earlier epoch as the "obliquity era" and the more recent epoch as the "eccentricity era". This seems strange because both obliquity and eccentricity constantly varied during both eras. No one understands why this transition took place although many have proposed explanations, none of which seem credible to this writer. As we pointed out in Section 3.2.10, Wunsch (1999) emphasized that "the purely random behavior of a rigorously stationary process often appears visually interesting, particularly over brief time intervals, and creates the temptation to interpret it as arising from specific and exciting deterministic causes." For example, Maslin and Ridgwell (2005) discussed the MPT by placing considerable emphasis on the separate roles of individual orbital parameters and their spectral periods.

Huybers (2009a) suggested "that Pleistocene glacial variability is chaotic and that transitions from 40 KY to 100 KY modes of variability occur spontaneously." However, there is no physical explanation why this might be so.

Clark *et al.* (2006) discussed the MPT at some length. They pointed out that this transition occurred over a time period from about 1.25 MYBP to about 700 KYBP. Figure 7.1 shows that on balance the cycles tended to increase somewhat in amplitude and period even after the MPT. As we pointed out at the end of Section 5.1, Clark *et al.* (2006) estimated that there was a "60/40 ice volume/deep-water temperature contribution to the global $\delta^{18}O$ signal over the last several glacial cycles." They then addressed the question of how this affects the MPT: "how much of the increase in amplitude of the $\delta^{18}O$ cycles represents an increase in ice volume relative to additional global cooling of deep-water during glaciations?" They argued that if they assumed contributions of 60% ice volume and 40% deepwater temperature to $\delta^{18}O$ cycles over the past 2.8 million years, then cycles prior to the MPT "indicate significantly smaller changes in ice volume than" cycles after the MPT. Alternatively, had they assumed that much of the increase in $\delta^{18}O$ across the MPT reflects mainly decreasing glacial deepwater temperatures, then similar changes in ice volume would have occurred prior to and after the MPT. They examined a range of data and concluded:

> "In summary, both ice-volume and deep-water temperature contributions to the [$\delta^{18}$O] signal likely changed across the MPT, with an increase in ice volume accompanied by a decrease in deep-water temperatures. The details of the trajectory that each component followed, however, remain unclear and await development of a high-resolution record of deep-water temperature during the MPT."

Since the cyclic variability of solar input to high latitudes has not changed over the past 2.7 million years, it seems evident that the origin of the MPT must lie in the internal climate system. Clark *et al.* (2006) provided a lengthy and detailed discussion of various models that have been proposed to account for the existence of the MPT, but none of these are convincing to this writer.

## 9.8 NORTH OR SOUTH?

If solar intensity variability at high latitudes due to orbital changes is the key factor in producing ice ages and interglacials, should we seek variability in the north, the south, or both? Figure 9.12 shows that solar intensity in the north and south are out of phase by about 11,000 years. Therefore, any model that predicts the accumulation of ice in the NH due to changes in solar intensity in the NH with a time lag of $T$ years is indistinguishable from a model that predicts the accumulation of ice in the NH due to changes in solar intensity in the SH with a time lag of ($T + 11{,}000$) years.

Most studies of glacial–interglacial cycles have assumed *a priori* that variations in solar intensity in the NH (rather than the SH) are relevant, since ice sheets form preferentially in the NH. However, since insolation in the NH and the SH are out of phase by merely 11,000 years, considerable uncertainty creeps into the procedure. Henderson and Slowey (2000) analyzed sediment cores taken in the Bahamas and used an improved dating technique based on $^{234}$U and $^{130}$Th. They concluded that the penultimate deglaciation (end of the previous ice age) took place over a period of about 5,000 years centered on $135.2 \pm 3.5$ KYBP. Henderson and Slowey (2000) pointed out that "this date is ~8 kyr before the peak in northern hemisphere insolation" and suggested: "deglaciation is initiated by a mechanism in the southern hemisphere or tropics." Figure 9.12 shows that solar intensity in the north was near a minimum at 135 KYBP, whereas that in the south was near a maximum. However, if ocean sediments can be used to measure global ice volume, then time lags must be involved. Nevertheless, the Imbrie model (Figure 9.14) does not show a significant reduction in ice volume until 120 KYBP and there is no sign of a termination as early as 135 KYBP in their model. A considerable amount of work has been done on terminations of ice ages since Henderson and Slowey's study in 2000, and this is documented in Section 10.2.3. There is evidence that the SH may play a significant role in terminations. However, it should be noted that the Earth is moving fastest through its perihelion when the Earth is close to the Sun producing high peak solar intensity, as mentioned previously. Conversely, the Earth is moving slowest through its aphelion when the Earth is far from the Sun producing low peak solar intensity. Some investigators have used the length of summer (defined as the number of days with some minimal solar intensity) as a measure of the driving force due to changes in the Earth's orbit (e.g., Huybers and Denton, 2008; Huybers, 2009a). However, the length of summer in one hemisphere varies with time in a very similar manner to peak intensity in the opposite hemisphere. Hence, it is difficult (if not impossible) to distinguish between a forcing due to length of summer in one hemisphere and peak solar intensity in the opposite hemisphere.

# 10

# The astronomical theory and data compared

## 10.1 INTRODUCTION

In attempting to compare astronomical theory with historical climate data, a number of issues arise. One issue is whether the relatively small percentage changes that occur in solar intensity are sufficient to cause major changes in global climate. However, this question is complicated by the possibility that large positive feedback forcings (albedo, ocean currents, wind changes, etc.) might be initiated by smaller changes in solar intensity, leading to large climate changes resulting from comparatively small perturbations. In this connection, it has been postulated that there might be nonlinearities in the way that the climate responds to perturbations, and there may be thresholds that cause discontinuous jumps to a new state when crossed.

Another important question is how one should compare isotope time series data with the time sequence of solar intensity variations? One relevant issue is whether isotope data indicate local temperatures or global ice volume. Temperature measurements are indicative of current climate conditions and are likely to fluctuate rather rapidly. Measurements of ice volume are cumulative and represent an integration of past climate trends as expressed in the accumulation of ice. The curves of ice accumulation vs. time tend to be less stochastic than temperature vs. time curves. Variations in solar intensity take place over many thousands of years and it is not immediately obvious how the timing of such variations should be related to the time variability of temperature or the time variability of ice volume—even assuming that astronomical forcing is the main driver of climate change. Thus, in comparing the timing of changes in solar irradiance with the timing of climate changes, one requires some sort of model that connects the two. The process of deriving the chronology of isotope data is typically a montage based on a number of different inputs. To the extent that some of these are tuned

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books, DOI 10.1007/978-3-642-30029-5_10, 

to the astronomical theory, one should be careful to take into account any circular reasoning in the process of validating the astronomical theory.

Assuming for the sake of argument that orbitally induced changes in solar intensity are the primary drivers for major climate change, a fundamental question is whether the variability of solar intensity in the NH or the SH is most important. While the major characteristic of ice ages is the expansion of ice sheets in the NH, it is not obvious *a priori* whether this results from changes in solar intensity in the NH, or whether it may be due to changes in solar intensity in the SH with consequent changes in ocean currents that affect ice sheet formation in the NH, or some combination of the two. While the overwhelming majority of researchers have assumed that solar variability in the NH is the only relevant factor, a case can be made for the contrary view (see Section 4.3). Some studies compare the isotope time series from ice cores or ocean sediments with variable NH solar intensity, using a time lag for the isotope time series (time lags of 9,000 to over 30,000 years have been used). But, since NH and SH solar intensities are 11,000 years out of phase, one could argue that solar intensity in the SH is the controlling factor and the time lag is artificial.

Finally, instead of comparing the timing of variability in solar intensity with that of the isotope time series, one might carry out spectral analysis of the variability of the two datasets. To the extent that they have similar structures in the frequency domain, that would suggest an underlying connection between the two. M&M provided a very extensive and detailed discussion of spectral analysis which is beyond the scope of this book. A brief discussion of spectral analysis results is given in Section 10.3.

## 10.2 DATA AND THE ASTRONOMICAL THEORY COMPARED

One of the stumbling blocks in the attempt to validate the astronomical theory with sediment core data is the fact that over the past ~2.7 million years there has been a systematic change in the character of climate variations whereas the astronomical theory does not predict such a change. As we showed in Figure 5.6, glacial–interglacial cycles gradually became longer and gained amplitude in the past million years or so. Whereas the period of oscillations in the early part of the 2.7-million-year era of ice ages tended to be near 41,000 years, the period lengthened to roughly 100,000 years over the last million years. In fact, as Figure 7.1 shows, this period has increased by about 40,000 years during the past 800,000 years. This dichotomy between the early and late parts of the past 2.7 million years has confounded scientists for many years, and many papers have been written on the subject, mostly in a vain attempt to resolve the issue in favor of the astronomical theory. In fact, it is rather common for scientists to refer to the early period as the "obliquity period" and the more recent period as the "eccentricity period", as if each of these orbital parameters acted independently on the Earth's climate rather than by contributing to changes in solar intensity (which depends on all three parameters: obliquity, eccentricity, and longitude of precession). There does not seem to be any credible mechanism by which one of these parameters could influence climate independently, so this description of action by independent parameters on climate seems to lack foundation.

Imbrie and Imbrie (1980) have been leaders for many years in the quest to find support for the astronomical theory from isotope data. However, even they admitted that:

> "One of the remaining major problems is the origin and history of the 100,000-year climatic cycle. At least over the past 600,000 years, almost all climatic records are dominated by variance components in a narrow frequency band centered near a 100,000-year cycle. Yet a climatic response at these frequencies is not predicted by the [conventional] astronomical theory—or any other version that involves a linear response .... Another problem is that most published climatic records that are more than 600,000 years old do not exhibit a strong 100,000-year cycle."

Nevertheless, in a rather remarkable twist of logic, they then went on to say:

> "Whatever the outcome of future research on the 100,000-year problem may be—and whatever stochastic or deterministic processes may operate in addition to the astronomical causes—the conclusion seems inescapable that for at least the past 730,000 years, the climate system has responded to orbital forcing at the frequencies of variation in obliquity and precession. Therefore, we argue that the time has come to make a fundamental shift in research strategy: instead of using numerical models of climate to test the astronomical theory, we should use the geological record as a criterion against which to judge the performance of physically motivated models of climate."

This paragraph summarizes the approach taken by the Imbries and, under their influence, by others over the years. The fact that the frequency spectrum of ocean sediment isotope data includes peaks corresponding to obliquity and precession makes it a *fait accompli* in their minds that the astronomical theory is correct, and now the issue is no longer validating the astronomical theory but rather testing climate models that relate solar variability to ice volume to determine which parameters in models agree best with ocean sediment isotope data. Thus, the task consists of curve fitting and parameter adjustment to seek a best fit. However, like George W. Bush in Iraq, they may have declared victory for the astronomical theory prematurely.

In the simplest approach, one could plot solar intensity at some high latitude (north or south?) vs. time on the same axes as long-term isotope data, perhaps with a time offset between the two. This has been done in several instances. Alternatively, one may attempt to develop models for how the variability of solar intensity at high latitudes affects the climate, in general, and the growth of ice sheets, in particular. Such processes are likely to be complex and may introduce nonlinearity, which makes direct comparison of the variability of solar intensity with the variability of isotope ratios difficult to interpret. Several simple models have been developed (as discussed in Section 9.6).

Maslin and Ridgwell (2005) used the term "Mid-Pleistocene Revolution" (MPR) to describe the transition from glacial–interglacial cycles of length ~41,000 years to roughly 100,000 years which occurred about one million years ago. They pointed out that eccentricity is often assumed to be the primary driver of post-MPR climate cycles. They called this the "eccentricity myth".

Lisiecki and Raymo (2005) were able to produce a change in the period of cycles within the Imbrie model by using different parameters for the early, middle, and late periods (see discussion above Figure 5.1 in Section 5.2). However, this seems to fall into the realm of curve fitting rather than physical reasoning.

### 10.2.1 Direct comparison of the variability of peak solar intensity with ice core data

***The last ice age***

Figure 10.1 presents a comparison of smoothed Greenland temperature with yearly solar input at 65°N over the past 150,000 years. In the lower graph representing solar input to 65°N, curve A shows a rise in solar intensity that overlaps with the evolution of the Eemian interglacial. However, the time period from 145

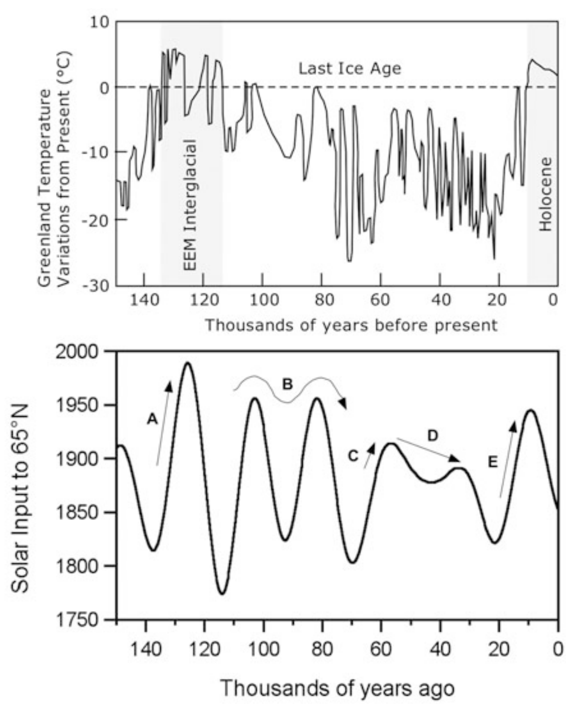


**Figure 10.1.** Comparison of smoothed Greenland temperature with yearly solar input at noon at 65°N over the past 150,000 years.

to 138 KYBP shows a decrease in solar intensity as temperatures were rising. Curves B, C, D, and E are suggestive of temperature variations over their corresponding time periods. There are no indications of any significant time lags in comparing solar intensity with temperature. One would have to conclude that Figure 10.1 is somewhat supportive of the astronomical theory, although the question of time lags (or lack thereof) remains. However, the drop in solar intensity in the past ~10,000 years has not produced a corresponding decrease in temperature.

One obvious conclusion from Figure 10.1 is that there are forces at play that produce very large rapid changes in climate, and there does not seem to be any way that slow ponderous changes in solar input could directly cause these sudden changes. On the other hand, it is possible that solar input, or its rate of change, could trigger other nonlinear effects that could introduce instability in the climate under some conditions. The three likely candidates for such nonlinear effects are (a) changes in average water vapor concentration, (b) changes in albedo due to variation in ice/snow cover, and (c) changes in cloudiness. The potential triggers to initiate such changes might include variability in the meridional overturning circulation (MOC) or changes in the wind field (see Section 8.6.2). Observations regarding Figure 10.1 are given in Table 10.1. While there is fairly good correlation between the overall envelope of temperature changes and the variability of solar input to high northern latitudes, the wild gyrations superimposed on this slowly varying background do not seem to be related to solar variability. But, since these abrupt climate changes are almost as great in magnitude as longer term secular changes, any explanation of long-term secular changes would

**Table 10.1.** Comparison of Greenland temperature trends with solar inputs for the past 150,000 years.

| *Time period* (KYBP) | *Greenland temperature trend* | *Solar input trend* | *Comment* |
|---|---|---|---|
| 140 to ~125 | Sharp rise | Sharp rise | Good correlation after 135,000 YBP. However, temperature rise began while insolation was decreasing |
| 130 to ~115 | Warm, not much change | Sharp drop | No correlation at all. Sharp drop in insolation was not matched by a drop in temperature |
| 110 to ~20 | Several large oscillations | Many oscillations but trending downward | Envelope of temperature data might suggest solar trends |
| 20 to ~10 | Sharp rise | Sharp rise | Good correlation |
| 10 to 0 | Warm, not much change | Sharp drop | No correlation at all |

presumably have to encompass short-term variations. It would seem likely that solar-driven processes are inadequate.

### *The termination of the last ice age*

The last period involving a major climate change was the termination of the last ice age that began roughly 20 KYBP. Figures 4.22 and 9.12 show the behavior of northern and southern insolation. As it turns out, southern insolation rose from a minimum around 31 KYBP to a maximum at 20 KYBP and then proceeded downward to the present low value. Is it possible that the termination of the last ice age began in the far SH as insolation rose to a peak around 20 KYBP? Stott *et al.* (2007) used radiocarbon ($^{14}C$) dating of ocean sediments to establish the timing of deep-sea and tropical surface ocean temperature changes during the last glacial termination and compared this history with the timing of $CO_2$ changes and deglacial warming in southern high latitudes during the last glacial termination. They concluded that the onset of deglacial warming throughout the Southern Hemisphere occurred long before deglacial warming began in the tropical surface ocean. Both the rise in $CO_2$ and the increase in tropical sea surface temperatures did not begin to change until approximately 1,000 years after Southern Ocean warming began. In a second paper, Timmermann *et al.* (2009) carried out modeling to show the likely cause of initiation of deglaciation after 20 KYBP was the increase in insolation during austral spring when the southern ice pack was at a maximum, coupled with the sea ice–albedo feedback as the sea ice went into retreat. As the $CO_2$ concentration rose, this added another warming feedback. This explanation seems to fit the last several deglaciations. However, there were many increases in SH insolation in the past few hundred years that did not lead to a deglaciation so this appears to be a *necessary* condition but not a *sufficient* one. Furthermore, their models for solar insolation do not agree with Figures 4.16b and 9.12.

### *The last few ice ages*

Figure 10.2 shows the variation of solar input to 65°N over the past 800,000 years. This figure shows that solar input to higher latitudes rapidly oscillates due to precession of the seasons as time progresses. The variability of eccentricity imposes an envelope on these oscillations with a period of about 100,000 years. Obliquity during periods of higher eccentricity affects the amplitude of the envelope. Some periods have higher amplitudes of oscillation. These are earmarked with +, ++, or +++ signs in the figure, depending on the relative amplitudes.

Figure 10.3 compares temperature measured at Antarctica with yearly solar input at 65°N over the past 800,000 years. In this figure vertical dashed lines are drawn at temperature peaks in the Antarctic ice core data. Arrows depict trends between cycles. The shaded areas correspond to the periods of high solar amplitude from Figure 10.2. In most cases, periods with high-amplitude solar oscillations correspond to interglacial periods, whereas periods with low-amplitude solar oscillations correspond to ice ages.

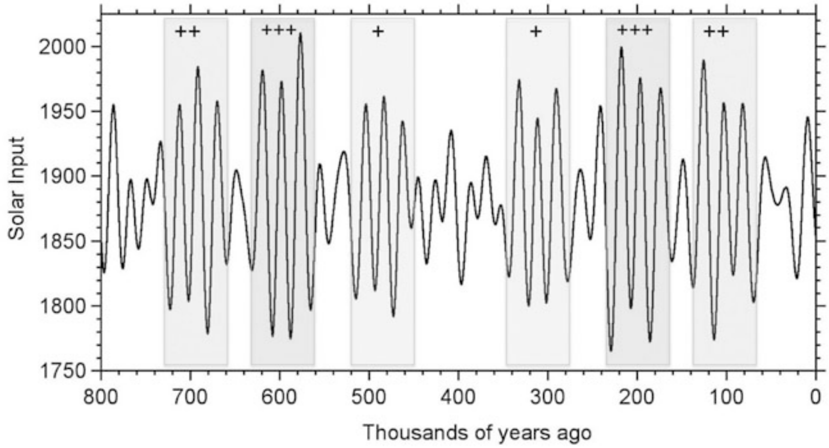


**Figure 10.2.** The variation of solar input to 65°N over the past 800,000 years.

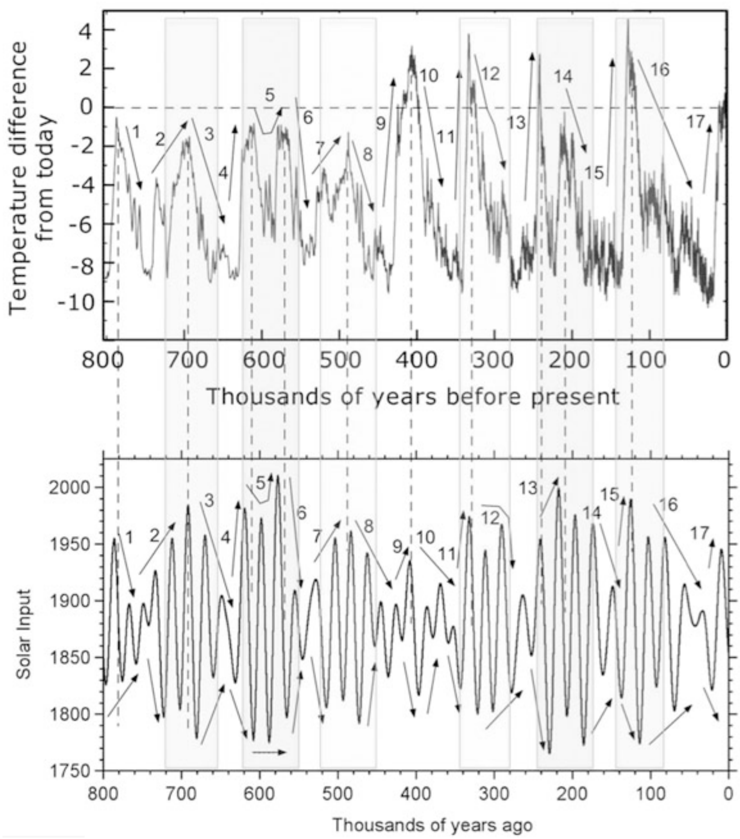


**Figure 10.3.** Comparison of Antarctic ice core data with calculated solar input at 65°N over 800,000 years: (upper panel) Antarctic data; (lower panel) solar input to 65°N.

Table 10.2 provides a summary of the relationships between trends in temperature over this time period and trends in yearly solar input at 65°N.

Table 10.2 shows that there tends to be a correlation (with some exceptions) between the amplitude of solar variations and temperature as measured in Antarctica. Temperatures do not increase or decrease in proportion to solar input. Instead, temperatures rise when solar input oscillates with high amplitude, and temperatures drop when solar oscillations are reduced in amplitude. Most periods with high-amplitude swings in solar input tend to be associated with higher temperatures and vice versa, although a few transitions do not fit this description.

**Table 10.2.** Comparison of Antarctic ice core data with calculated yearly solar input at 65°N over 800,000 years based on Figure 10.3.

| *Transition in Figure 10.2* | *Antarctica temperature* | *Solar input trend* | *Comments* |
|---|---|---|---|
| 1 | Decreasing | Decreasing oscillations | Agreement |
| 2 | Increasing | Increasing oscillations | Agreement |
| 3 | Decreasing | Decreasing oscillations | Agreement |
| 4 | Sharp increase | Increasing oscillations | Agreement |
| 5 | Double peak | Several high oscillations | Rough agreement |
| 6 | Decreasing | Decreasing oscillations | Agreement |
| 7 | Slowly rising | Slowly increasing oscillations | Agreement |
| 8 | Decreasing | Decreasing oscillations | Agreement |
| 9 | Very sharp rise | Very small increase in oscillation; trend slightly up | Disagreement |
| 10 | Strong decrease | Decreasing oscillations | Agreement |
| 11 | Very sharp rise | Increasing oscillations | Agreement |
| 12 | Strong decrease | Not much change | Disagreement |
| 13 | Sharp increase | Large increase in oscillations | Agreement |
| 14 | Decreasing | Decreasing oscillations | Agreement |
| 15 | Sharp increase | Large increase in oscillations | Agreement |
| 16 | Decreasing | Decreasing oscillations | Agreement |
| 17 | Sharp increase | Small increase in oscillations | Poor agreement |

One violation of this correlation is the sharp rise in temperature that occurred about 400,000 YBP (Transition 9 in Figure 10.3), when solar oscillations were minimal. Another exception occurred in the sharp rise in temperature at around 800,000 YBP when solar oscillations were moderate. The problem at 400,000 YBP has been widely discussed in the literature and is referred to as the "Stage 11 problem" (based on SPECMAP Stages, see Figure 5.2). M&M discussed the "Stage 11 problem". They concluded that there is no good solution to this problem in the astronomical theory. They noted that Raymo (1997) attempted to account for this problem by developing a complex criterion by which even small changes in solar input could trigger a termination if enough ice had accumulated, but that approach has serious problems (see Section 6.4.4 of M&M). Two other possible approaches to deal with the Stage 11 problem were discussed by M&M. One approach was to postulate that the same resonant system that drives the 100,000-year cycle also acts as a flywheel to keep the cycle oscillating when the driving force is small. "Thus, you don't have to push on a swing every cycle to keep it high." Berger (1999) did this with his resonance memory model. However, this model seems very artificially contrived to this writer. M&M claim that the orbital inclination theory "solves the Stage-11 problem immediately, since no such minimum in dust accretion occurs at Stage-11 ..." However, the detailed mechanisms involved in this theory are obscure to this writer.

One possible interpretation of Figure 10.3 is that the natural state of the Earth's climate in the past 800,000 years may have been glacial. During those periods, of the order of perhaps ~50,000 to 60,000 years, when oscillations in solar input are minimal, solar input never gets high enough to melt summer ice, climate cools, and ice sheets build up. However, during those periods when oscillations in solar input are large, solar input gets high enough during the up-lobes of oscillations to melt summer ice, ice sheets diminish, and climate warms. Even though there are also steep downward oscillations in solar input, the down-lobes are insufficient to rebuild ice sheets lost in the previous upward oscillation, probably due to albedo effects and the likelihood that ice sheets build slowly and disintegrate more rapidly.

Thus, we find that solar input to higher latitudes oscillates relentlessly with a 22,000-year period due to precession of the equinoxes. These oscillations act like a radio carrier signal. It is the amplitude of the oscillations—not the frequency—that seems to be of importance. As in AM radio, the signal is amplitude-modulated due to changes in eccentricity and obliquity. When the amplitude of oscillations is high, there is a tendency toward reducing global ice and heading into an interglacial period. When the amplitude is small, ice volume tends to increase and the ice age deepens. According to this interpretation, the Earth naturally tends toward an ice age (at least over the last few hundreds of thousand years). Ice sheets build more slowly than they disintegrate. During periods of small oscillations, solar input does not reach high enough levels to impede this natural growth of ice sheets. During periods of high amplitude of oscillations, solar input reaches high enough levels on the up-lobes to reverse ice sheet growth, and rebuilding of ice sheets in the down-lobes does not occur fast enough to stop

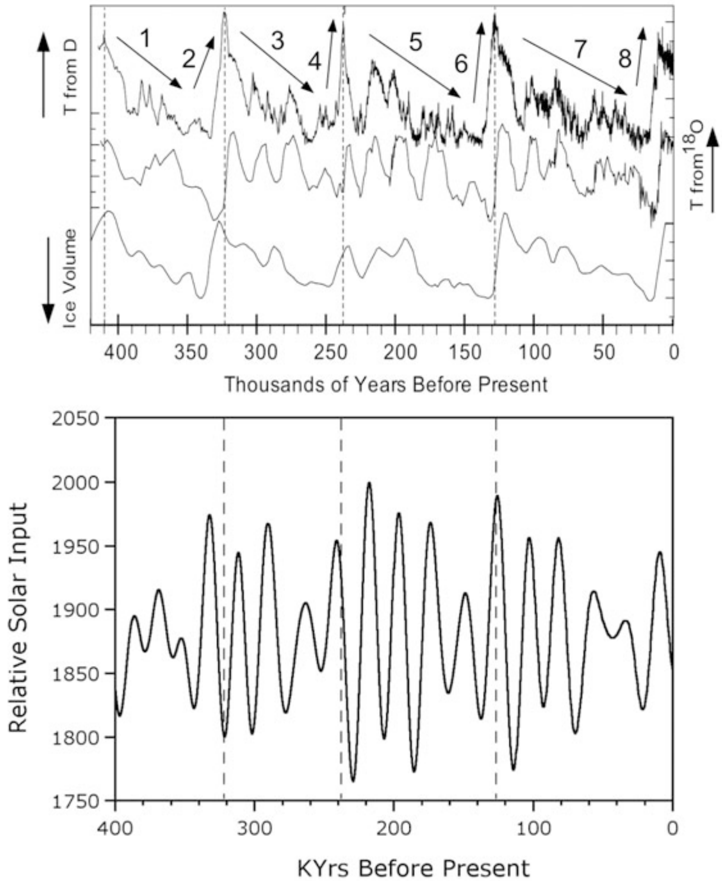


**Figure 10.4.** Comparison of Antarctic ice core data with calculated solar input at 65°N over 400,000 years: (upper panel) Vostok data; (lower panel) solar input to 65°N.

the decay of ice sheets. This model does not work perfectly at all times but it does seem to fit the data to some extent. It would explain why the 22,000-year precession frequency does not show up in the frequency spectrum of the ice core time series.

A similar effect occurs with Vostok data over 400,000 years (as shown in Figure 10.4). Temperature increases shown as paths 2, 4, 6, and 8 seem to be associated with sharp upward oscillations in solar intensity, producing short-lived (e.g., about half of the 22,000-year precession cycle) interglacial periods. However, these are always followed by sharp downward oscillations in solar intensity that begin new ice ages. Even though significant solar oscillations persist, once a downward trend in temperature is established (and ice sheets form) the ice age deepens along paths 1, 3, 5, and 7.

While there is some circular reasoning in the fact that tuning was used to establish the chronology of Antarctic ice core data, Figures 10.3 and 10.4 are suggestive of a relationship between large solar oscillations and the occurrence of interglacial periods (and vice versa). However, the agreement is far from perfect. For example, the period from 240 to 160 KYBP has large solar oscillations, yet temperatures drop after peaking around 240 KYBP. It is also noteworthy that the abrupt climate changes observed at Greenland are heavily muted in Antarctic data. Furthermore, as Wunsch pointed out, there is a danger that the more one looks at these figures, the more one "sees" until perhaps one can see things that are not statistically meaningful. Many solar oscillations occur during ice ages and it is not immediately clear why some seem to produce interglacials and some do not.

### 10.2.2 The Imbrie ice volume model and ocean sediment data compared

The Imbrie ice volume model integrates solar irradiance with time, and its use of longer time constants for the buildup of ice sheets than the decay assures that during periods of strong solar oscillations the loss of ice during high solar input will outweigh the gain in ice during low solar input, so that on balance ice sheets will diminish when solar input is oscillating wildly. Conversely, during periods when solar input is not oscillating widely the Earth system will revert to its (presumably) natural glaciated state.

When the Imbrie model is compared with data over 800,000 years, the result is as shown in Figure 10.5. Our independently calculated rendition of their model agrees exactly with Figure 6.10 of M&M. However, the Imbries' presentation of their results (in the upper graph of Figure 10.5) differs somewhat from our version. In general, our rendition of the Imbrie model provides much larger (and more frequent) oscillations than those of ocean sediment data. Although there are some similarities between the model and the data, there are also significant differences.

A serious problem with the astronomical model is accounting for the fact that the character of glacial–interglacial cycles changed fundamentally over the past several million years. As Figure 5.6 shows, the overall average trend of Earth temperature has been downward for the past 3,000,000 years, permeated by frequent oscillations about the long-term secular trend. The oscillations were initially rapid and small. From about 3 to about 1 MYBP the oscillations increased in amplitude but remained rapid. Over the past million years or so, the oscillations increased dramatically in amplitude and became less frequent. As Figure 7.1 shows, the spacing between ice ages has increased by about 40,000 years over the past 800,000 years. Yet the long-term behavior of solar input to high latitudes did not change much over that 3-million-year period. Lisiecki and Raymo (2005) modified the Imbrie ice accumulation model by utilizing different parameters before and after 1 MYBP, but there does not seem to be any fundamental physical reason for making this choice except as an exercise in curve fitting.

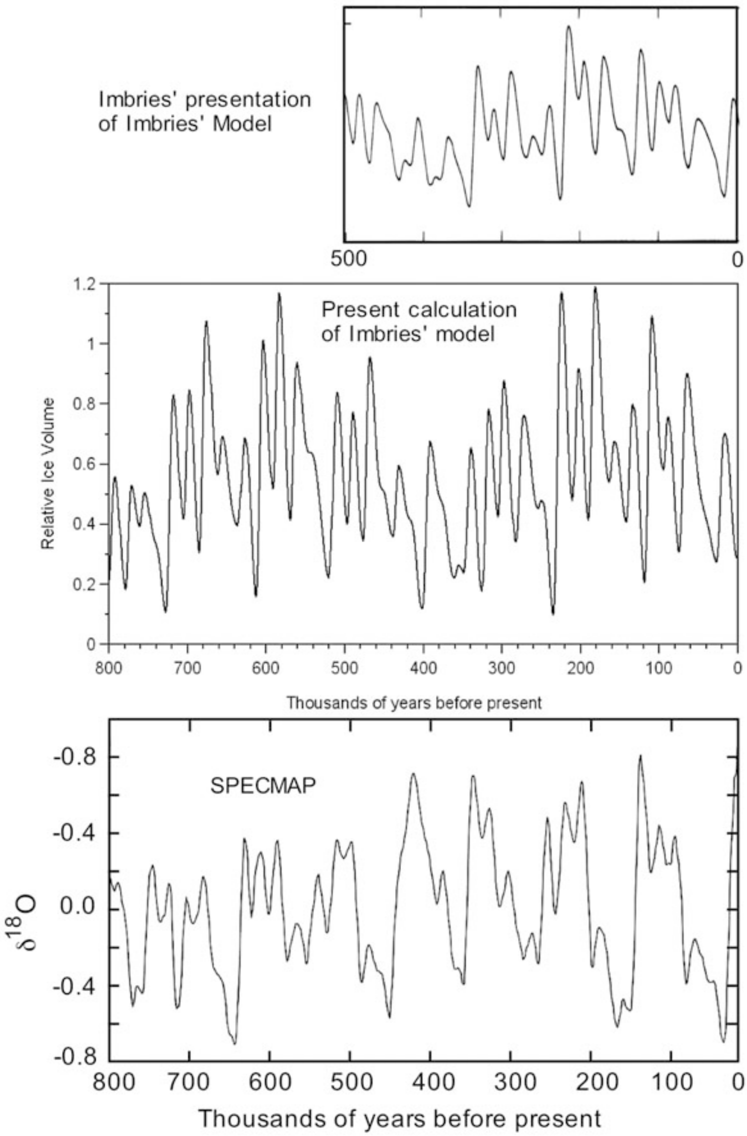


**Figure 10.5.** The Imbrie model and SPECMAP compared: (upper) the Imbries' presentation of their ice volume model; (middle) the present evaluation of the Imbrie model (which agrees with M&M's Figure 6.10); and (lower) SPECMAP.

### 10.2.3 Change in ice sheet volume and peak solar intensity compared

The usual procedure for comparing the astronomical theory with ocean sediment data is based on the assumption that benthic ocean sediment data represent ice sheet volume ($V$) and, thus, it is necessary to integrate insolation (e.g., via the

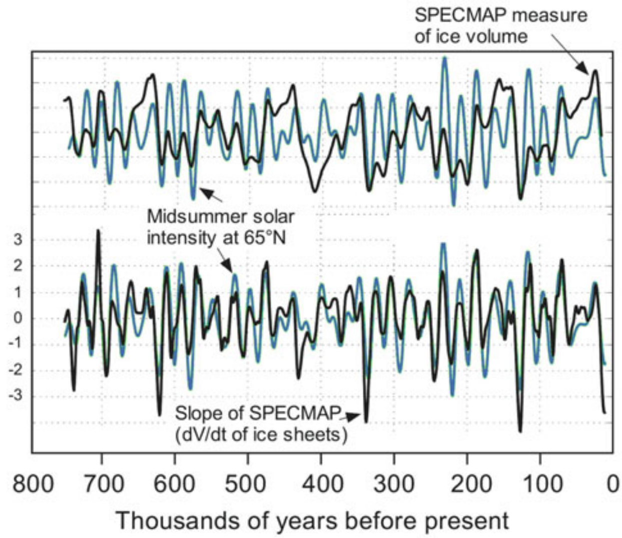


**Figure 10.6.** Comparison of inverse solar input to 65°N (Figure 9.11) with the slope of SPECMAP (Figure 5.4) over the past 800,000 years. Note that the solar curve is plotted inversely so that higher solar intensities lie lower on the vertical scale (adapted from Roe, 2006).

Imbrie ice accumulation model) to obtain a function proportional to ice sheet volume that can be compared with ocean sediment data. Figure 10.5 shows the result of such a comparison.

An alternative approach was suggested by Roe (2006).[1] In this approach one differentiates benthic ocean sediment data to obtain $dV/dt$ instead of integrating insolation. The slope of ocean sediment data is interpreted as the rate of change of the ice volume, and this is compared directly with the variability of insolation on the same time scale. One of Roe's results is shown in Figure 10.6. The agreement between the slope of the SPECMAP curve and the solar curve is impressive.

Nevertheless, a few caveats are in order. First, the fact that SPECMAP was tuned to the solar intensity curve forces the oscillations in $dV/dt$ to match the oscillations in the solar curve. Second, the SPECMAP curve is not very precise, and assessing slopes on nearly vertical trends can be tricky. Some chartsmanship is involved. Third, as we pointed out in Section 5.4, the time scale for SPECMAP is believed to contain serious errors prior to 600 KYBP. Fourth, as shown in Section 5.1, Lisiecki *et al.* (2008) discussed the assumption that benthic $\delta^{18}O$ represents a phase of changing ice volume despite the fact that benthic $\delta^{18}O$ is also affected by deepwater temperature change. However, they put forth a basis for assuming that the benthic $\delta^{18}O$ can be interpreted as representing ice volume. They also said: "Generating a robust age model for benthic $\delta^{18}O$ or ice volume

[1] Seemingly unknown to Roe, Nigel Calder came up with a similar idea back in 1974. See *http://calderup.wordpress.com/2010/07/10/milankovitch-back-to-1974/*

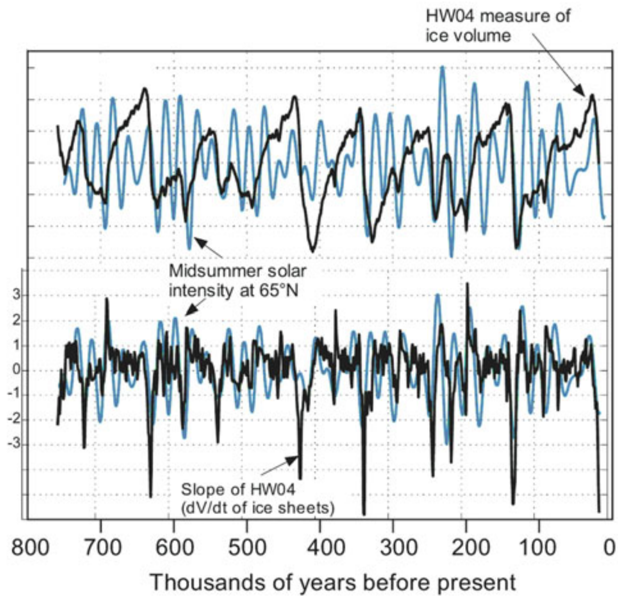


**Figure 10.7.** Comparison of inverse solar input to 65°N (Figure 9.11) with the slope of HW04 over the past 800,000 years. Note that the solar curve is plotted inversely so that higher solar intensities lie lower on the vertical scale (adapted from Roe, 2006).

without the assumptions of orbital tuning remains an important, unsolved problem.'' While tuning was used to generate the chronology of SPECMAP, the agreement between $dV/dt$ and solar intensity in Figure 10.6 is nevertheless impressive.

Roe (2006) also carried out a similar analysis for the ocean sediment record developed by Huybers and Wunsch (2004), which did not utilize orbital tuning. In this case, however, comparison of $dV/dt$ with the solar curve is not as good. Figure 10.7 shows the result of comparing the HW04 sediment curve with the solar curve and the slopes of the HW04 sediment curve with the solar curve.

At first glance, there seems to be fair agreement between the slopes of the HW04 curve and the solar intensity curve. However, when one increases the size of the graphs, difficulties appear.

Figure 10.8 highlights six specific time periods where further discussion is appropriate (these are not the only ones). Between about 730 and 700 KYBP, solar intensity went through two oscillations. The first had an upturn in solar intensity at around 720 KYBP producing a sharp drop in $dV/dt$. The second had an upturn at around 700 KYBP producing almost no change in $dV/dt$. It might be supposed that the first downturn reduced the ice sheet to the point that further increases in solar intensity would have little effect, but there is nothing unique about the upturn at 720 KYBP. Between about 620 and 590 KYBP, solar intensity underwent wild gyrations while the ice volume hardly changed. The small sawtooth features in the $V$ curve then translate into larger gyrations in $dV/dt$. Are those small saw-

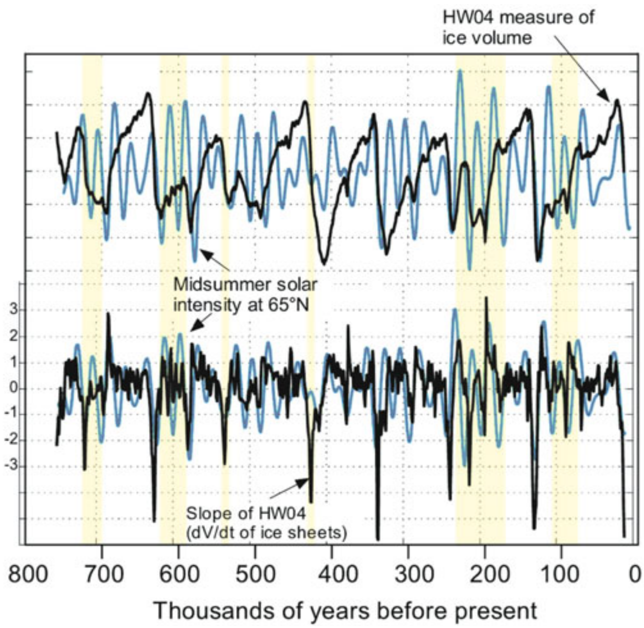


**Figure 10.8.** Comparison of inverse solar input to 65°N (Figure 9.11) with the slope of HW04 over the past 800,000 years. Note that the solar curve is plotted inversely so that higher solar intensities lie lower on the vertical scale (adapted from Roe, 2006). The vertical yellow bands are time periods discussed in the text. Note the horizontal offset of the $dV/dt$ curve from the $V$ curve. This was necessary to make the near-vertical features of the $dV/dt$ curve match the near-vertical features of the $V$ curve.

tooth features in the $V$ curve reliable? At around 540 KYBP, there was a modest increase in solar intensity accompanied by a large decrease in the ice volume. Why did this relatively small change in solar intensity produce a large change in the ice volume? Around 430 KYBP an even smaller increase in solar intensity produced a much larger reduction in the ice volume. Between about 230 and 180 KYBP, there were three large oscillations in solar intensity. The first and third produced increases in ice volume while the second produced a decrease. Between about 100 and 70 KYBP, the situation was similar to that between 620 and 590 KYBP when large changes in solar intensity are associated with small sawtooth features on the ice sheet volume curve. If the small sawtooth features on the ice volume curves are credible, the comparison of $dV/dt$ with solar intensity is better, but it is far from perfect. There is a degree of chartsmanship in Figures 10.6 and 10.7 and, when the graphs are expanded to much larger sizes, the discrepancies are more discernible. Nevertheless, the results, even for HW04, are highly suggestive of solar influence. Roe's final conclusion sums up the situation well:

> "The Milankovitch hypothesis as formulated here does not explain the large rapid deglaciations that occurred at the end of some of the ice age cycles: many

studies point to the need to invoke internal dynamics of ice sheets as a mechanism for occasional rapid collapses if a threshold size is exceeded. Nor do the results explain the mid-Pleistocene transition between an earlier interval characterized by 40 kyr durations of ice ages and a later interval with 80 kyr to 120 kyr durations .... The prevailing view to date has been that ice sheet volume is the most important variable to consider. While this is obviously the case for global sea level, it is ice sheet extent that matters most for albedo, and ice sheet height that matters for atmospheric circulation .... Ice sheets are dynamic systems and these properties can vary quite differently from each other. However, the results presented here demonstrate the critical physical importance of focusing on the rate of change of ice volume, as opposed to the ice volume itself. The available evidence supports the essence of the original idea . . . [that] (1) the strong expectation on physical grounds that summertime insolation is the key player in the mass balance of great Northern Hemisphere continental ice sheets of the ice ages; and (2) the rate of change of global ice volume is in antiphase with variations in summertime insolation in the northern high latitudes that, in turn, are due to the changing orbit of the Earth."

### 10.2.4 Terminations of ice ages and origins of interglacials

We have previously seen that ice ages tend to end rather abruptly compared with their slow rate of formation over many tens of thousands of years. A number of studies have been carried out in an attempt to understand why this occurs, but none of these are entirely satisfactory.

Rothlisberger *et al.* (2008) investigated the phasing between a South American dust proxy (non sea salt calcium flux, nssCa), a sea ice proxy (sea salt sodium flux, ssNa), and a proxy for Antarctic temperature (deuterium, $\delta$D) to determine whether a similar sequence of events applied to the last nine ice age terminations. The connections between nssCa, ssNa, and $\delta$D are discussed in the paper; these did not appear very illuminating to this writer. However, the $\delta$D over nine terminations was very interesting. The data were analyzed using a simple model of a linear ramp connecting pre- and post-termination properties, with the ramp constituting the termination period. In some cases, the transition from pre- to post-termination conditions occurred not merely with one ramp—but several. The ramp data are summarized in Table 10.3.

It is interesting to compare the termination periods from Table 10.3 with the peak solar intensity at 65°N (as shown in Figure 10.9). It is rather impressive that every single termination occurs on an upswing in solar input. However, some of these upswings in solar input are very modest. The last four terminations were coincident with stronger upswings in peak solar intensity at 65°N.

We can compare the results of Rothlisberger *et al.* (2008) for the onset of terminations with dates compiled by others (as shown in Table 10.4). There is fairly good agreement between investigators.

**Table 10.3.** Data on the origins and completions of ramps from pre-termination to post-termination conditions (Rothlisberger *et al.*, 2008). Dates are in thousands of years before the present, and temperature is measured by δD.

| | KYBP | δD | | KYBP | δD |
|---|---|---|---|---|---|
| | 8 | 395 | | 416 | 395 |
| | 11.5 | 395 | Post-termination | 426 | 395 |
| | 12.3 | 410 | Pre-termination | 430.6 | 438 |
| Post-termination | 14.8 | 410 | | | |
| Pre-termination | 17.6 | 440 | | 520 | 416 |
| | 20 | 440 | Post-termination | 529 | 416 |
| | | | Pre-termination | 540 | 432 |
| | 120 | 390 | | | |
| | 126 | 390 | | 620 | 403 |
| | 128 | 370 | Post-termination | 626 | 403 |
| Post-termination | 129.5 | 370 | Pre-termination | 629.5 | 438 |
| Pre-termination | 135.4 | 435 | | 640 | 438 |
| | 140 | 435 | | | |
| | | | | 730 | 420 |
| | 240 | 400 | | 733 | 413 |
| Post-termination | 242 | 380 | Post-termination | 737.5 | 413 |
| Pre-termination | 246 | 430 | Pre-termination | 741 | 440 |
| | 260 | 430 | | 750 | 440 |
| | 330 | 390 | | 780 | 400 |
| | 332 | 390 | Post-termination | 788 | 400 |
| Post-termination | 333.7 | 370 | Pre-termination | 796 | 440 |
| Pre-termination | 341.2 | 440 | | 800 | 440 |
| | 350 | 440 | | | |

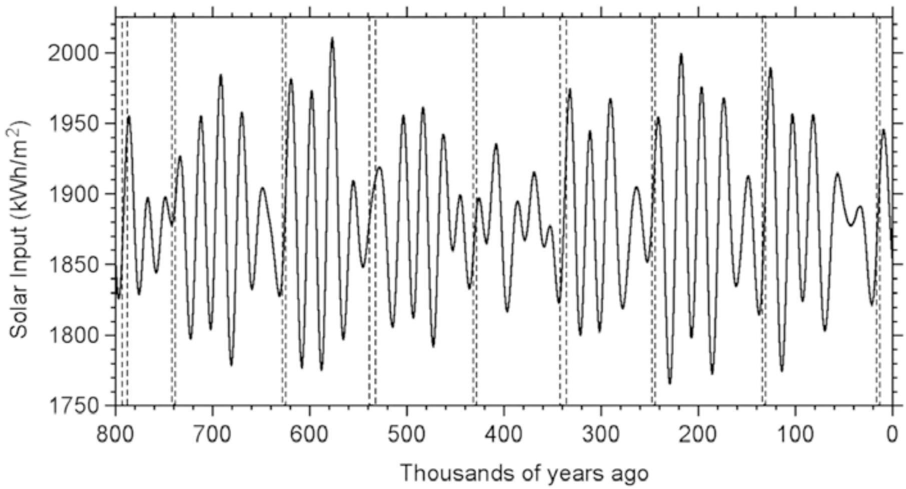


**Figure 10.9.** Peak solar intensity at 65°N shown along with termination ramps (from Rothlisberger *et al.*, 2008).

**Table 10.4.** Comparison of estimated dates for onset of terminations (KYBP).

| *Termination* | *Rothlisberger et al. (2008)* | *Raymo (1997)* | *Lisiecki and Raymo (2005)* | *Huybers and Wunsch (2004)* | *Schulz and Zeebe (2006)* |
|---|---|---|---|---|---|
| 1 | 17.6 | | 14 | 11 | 23 |
| 2 | 135.4 | | 130 | 129 | 139 |
| 3 | 246 | 248 | 243 | 239 | 253 |
| 4 | 341 | 339 | 337 | 332 | 345 |
| 5 | 431 | 424 | 424 | 419 | 419 |
| 6 | 540 | 535 | 533 | 532 | 546 |
| 7 | 629.5 | 622 | 621 | 623 | 632 |
| 8 | 741 | | | | |
| 9 | 796 | | | | |

Kawamura *et al.* (2007) presented high-resolution chronologies of the last four glacial terminations. Their results are compared with those of Rothlisberger *et al.* (2008) in Figures 10.10 to 10.13. There is very good agreement between these two investigations. The variation in peak solar intensity at 65°N and 65°S is also

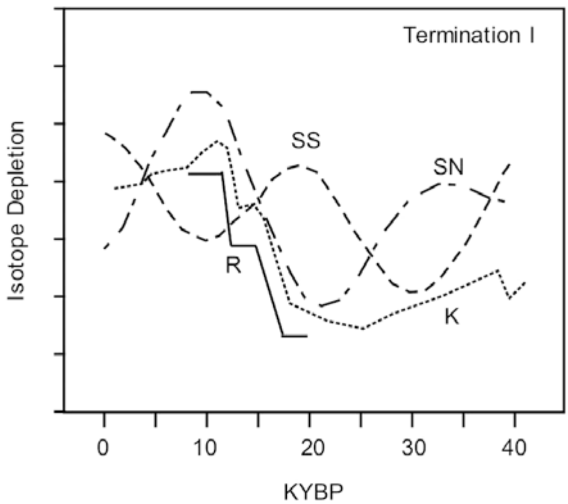


**Figure 10.10.** Chronology of Termination I: K = results of Kawamura *et al.* (2007); R = results of Rothlisberger *et al.* (2008); SN = relative peak solar intensity at 65°N; SS = relative peak solar intensity at 65°S.

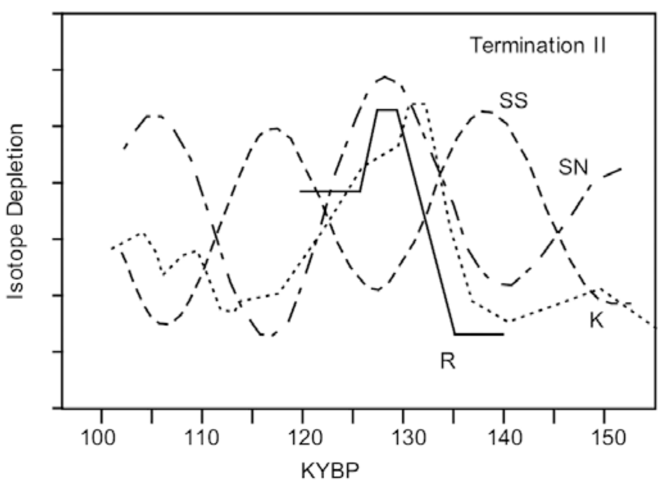


**Figure 10.11.** Chronology of Termination II: K = results of Kawamura *et al.* (2007); R = results of Rothlisberger *et al.* (2008); SN = relative peak solar intensity at 65°N; SS = relative solar insolation at 65°S.

shown in these graphs. A number of investigators have proposed alternative explanations for the source of ice age terminations. These tend to revolve about changes in insolation in the NH or the SH, often with quite contradictory interpretations.

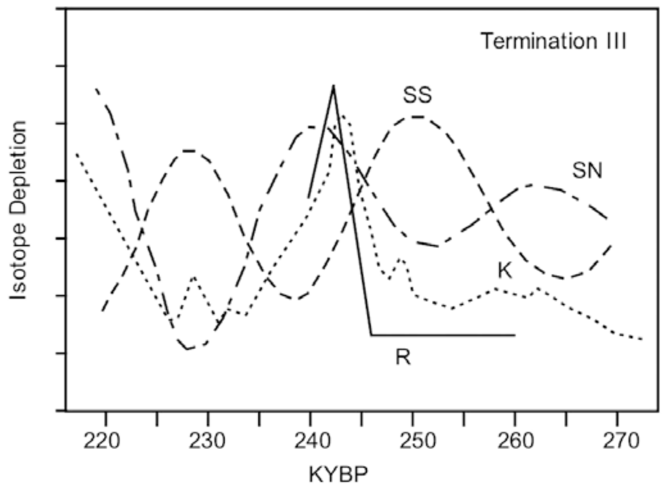


**Figure 10.12.** Chronology of Termination III: K = results of Kawamura *et al.* (2007); R = results of Rothlisberger *et al.* (2008); SN = relative peak solar intensity at 65°N; SS = relative solar insolation at 65°S.

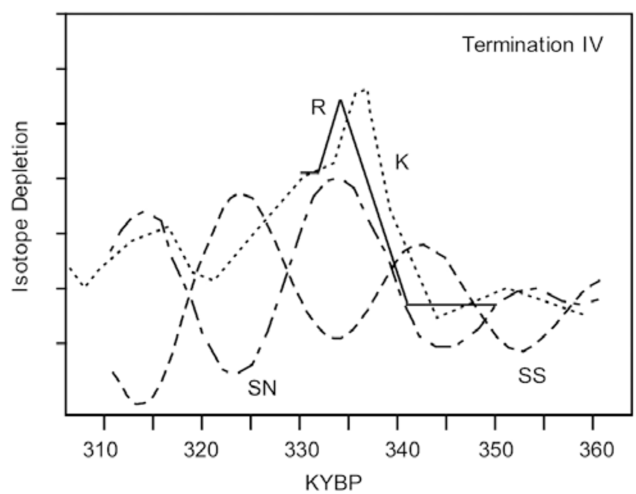


**Figure 10.13.** Chronology of Termination IV: K = results of Kawamura *et al.* (2007); R = results of Rothlisberger *et al.* (2008); SN = relative peak solar intensity at 65°N; SS = relative solar insolation at 65°S.

The durations required for transitions from glacial to interglacial conditions in the last nine deglaciations are listed in Table 10.5. On average, the duration of these transitions was about 6,000 years.

In discussions of terminations most authors are convinced that terminations

**Table 10.5.** Durations required for the transition from glacial to interglacial conditions.

| *Time period* (KYBP) | *Duration of transition* (kyr) |
|---|---|
| 18–11 | 7 |
| 135–130 | 5 |
| 246–242 | 4 |
| 341–334 | 7 |
| 431–426 | 5 |
| 540–529 | 11 |
| 630–626 | 4 |
| 741–738 | 3 |
| 796–788 | 8 |

are solar driven: some find SH insolation to be important, others find NH insolation to be important, and at least one believes it is the combination of NH and SH insolation that is important. The problem is that identifying the connection between ice core chronology and variable insolation (whether NH, SH, or both) is a subjective process that depends mostly on the perception of the viewer. Furthermore, as pointed out previously, the pattern of variability of peak solar intensity in one hemisphere is indistinguishable from that for the length of summer in the other hemisphere. Establishing a cause–effect relationship is difficult, and too many scientists seem to have formed premature judgments based on inadequate data. In several cases, authors have not adequately distinguished between *necessary* and *sufficient*. Solar patterns that occur with deglaciations may occur when no deglaciation occurs. These analyses would be more palatable if they were not so emphatic; a little humility would go a long way.

Kawamura (2009) pointed out that Figures 10.10 to 10.13 show that each of the past four terminations occurred during an upswing in NH insolation and, therefore, he concluded that NH insolation drives deglaciations and claims that warming in Antarctica causes deglaciation are not valid. While it appears to be true that deglaciations occurred during upswings in NH insolation, some of these upswings were quite moderate in amplitude and larger upswings occurred at other times that did not cause a deglaciation. Figure 10.9 shows the onsets of deglaciation for the past nine terminations (from Rothlisberger *et al.*, 2008) on the same timeline as peak solar intensity at 65°N. It is impressive that all nine onsets of deglaciation were associated with upswings in insolation. The problem with this is that some of these upswings are quite small in amplitude. Why were there no deglaciations at other large-amplitude upswings? As previously stated, there is a difference between *necessary* and *sufficient*.

Spotl *et al.* (2002) analyzed an alpine speleothem and found the termination date for the previous ice age to be 135 KYBP. Cheng *et al.* (2009) used $\delta^{18}O$ isotope records from stalagmites from Sanbao Cave, China, to characterize Asian Monsoon precipitation through Terminations III and IV. Combining these with earlier Chinese cave results, Asian Monsoon records were presented for the past four glacial terminations. Because these records were dated with $^{230}Th$, the chronology is claimed to be quite accurate. The interpretation of $\delta^{18}O$ isotope records is complex. It is believed that most of the variability in $\delta^{18}O$ records derives from changes in the $\delta^{18}O$ of precipitation. Most precipitation in southeastern China is summer monsoon rainfall, with distinctly lower $\delta^{18}O$ than precipitation during the rest of the year, and thus the value of $\delta^{18}O$ indicates the relative amount of precipitation during the summer monsoon compared with precipitation during the rest of the year. These measurements of $\delta^{18}O$ do not measure temperature. Monsoon rainfall has a distant source whereas other rainfall is believed to be local. To the extent that the amount of precipitation in the annual southeastern China summer monsoon depends on the climate in the NH, the measurements in the Chinese caves might provide a measure of climate fluctuations in the NH over the past several hundred thousand years. The results of Cheng *et al.* (2009) for the variation in $\delta^{18}O$ isotope records during the past four termination periods show remarkable similarity to the peak insolation curves for 65°N during those periods. This suggests that the variability of monsoon precipitation levels is controlled by insolation in the far north of the NH. The timing of the steepest rise in terminations is similar to that from ice cores although the remaining $\delta^{18}O$ isotope records from caves deviate considerably from those obtained from ice cores. Cheng *et al.* (2009) argued that their chronology could be applied to ice core records at various tie points, but this may not be justifiable. While the cave data seem to religiously follow peak insolation curves, ice core data do not. They claimed: "in all four [terminations], observations are consistent with a classic Northern Hemisphere summer insolation intensity trigger for an initial retreat of northern ice sheets." The data do not require this claim to be true, although it may ultimately prove to be.

Severinghaus (2009) wrote a brief commentary on the paper by Cheng *et al.* (2009). Severinghaus apparently accepted the claim of Cheng *et al.* (2009) of being able to date ice core and ocean sediment records accurately, despite admitting that "the exact mechanism that links cold winters to weak monsoons is still debated." He also emphasized: "the authors find that the last four meltdowns began when northern sunshine was intensifying, in accordance with the classical Milankovitch or astronomical theory of the ice ages." However, there were other upswings that did not produce deglaciation. Why were there no deglaciations at other large-amplitude upswings?

Severinghaus also accepted the theory that the MOC is involved in the melting of ice sheets. However, his discussion of this theory seems rather convoluted. He said:

> "The melting ice sheets inject so much low-density fresh water into the North Atlantic that they weaken or entirely shut down the normal sinking of dense water that fuels the ocean circulation .... The loss of this circulation allows sea ice to cover the North Atlantic in winter, preventing ocean heat from warming the air and leading to extremely cold winters in Europe and Eurasia, ...."

This statement does not explain what made the ice sheets melt in the first place, nor does it explain how this putative shutdown of the MOC contributes to warming when it seems to be a cooling process. To answer this, he invoked the following hypothesis:

> "Is there something about an 'off' MOC that helps to destroy an ice sheet? Cheng *et al.*'s timing data provide support for the hypothesis that an 'off' MOC forces $CO_2$ out of the Southern Ocean, warming the globe by its greenhouse effect, which in turn causes more melting of the ice sheets, ensuring that the MOC stays in its 'off' position in a positive-feedback loop."

Severinghaus claimed that "an 'off' MOC forces $CO_2$ out of the Southern Ocean, warming the globe by its greenhouse effect." He went on to say: "an alternative hypothesis is that massive ice sheets are inherently vulnerable and cannot survive the combined onslaught of Milankovitch and $CO_2$." Severinghaus seems to have been determined to make rising $CO_2$ concentration a cause of termination rather than an effect; yet it is not clear why the $CO_2$ concentration should rise due to the putative self-inflicted shutoff of the MOC.

Like Severinghaus, there are a number of proponents of the hypothesis that the MOC can be turned on and off, with consequences for climate change. Broecker originated this concept in the 1980s and 1990s. Rahmstorf (2002) discussed the role of the MOC in climate change (see Section 8.6.1). The impacts on climate of the putative on/off behavior of the MOC have been interpreted in various ways, often with contradictory conclusions. It seems likely that, if this process occurs at all, it probably accounts for some sudden climate fluctuations, but it is not clear if it is related to longer term climate change.

Knorr and Lohmann (2003), citing the results of Sowers and Bender (1995) and Petit *et al.* (1999), asserted: "during the two most recent deglaciations, the Southern Hemisphere warmed before Greenland." This is one possible interpretation. Another interpretation is that both polar areas warmed over roughly the same time period but there was a qualitative difference. In the south, the warming was steady and continuous. In the north, the warming caused ice sheets to melt, which periodically plunged the regional climate back to cold for a period, resulting in jagged ups and downs in regional climate, superimposed on the secular upward trend in temperature. In contrast to Severinghaus (2009), Knorr and Lohmann assert that the MOC switches off during ice ages and is turned on when the south warms before the north does so. This warms the north with a time lag. This hypothesis seems very speculative and appears to be only one of many interpretations.

Huybers and Wunsch (2005) concluded: "the Earth tends to a glacial state (anthropogenic influences aside) and deglaciates near some, but not all, obliquity maxima." This is closely related to the theory suggested in this book that during the past ~800,000 years (or more) the Earth has tended to be in a glacial state and terminations occur when a series of major oscillations in insolation in the NH occur. Such oscillations occur continually with a period of about 22,000 years due to precession. The amplitude is controlled by obliquity and eccentricity. Huybers and Wunsch singled out obliquity. If peak solar intensity, rather than integrated solar intensity, is the key factor, eccentricity should also be included. In the astronomical theory, the driving force for terminations is insolation. Obliquity is involved to the extent that variable obliquity affects insolation, but only in a secondary way.

Schulz and Zeebe (2006) noticed that when peak solar inputs to latitudes 65°N and 65°S are compared over the past several hundred thousand years there occur occasional periods of up to about 3,000 years in which irradiance increases with time at both latitudes. This occurs despite the fact that solar inputs to these latitudes are overall mostly out of phase, with one increasing while the other decreases. This can be discerned in Figure 10.14 (see p. 308) at around 22,000 and 137,000 YBP. What appears to happen is that there is a brief period when the 65°N curve starts to turn upward after bottoming out while the 65°S curve has not quite reached its apex. Schulz and Zeebe (2006) also noted that periods where NH and SH irradiances have been simultaneously increasing for at least 1,000 years always seem to occur near times when ice age terminations occur. Therefore, they "hypothesized that the glacial termination trigger is the synchronous, prolonged ($\geq$1,000 yr) increase in SH and NH insolation, the insolation canon." Further, they showed that prior to about 800,000 years ago such overlapping periods where NH and SH irradiances have been simultaneously increasing did not occur as frequently, and they suggested that this may be tied to the change from the "41K world" prior to 800 KYBP to the "100K world" over the past 800,000 years.

While Schulz and Zeebe (2006) seem to have found a correlation between simultaneous increase in NH and SH insolation, Figure 10.14 provides no evidence that there was a unique cause–effect relationship between these occurrences and terminations of ice ages. There is no physical reason to believe that the "insolation canon" has any validity at all. It is more instructive to note that both of these periods occur at the end of a prolonged rise in insolation in the SH. The fact that insolation in the NH has turned upward seems irrelevant considering that insolation in the NH was very low during both periods. The insolation canon seems to be merely a statistical quirk of no significance.

Clark *et al.* (2009) carried out a rather thorough chronology of the last 50,000 years with particular emphasis on the Last Glacial Maximum around 20,000 years ago. They concluded that the onset of deglaciation is induced by some combination of peak northern insolation in summer, tropical Pacific sea surface temperatures, and atmospheric $CO_2$. However, there is no reason to believe that tropical Pacific sea surface temperatures and atmospheric $CO_2$ should change of their own volition; they seem more likely to be effects than causes. In the end, it

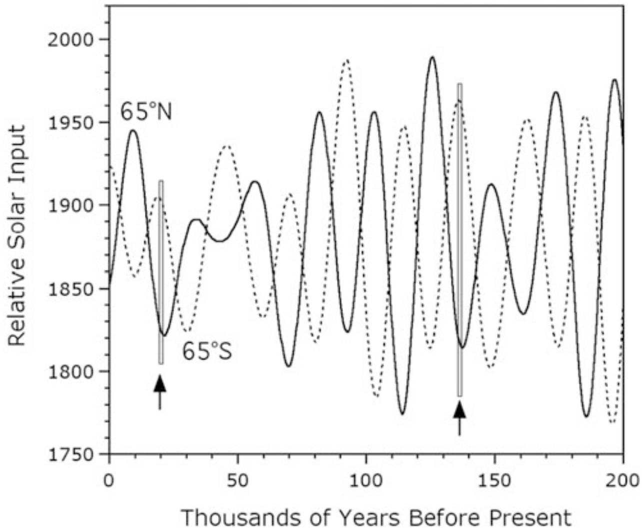


**Figure 10.14.** Relative peak solar input to 65°N and 65°S showing the two time periods during which both solar inputs increase simultaneously (see arrows).

was concluded that it is "an open question" as to whether deglaciation is initiated in the north or the south.

Stott *et al.* (2007) utilized a high-resolution chronology of surface-dwelling planktic formanifera and bottom-dwelling benthic formanifera in a tropical location to establish the relative timing of high-latitude vs. low-latitude climatic change at glacial terminations. They found that the onset of deglacial warming throughout the Southern Hemisphere occurred long before deglacial warming began in the tropical surface ocean. In a second paper (Timmermann *et al.*, 2009) this group carried out modeling that suggested the likely cause of initiation of deglaciation after 20 KYBP was the increase in southern insolation coupled with the sea ice–albedo feedback as the sea ice went into retreat. As the $CO_2$ concentration rose, this presumably added another warming feedback. They also showed that each of the last four major ice age terminations were associated with increases in solar input to the far SH. Solar input to the far SH during the austral spring period when the ice pack is at a maximum may be a major factor in initiating deglaciation. As before, however, this may be a *necessary* condition but might not be *sufficient*.

Toggweiler and Lea (2010) distinguished between millennial-scale temperature variability (over thousands of years) and long-term records over hundreds of thousands of years. They claimed that long-term temperatures are controlled by $CO_2$ levels:

> "Hence, it is natural to assume that the $CO_2$–temperature relationship in the long records from Antarctica is causal, i.e., that the increases in atmospheric $CO_2$ warmed Antarctica and the rest of the planet."

In contrast, they argued that millennial-scale variability cannot be attributed to $CO_2$ variations and, hence, they posed the question: "Can two such disparate views both be correct?" However, there is no evidence that long-term temperatures are controlled by $CO_2$ levels; indeed, there is no possible mechanism to cause the $CO_2$ level to independently rise and fall every 100,000 years or so of its own volition and, thus, create ice ages. So the very thesis of Toggweiler and Lea (2010) does not make much sense.

Toggweiler and Lea (2010) further asserted:

> "A close look shows that Antarctica and the polar north did not warm and cool at the same times; the two hemispheres became warm together over the longer cycles but only after the big transitions in Antarctica had already occurred. Both kinds of transitions, millennial and long term, seem to involve displacements of heat that allow the south to warm at the expense of the north."

This assertion, like many others made by Toggweiler and Lea (2010), has little basis in fact. Toggweiler and Lea (2010) drew the following conclusions:

> "The whole Earth did not warm and cool together during the big transitions of the ice ages. The south warmed, in particular, while the north remained cold. The north also became very cold toward the ends of the glacial stages long after the south had reached its glacial minimum. The big transitions took place when a resurgent precessional cycle produced inputs of melt water to the North Atlantic that lasted for thousands of years. The melt water inputs suppressed the AMOC, flattened the temperature contrast between the hemispheres, and produced a redistribution of heat from north to south that warmed Antarctica and the Southern Ocean. The same factors caused the level of $CO_2$ in the atmosphere to rise along with the temperatures in Antarctica.
>
> Atmospheric $CO_2$ was important during the ice ages because it varied with such a long time scale. The long time scale allowed the oceanic $CO_2$ system and northern ice sheets to interact in ways that gave rise to large temperature changes in the Earth's polar regions. The long time scale also allowed the variability in northern ice volume to enhance the variability in atmospheric $CO_2$, and vice versa. Without the long time scale for $CO_2$, the overall level of climate variability during the ice ages would have been much smaller."

These claims do not seem to have any experimental basis. Unless Toggweiler and Lea (2010) have powers of perception beyond those of this writer, they appear to represent supposition and speculation. As we pointed out in Section 4.3, the data in Figure 4.16 suggest that during the most recent ice age each sudden increase in temperature in Greenland was preceded by a rather slow moderate temperature rise in Antarctica for a few thousand years. This led to a number of scientists proposing that the connection between these events lies in heat transport known as the "bipolar seesaw" (see Section 4.3) between the south and the north through ocean currents. This is an unproven theory. Yet Toggweiler and Lea (2010) treat it as if it were proven fact.

Toggweiler and Lea (2010) claimed: "The two hemispheres therefore do not warm and cool together." They said:

> "Antarctica is warmest on the terminations when the ice sheets in the north are melting back but are still fairly large and are still keeping the north relatively cool. During glacial onsets, Antarctica has cooled to its glacial minimum level by the ends of stages 5, 7, and 9 when the northern ice sheets are just starting to grow. Thus, terminations are times with the smallest temperature difference between the hemispheres. Glacial onsets, delineated by the isotope stage boundaries 5/4, 7/6, and 9/8, are the times with the largest temperature difference. This would appear to be no accident: the biggest climate transitions seem to occur when the temperature differences between the hemispheres are most extreme."

The implication is that Antarctic climate changes precede NH climate changes. This is in contrast to the widely held belief that events in the NH produce ice ages. As before, there is no experimental basis for these claims. It is true, however, that solar inputs to the NH and the SH are out of phase by 11,500 years corresponding to precession of the Earth's orbit about the Sun. However, as discussed in Section 10.2.1, oscillations in the phase of solar input seem to be unimportant compared with the variability of eccentricity and obliquity.

Wolff *et al.* (2009) emphasized that "… the detailed sequence of events that leads to a glacial termination remains controversial. It is particularly unclear whether the northern or southern hemisphere leads the termination." They also said: "the reason for the spacing and timing of interglacials, and the sequence of events at major warmings, remains obscure." They presented a hypothesis that "glacial terminations, in common with other warmings that do not lead to termination, are led from the southern hemisphere, but only specific conditions in the northern hemisphere enable the climate state to complete its shift to interglacial conditions." Their hypothesis seems rather speculative.

Huybers and Langmuir (2009) found that volcanic activity increased by a factor of 2 to 6 during the second half of the last termination. They conjectured that magma production increases with mantle decompression as the ice sheets melt. Volcanoes located in polar areas would then emit significant amounts of $CO_2$, adding to the already rising $CO_2$ concentration during termination. Volcanoes also produce aerosols, but the cooling effects of aerosols from volcanoes are relatively short lived, whereas $CO_2$ accumulates in the atmosphere adding to ongoing warming. This would imply that reduction of the $CO_2$ concentration as glacial ice sheets build up might be augmented by a decrease in volcanic activity.

Stott and Timmerman (2011) wrote a very interesting paper on the close relationship between the rise and fall of the $CO_2$ concentration and glacial–interglacial cycles. They noted that there is ample data showing that over the past 20,000 years, as the Earth moved from the LGM to the present interglacial state,

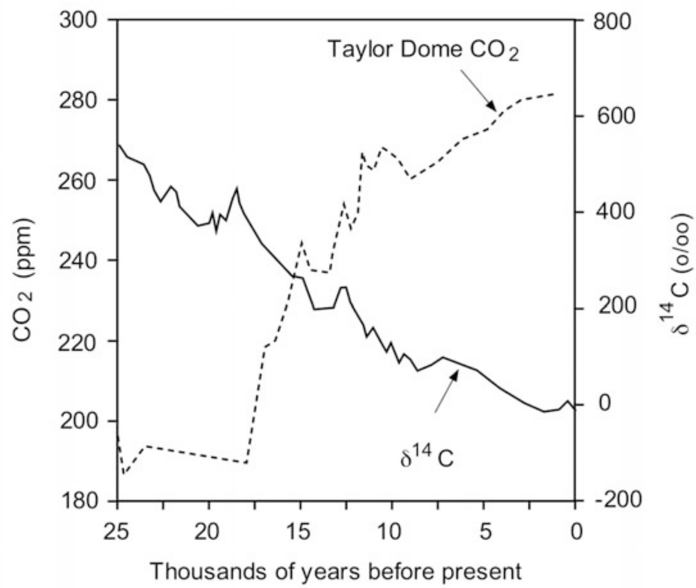


**Figure 10.15.** Taylor Dome record of atmospheric $CO_2$ over the most recent glacial termination and the INTCAL reconstruction of atmospheric $\delta^{14}C$ over the past 25,000 years (Stott and Timmerman, 2011).

the relative abundance of $^{14}C$ in the atmosphere decreased remarkably (as recorded in ice cores). The variability of the cosmic ray production of $^{14}C$ cannot possibly account for such a large change. During the period after the LGM when the $CO_2$ concentration in the atmosphere was steadily increasing, the $^{14}C$ proportion steadily decreased (see Figure 10.15). Therefore, Stott and Timmerman (2011) reasoned that there must have been a source of $^{14}C$-depleted water in the upper ocean and, as $CO_2$ was emitted from the ocean surface, it carried low levels of $^{14}C$ into the atmosphere.

As Stott and Timmerman (2011) pointed out:

> "The record of surface ocean $\delta^{14}C$ change during the last glacial termination provides an important constraint to any hypothesis that attempts to explain glacial/interglacial atmospheric $CO_2$ variability via an ocean-only mechanism. The rise in atmospheric $CO_2$ during the last deglaciation coincided with a long-term decrease in atmospheric radiocarbon ($\delta^{14}C$). The atmospheric $\delta^{14}C$ change during the last deglaciation implies either a change in production of $^{14}C$ in the atmosphere or large redistribution of carbon between the surface ocean and a $^{14}C$-depleted reservoir. Reconstructions of surface ocean $\delta^{14}C$ reveal several shorter-term excursions during the past 30 kyr that were not associated with cosmogenic isotope events, and thus, the excursions cannot be explained by changes in the production rate of $^{14}C$."

They also pointed out that "the largest $\delta^{14}C$ excursion was a 190‰ decrease between 17.5 and 14.5 KYBP (Figure 10.15) at the beginning of the last glacial termination. This excursion accompanied a 40 ppm rise in atmospheric $CO_2$."

Stott and Timmerman (2011) concluded that there must be a reservoir of $^{14}C$-depleted water in the oceans which displaces $^{14}C$-rich water. They noted that recent research has shown that "... active submarine volcanic arcs in the Pacific and hydrothermal vents in the northeastern and tropical eastern Pacific have documented $CO_2$-rich fluids venting at intermediate water depths (~1,000 m)." Although estimates of the $CO_2$ flux at these sites are sparse, recent data indicate that submarine vents in the Pacific may represent a greater source of carbon to the global carbon budget than previously estimated. Carbon dioxide can exist in liquid state at surprisingly high temperatures if the pressure is high enough. The critical temperature of $CO_2$ is 31.1°C at 1,070 psi. Stott and Timmerman (2011) drew a phase diagram for $CO_2$ in which they replaced pressure by depth in the ocean (100 m ~ 160 psi). Carbon dioxide can exist as a hydrate or as liquid $CO_2$ at sufficient depth (see Figure 10.16). The current estimate for temperature vs. depth is shown in Figure 10.16. It is hypothesized that the cooling that occurred during the LGM produced a temperature profile vs. depth similar to that shown in Figure 10.15. $CO_2$ stored as hydrates and liquid at great depths was raised to higher levels by "several hundred meters". It is proposed that this $CO_2$ was depleted in $^{14}C$ and, as the oceans warmed after the LGM, this water became an important source of $CO_2$ emitted to the atmosphere.

It is still not clear to this writer exactly how various levels in the ocean contribute to the rise and fall of $CO_2$ in glacial–interglacial cycles within the

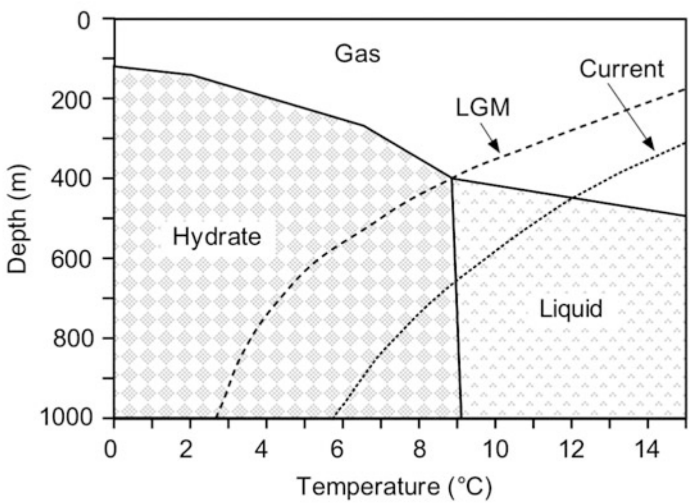


**Figure 10.16.** Phase diagram for $CO_2$ as a function of temperature and pressure showing how cooling during glaciations would shift the depth of hydrate stability upward (Stott and Timmerman, 2011).

framework of the hypothesis of Stott and Timmerman (2011). They discuss various aspects of their concept at some length, yet the details seem somewhat ephemeral. They concluded:

> "Our hypothesis does not necessarily account for the entire glacial/interglacial $CO_2$ change. However, it would reconcile the lack of evidence for an isolated deepwater mass during glacials that is otherwise required to explain the large $\delta^{14}C$ excursion during the last deglaciation. It would also explain why atmospheric $CO_2$ began to rise very soon after the Southern Ocean began to warm .... A comprehensive test of our $CO_2$ hypothesis requires a more thorough assessment of the present-day $CO_2$ flux at sites of active magmatism and the extent of liquid and hydrate $CO_2$ accumulations. There is also need to trace the flow of $^{14}C$-depleted waters during the last deglaciation to determine where it was ventilated to the atmosphere. In the meantime, the hypothesis presented here offers an important opportunity to reexamine the causes of glacial/interglacial $CO_2$ variations and the sequence of events that punctuated the last deglaciation."

## 10.3 SPECTRAL ANALYSIS

### 10.3.1 Introduction

M&M provided an extensive detailed discussion of spectral analysis. Only a very brief discussion is given here. Spectral analysis is based on the mathematical principle that almost any function (in particular, time series for ice core or ocean sediment climate data) can be expressed as a sum of sine and cosine functions that oscillate with variable frequency. If the time series oscillates in a regular fashion with time, the coefficient of the sine or cosine function with the frequency that most closely matches the frequency of the time series will be the dominant term in the expansion over all sine and cosine functions. Even though the time series may be noisy and somewhat irregular, if its underlying structure contains regular oscillations with time the spectrum of coefficients vs. frequency will show peaks at the frequencies that most closely match an appropriate sine or cosine function. Thus, by expressing the time series as an expansion over all sine and cosine functions with variable frequency, one can identify the most important underlying frequencies (or time periods) that govern the variability of the time series. A plot of the square of the coefficients in the expansion in cosines and sines vs. frequency will then reveal the underlying tempo of the variability of the time series. However, there are a few caveats that must be mentioned here. First, there are many procedures for estimating the principal frequencies underlying a time series, and they do not always agree with one another. Second, low frequencies might not show themselves clearly if the time series oscillates rapidly. Third, in comparing solar variability with time series variability, it is insufficient to compare principal frequencies on their own. The phasing of the two functions is critical in establishing a putative cause–effect relationship. Finally, to the extent that tuning was used to establish the chronology of the time series, agreement between the frequency spectra of solar and time series data might be to some extent a consequence of circular reasoning. M&M placed great emphasis on spectral analysis. However, in this book I have relegated spectral analysis to a secondary role.

Consider some arbitrary function $G(t)$. If the average value of $G(t)$ over all $t$ is $\langle G\rangle$, we define deviation from the average as $F(t) = G(t) - \langle G\rangle$.

Spectral analysis is based on the fact that almost any such function $F(t)$ can be expressed as a Fourier transform in terms of an integral over cosine and sine functions over all frequencies. Thus, if we consider an arbitrary function $F(t)$ (measured from the average of $G(t)$ as specified above) which varies with the independent variable $t$ (in our case $t$ is time and $F(t)$ may be temperature, ice volume, or solar intensity) we may express $F(t)$ as:

$$F(t) = \int_{-\infty}^{+\infty} H_{\mathrm{Tr}}(f)\, e^{2\pi i f t}\, df$$

$$e^{2\pi i f t} = \cos(2\pi f t) + i \sin(2\pi f t)$$

where $f$ is frequency, and $H_{\mathrm{Tr}}(f)$ is the weighting function for various frequencies that contribute to making up $F(t)$. The subscript "Tr" is assigned to $H$ to indicate that this is the "true" mathematical distribution of frequencies that produce the function $F(t)$ when integrated over all frequencies. The inverse of this integral is:

$$H_{\mathrm{Tr}}(f) = \int F(t)\, e^{2\pi i f t}\, dt$$

and the integral is taken over all time.

In actual practice, one does not deal with a continuous function but, rather, a set of discrete data points. Thus, one has a table of data representing a time series such as:

| | | | | | |
|---|---|---|---|---|---|
| $t$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | ... |
| $F(t)$ | $F_1$ | $F_2$ | $F_3$ | $F_4$ | ... |

The goal is to fit the data in this table to an expansion of cosines and sines to find the frequency spectrum of $F(t)$. If the function varies in a regular repeatable way, the frequencies that contribute to the function may be narrowly peaked. However, if the function varies haphazardly and randomly, the frequency spectrum may be very broad.

When a set of discrete data points are involved, we approximate the integral as:

$$H(f) = \sum F_j(\cos(2\pi f t_j) + i \sin(2\pi f t_j))$$

where the sum is taken over all the data points ($j = 1$ to $N$). Here, $H(f)$ is an approximation to the true $H_{\mathrm{Tr}}(f)$.

Many sophisticated procedures have been developed for estimating $H(f)$ from the dataset $(t_j, F_j)$ for $j = 1$ to $N$. However, M&M described a simple brute force procedure that works very transparently even though it is not efficient. Nevertheless, with modern desktop computers, it is fast enough for many purposes. The procedure involves the following steps:

(1) Choose a value of $f$.
(2) Calculate the sum over all $j$:

$$H_c(f) = \sum F_j \cos(2\pi f t_j)$$

(3) Calculate the sum over all $j$:

$$H_s(f) = \sum F_j \sin(2\pi f t_j)$$

(4) The "strength" of frequency $f$ in representing the function $F(t)$ is:

$$S = (H_s(f))^2 + (H_c(f))^2$$

(5) Repeat steps 1–4 for many values of $f$, and plot the strength vs. $f$ to determine which frequencies contribute the most to $F(t)$.

This process works in the following way. As M&M pointed out, this procedure takes your set of data, multiplies it by a sine wave, and then sums the results. If the data oscillate in phase with the sine wave, so that they are positive together and negative together, then all the terms in the sum are positive and the Fourier amplitude is large. If they drift into phase and out of phase, then roughly half of the values in the product will be positive and half will be negative, and the sum will be small. The sum is not particularly sensitive to sharp changes in the data (e.g., sudden terminations); it is more sensitive to the bulk behavior of the data (e.g., are most of the data points positive when the sine wave is positive?). Sharp changes in $F$ vs. $t$ lead to a broad range of frequencies that contribute. Regular oscillations in $F(t)$ lead to narrow peaks in the plot of strength vs. frequency.

M&M provided the examples of a simple sine wave with a 100,000-year period and a sawtooth wave with a 100,000-year period. The resultant spectra are given in Figure 10.17.

A few additional simple examples are now given. Consider Figure 10.18. In this figure we not only plot the function $F(t) = \cos(2t)$ at 17 discrete points but two further modifications of this function with some noise added.

Let us pretend we know nothing about the three functions and we desire to undertake spectral analysis to determine which frequencies contribute most to the underlying functions. We use the above procedure and the results are as shown in Figure 10.19. The prime frequency is 0.32 cycles per unit time, corresponding to a period of $1/0.32 \sim 2\pi/2$ time units. Adding noise broadens the strength vs. frequency curve but the main peak remains close to the original frequency without noise.

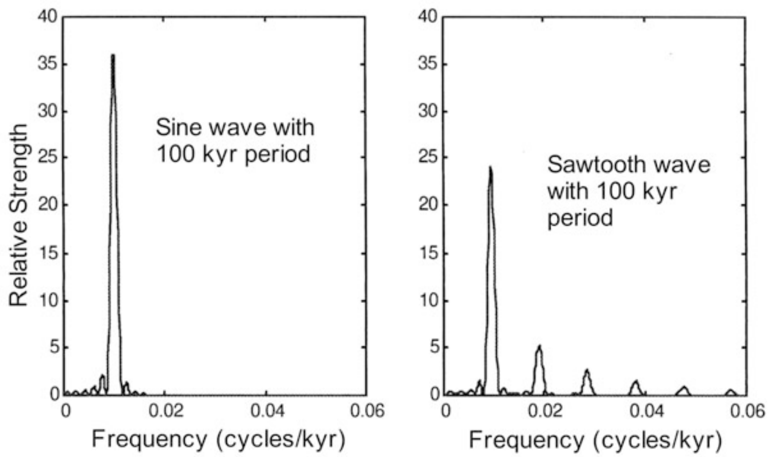


**Figure 10.17.** Spectra of sine wave and sawtooth wave with 100,000-year periods.

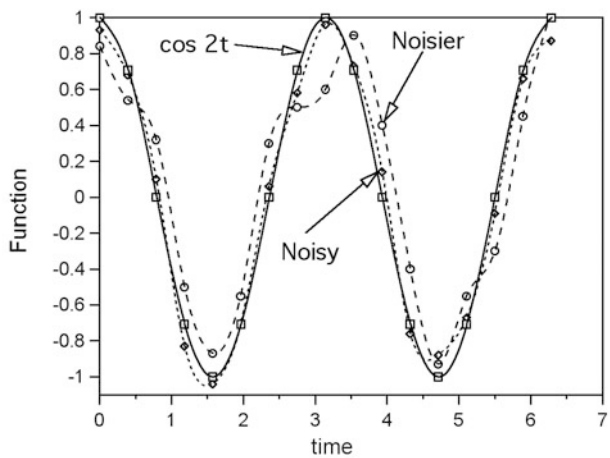


**Figure 10.18.** Three simple functions for spectral analysis. The solid curve is $\cos(2t)$ and the dashed curves add noise to this curve. The period of the solid curve is $\pi$.

Another simple example is given in Figure 10.20, which displays 17 points from the curve:

$$F(t) = \cos(2.5t) + \cos(1.5t)$$

When the same spectral procedure is carried out on these 17 points, the resultant frequency distribution is as shown in Figure 10.20. There are now two primary frequencies at 0.23 and 0.42 cycles per unit time, corresponding to periods of $4.5 \sim 2\pi/1.5$ and $2.4 \sim 2\pi/2.5$ time units (see Figure 10.21).

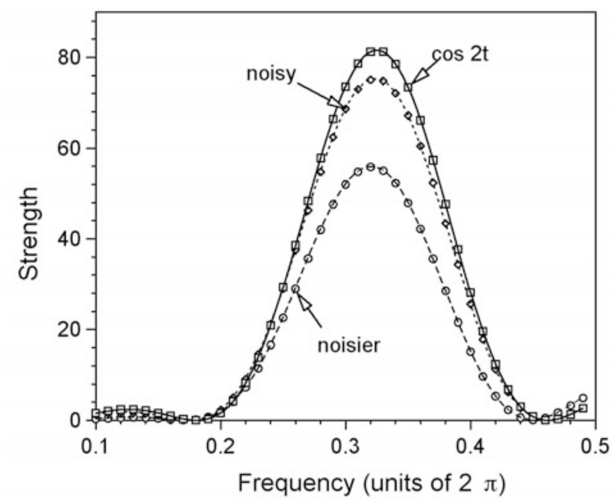


**Figure 10.19.** Frequency distribution corresponding to the functions in Figure 10.17.

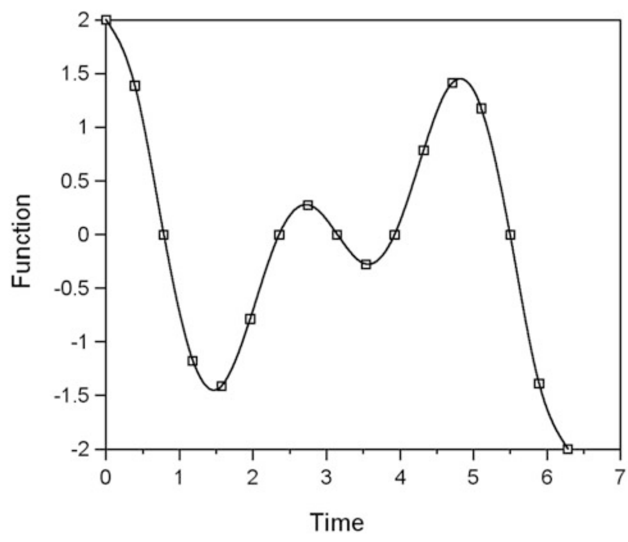


**Figure 10.20.** Function $F(t) = \cos(1.5t) + \cos(2.5t)$.

A final simple example is given in Figure 10.22, which shows a hypothetical function that was arbitrarily formed with a quasi-periodic structure. The frequency distribution corresponding to this function is shown in Figure 10.23. The principal frequency is 0.5 per unit time. The period is 2 time units.

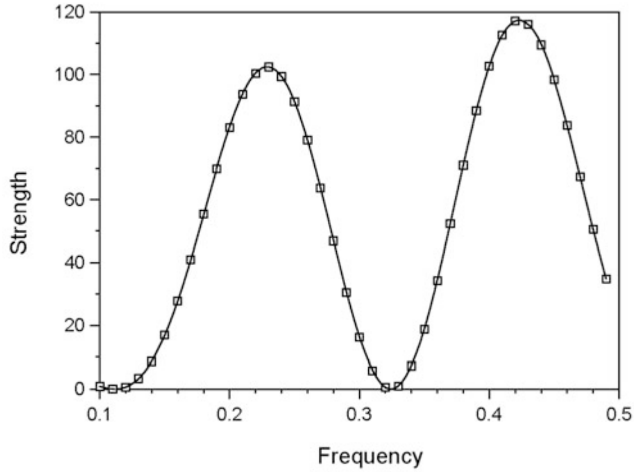


**Figure 10.21.** Spectral distribution of frequencies corresponding to function $F(t) = \cos(1.5t) + \cos(2.5t)$. Principal frequencies are at 0.23 and 0.42 units.

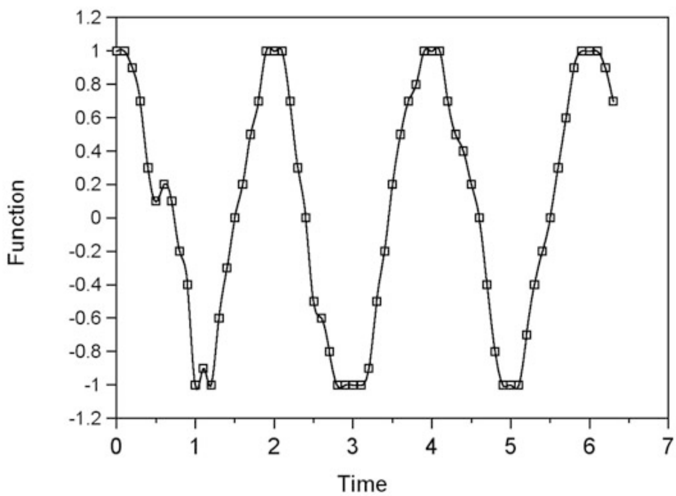


**Figure 10.22.** A hypothetical function with quasi-periodic behavior.

### 10.3.2 Spectral analysis of solar and paleoclimate data

M&M described a number of alternative approaches for estimating the spectral distributions corresponding to solar and paleoclimate data. These are beyond the scope of this book and we refer the reader to M&M for information on these methods. We will content ourselves here with merely commenting on their results.

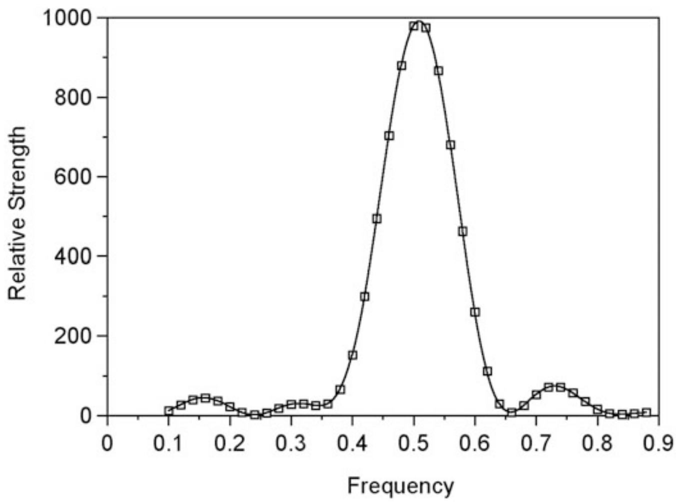


**Figure 10.23.** Frequency distribution corresponding to the function in Figure 10.22.

#### *10.3.2.1 Spectral analysis of solar data*

We know from the analysis provided in Section 9.2.1 and Figures 9.2, 9.3, and 9.4 that the primary cycle periods that characterize variability of the longitude of perihelion, obliquity, and eccentricity are roughly 22,000, 41,000, and ~100,000 years, respectively. Therefore, one would expect that the frequency spectrum of solar intensity at high latitudes would show peaks at frequencies of about 0.045, 0.024, and 0.01 $(\mathrm{kyr})^{-1}$. Figure 9.7 shows that the dominant factor in determining the oscillations of solar intensity is the longitude of precession. The heights of the peaks in the upper part of this figure are not directly correlated with the heights of the peaks of solar intensity in the lower half of the figure. This suggests that obliquity is more important than eccentricity in determining the heights of solar peaks. Nevertheless, the effect of eccentricity is discernible in Figures 9.10 and 9.11. The amplitude of oscillations appears to maximize at roughly regular intervals of about 100,000 years at 800,000, 700,000, 600,000, etc. years before the present although 400,000 YBP is anomalous. Yet, this clearly cyclical behavior does not seem to be reflected in the spectrum. This suggests that spectral analysis may not properly identify low frequencies against the background of a rapidly oscillating time series.

As Figure 9.13 shows, solar intensity at 65°S is similar to that at 65°N, except that they are out of phase by 11,000 years. Thus, we expect the frequency spectrum for 65°S to be essentially the same as that for 65°N, and this spectrum is expected to have a dominant frequency corresponding to precession of the longitude of perihelion, a secondary peak corresponding to obliquity, and a weaker peak corresponding to eccentricity. Figure 10.24 shows the spectra reported by M&M for 65°N and 65°S. On the left-hand side of this figure (65°N), we clearly observe the primary peak corresponding to precession of the longitude

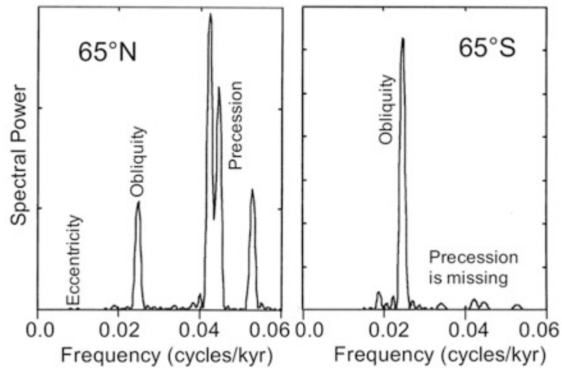


**Figure 10.24.** Spectra for solar intensity at 65°N and 65°S according to M&M. The 65°S spectrum does not contain a peak corresponding to precession of the longitude of perihelion and, since there is no fundamental difference between the south and the north, it seems likely that the reported spectrum for 65°S is erroneous.

of perihelion and a secondary peak corresponding to obliquity. There is a bare hint of a contribution from eccentricity. But, the frequency distribution at 65°S only includes a peak corresponding to obliquity and this makes no sense because the oscillatory nature of solar intensity is similar for the two polar regions. Hence, it seems likely that the right-hand side of Figure 10.24 (taken from M&M) as the reported spectrum for 65°S is erroneous.

#### *10.3.2.2 Spectral analysis of paleoclimate data*

The Vostok deuterium time series is shown in Figure 10.25.

Spectral analysis of the Vostok deuterium time series was given by M&M and is shown here in Figure 10.26. Even a casual glance at Figure 10.25 indicates the

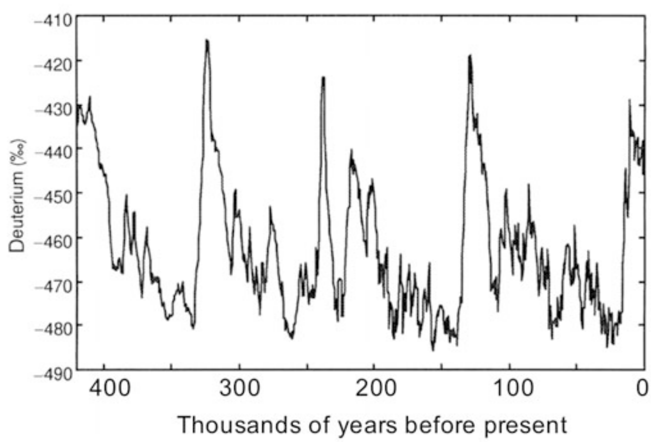


**Figure 10.25.** Vostok time series (M&M).

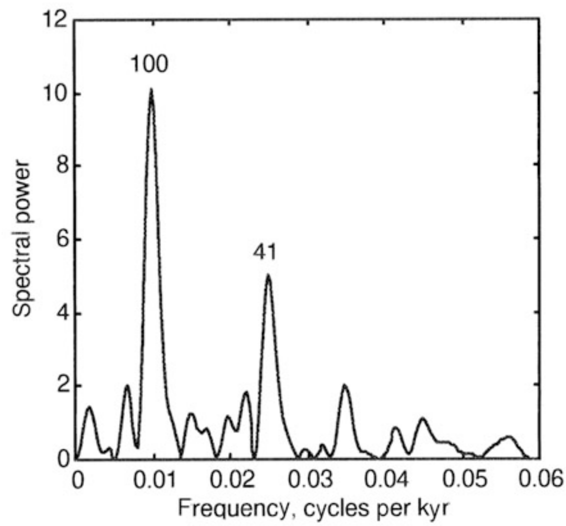


**Figure 10.26.** The spectrum of Vostok deuterium data according to M&M. Two principal peaks occur at periods of 100,000 and 41,000 years.

presence of a cycle with a period of roughly 100,000 years. The influence of the spectral peak at 41,000 years in the time series of Figure 10.25 is less obvious. There is a very small peak corresponding to ~22,000 years.

The results shown in Figure 10.26 create a conundrum. On the one hand, the presence of strong peaks at periods of 100,000 and 41,000 years suggests that eccentricity and obliquity are playing predominant roles in determining the temperature history at Vostok. This should be tempered by the fact that since some tuning was used to assign the chronology for Vostok data one might expect that elements of the astronomical model will appear in the spectrum for Vostok temperatures. On the other hand, the lack of a significant peak corresponding to ~22,000 years is disturbing because the variability of solar input to high latitudes is dominated by precession of the longitude of perihelion. Furthermore, the spectrum for the variability of Vostok temperature does not resemble the spectrum for solar input (Figure 10.24). Whereas eccentricity is the primary peak in the Vostok spectrum, eccentricity is hardly visible in the solar input spectrum. Thus, comparison of the frequency spectrum of Vostok ice core data with the frequency spectrum of solar input to high latitudes provides a mixed result of some overlap, but significant differences remain. However, if precession of the equinoxes acts merely as a carrier wave for changes in obliquity and eccentricity, precession would not affect climate, and the non-appearance of a spectral peak corresponding to precession would be understandable.

The ice core at EPICA Dome C yielded 800,000 years of data (see Figures 4.10 and 4.12) (Jouzel *et al.*, 2007). Spectral analysis of these data was carried out for two time periods: 0–400 and 400–800 KYBP (see Figure 10.27). As was the case

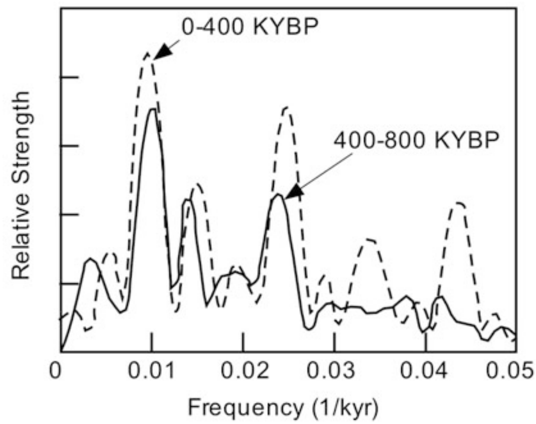


**Figure 10.27.** Frequency spectra of EPICA Dome C Antarctic ice core data (Jouzel *et al.*, 2003).

at Vostok, the spectrum for the most recent 400,000 years has a major peak corresponding to eccentricity and a secondary peak corresponding to obliquity, but there does not appear to be a peak corresponding to precession. Prior to 400 KYBP, there is a peak that could be associated with precession. As in the case of Vostok, there are some tantalizing correspondences with solar variability, but there remains enough disagreement that the matter is hardly settled.

One possible explanation for the lack of a precession peak in the frequency spectrum of ice core data relates to the discussion given in Section 10.2.1, in which it was suggested that ice sheet buildup reacts to the 22,000-year precession oscillations of solar intensity by growing when the amplitude of oscillations is small and diminishing when the amplitude of oscillations is large. Thus, it may well be that precession oscillations act as a sort of carrier signal as in AM radio, and this carrier signal is amplitude-modulated by the variability of eccentricity and obliquity. The 22,000-year period has no consequence for climate change except to carry the signal for the 41,000 and 100,000-year variability of obliquity and eccentricity. Hence, from this point of view the 22,000-year period due to precession is not important when examining the frequency spectrum of ice core data; what is important is the amplitude of precession oscillations, and these are dictated by variations in obliquity and eccentricity.

The SPECMAP representation of ocean sediment data was given in Figure 5.4. Comparison of solar input to high latitudes with ocean sediment data was illustrated by M&M for the SPECMAP. The spectrum for the SPECMAP is shown in the left half of Figure 10.28. As can be seen from this figure, all three solar frequencies are represented. The SPECMAP chronology was based on tuning to solar variations as expressed in the Imbrie ice model (see Figure 9.14), so it is not surprising that solar frequencies appear. The spectrum corresponding to the Imbrie model is shown in the right half of Figure 10.28. In the Imbrie model, the lowest frequency corresponds to a period of about 400,000 years, and the peak

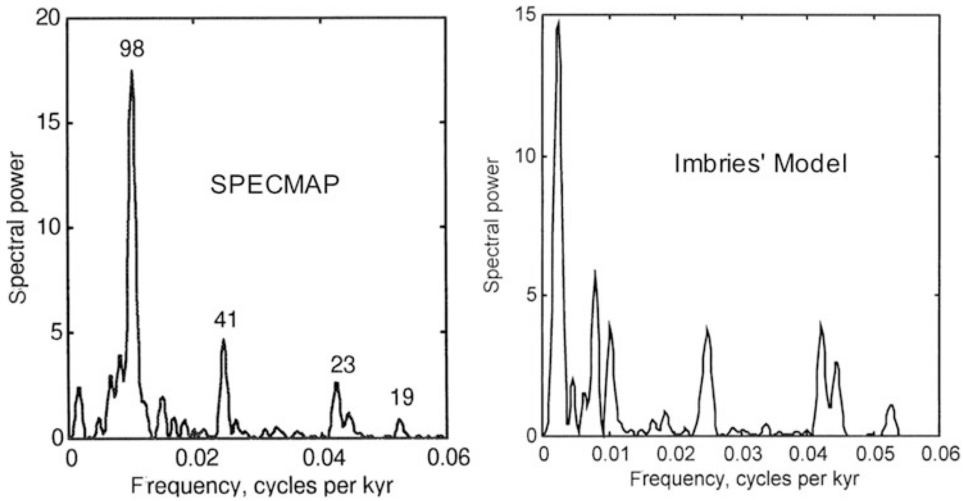


**Figure 10.28.** (Left) The spectrum of SPECMAP according to M&M. Numerical figures are time periods in thousands of years associated with principal frequencies. (Right) The spectrum of the Imbrie ice model (see Figure 9.14).

near 100,000 is no longer dominant. In this case a peak corresponding to precession appears. As in the case of ice core data, the results are suggestive of the astronomical theory in some ways, but the case is far from ironclad.

Sudden terminations of ice ages occur with nearly vertical lines on the time series plots that appear at the end of each glacial period. There is a significant low-level background in the spectral plots which is difficult to resolve. As M&M said: "Such sharp changes require a conspiracy of a large number of small components at many different frequencies. These small contributions are well hidden in the frequency domain."

## 10.4 STATUS OF OUR UNDERSTANDING

The overall heat balance of the surface of the Earth is dictated by a number of factors. Three important elements are

- the rate at which solar energy impinges on the Earth;
- the fraction of solar energy reflected by the Earth into space (albedo);
- the effect of greenhouse gases (particularly water vapor, $CO_2$, and $CH_4$) in the atmosphere in preventing the escape of radiation emitted by the Earth.

The net albedo of the Earth depends on the global average of all land areas, but clouds add significantly to global average albedo. The albedo of snow/ice cover may be as high as 0.9. The albedo of land depends upon the nature of the land (forest, desert, plains, etc.), but on average it is probably something like 0.35. The albedo of the oceans is probably about 0.1. The distribution and character of landmasses on the Earth are likely to have a profound effect on climate, affecting greenhouse gas concentrations, ocean currents, and world average albedo. In addition, landmasses in near-polar areas provide foundations for building ice sheets. Over long time periods, continental drift changes the distribution of landmasses, leading to variations in the Earth's climate. Mountain building provides sites for glaciers to form and affects wind patterns.

The Earth is about 4.6 billion years old. During its history the Earth has probably passed through a number of very marked climate changes ranging from a snowball Earth in which the entire Earth was covered in a blanket of ice and snow to a hothouse Earth when all glacial ice melted and the polar areas were tropical.

Prior to about 34 MYBP the Earth was much warmer than it is today. About 34 million years ago, the Earth entered a significant cooling trend and the East Antarctic Ice Sheet (EAIS) began to form. The great ice sheets over Antarctica gradually evolved over the ensuing millions of years. One theory is that this occurred because of a series of movements in Earth's major tectonic plates. Another theory is that the timing of ice sheet growth in Antarctica coincided with sea-floor spreading, which pushed Antarctica away from Australia and South America. The opening of these ocean gateways produced a strong circumpolar current in the Southern Ocean that is thought to have thermally isolated the Antarctic continent, cooling it to a level where an ice sheet could rapidly grow. Yet another theory postulates a declining $CO_2$ concentration in the atmosphere as the primary cause of Antarctic glaciation.

About 2.7 MYBP, the Earth entered an enhanced cooling phase that has continued unabated to the present day, although there have been significant fluctuations about this long-term downward trend in temperature. One theory is that this cooling trend was initiated by the gradual closing of the Isthmus of Panama, which in turn affected ocean circulation in the North Atlantic.

Since then the Earth has undergone a large number of climate cycles ranging from ice ages with large ice sheets in the Northern Hemisphere and a general cooling of the entire Earth to interglacial periods that were comparable or warmer than the present climate. As Figure 5.6 illustrates, these cycles have become lengthier and of greater amplitude in the last million years.

During periods of glaciation great ice sheets formed in the NH. When great ice sheets form they affect the overall climate of the Earth in a number of ways. First, they increase the albedo by reflecting incident sunlight. Second, the presence of large amounts of sea ice can affect ocean circulation that in turn may affect heat transport to higher latitudes. Third, it is likely that cooler temperatures will reduce the concentration of water vapor, thus reducing the greenhouse effect, and have an (unknown) effect on cloudiness affecting the Earth's albedo. Fourth, as the Earth cools a large reduction in $CO_2$ and $CH_4$ occurs in the atmosphere producing a significant forcing that drives down worldwide temperatures. Hansen and Sato (2011) estimated this effect to be about as great as the albedo effect.

Fifth, as ice sheets expand ocean levels drop increasing land area at the expense of the surface area of the oceans. Since land has a higher albedo than oceans this would provide positive feedback for further cooling. In addition, the presence of such ice sheets apparently increases world storminess as evidenced by dust and salt content in ice cores. Hence, once an era of heavy glaciation begins there are natural forces that propagate this trend forward in time. This raises the following questions: (1) what triggers the origin of such ice ages and, even more baffling, (2) why do ice ages end at all and why do they end precipitously?

The Earth system is complex. The distribution and movement of water is a key factor. Water on Earth exists in three phases (solid, liquid, and gas) and transitions between these phases occur with large transfers of thermal energy as a result of the high heat of the vaporization and crystallization of water. Heat input to the Earth from the Sun is heavily weighted toward low latitudes, and there are significant temperature gradients from the tropics to the polar areas. Were it not for heat transfer toward polar areas (by oceans and atmosphere) along this gradient, the polar areas would freeze over, extending glacial conditions down to mid-latitudes via the various feedback mechanisms described above. A tenuous balance is achieved between natural forces tending to extend glacial conditions in polar areas toward mid-latitudes vs. the transfer of heat from lower latitudes to counterbalance this tendency. Apparently, this unstable equilibrium can be upset by relatively small perturbations, driving the Earth's climate either toward glacial or interglacial conditions, amplified by significant positive feedback effects.

Data are available from ice cores, ocean sediments, and other sources which reveal aspects of past climates dating back hundreds of thousands and even millions of years. These data indicate that there has typically been a long-term secular pattern of very roughly repeatable cycles whereby great ice sheets have slowly built up over many tens of thousands of years culminating in a glacial maximum, followed shortly by a rather abrupt end of the ice age with rapid global warming leading to an interglacial period of perhaps 10,000 or more years. Interglacial periods seem to end with abrupt climatic cooling to start a new ice age that gradually expands over many tens of thousands of years. This pattern is actually quite variable, but the outline described here seems to describe the last four ice age cycles fairly accurately. Prior to that, the regularity of cycles was less evident. Superimposed upon this longer term secular variation, there have been numerous significant sudden climate changes that may be viewed as noise in the main signal. When examined at higher resolution these short-term fluctuations often show an extremely rapid increase in temperature over perhaps decades followed by a slow decline back to glacial conditions over a millennium or two. It is not clear whether or how these short-term climate fluctuations are related to longer term secular trends.

While ice core and ocean sediment data clearly reveal the existence of past cycles and fluctuations in the Earth's climate, these data are couched in terms of isotope ratios and other contents of cores and sediments. Converting these data into specific climatological variables (e.g., global average temperature, global ice volume, etc.) is not straightforward. The models originally developed (and accepted for a number of years) to convert Greenland ice core isotope ratio data to Greenland temperatures appear to be off by a factor of 2 according to borehole temperature models. Nevertheless, Greenland isotope ratio data are believed to represent regional temperature conditions even if the absolute conversion to temperature is uncertain. Similarly, Antarctica isotope ratio data are believed to represent global temperatures accurately. Ocean sediment data from benthic sources are believed to represent mainly global ice volume, although Lisiecki *et al.* (2008) recently concluded: "Generating a robust age model for benthic $\delta^{18}O$ or ice volume without the assumptions of orbital tuning remains an important, unsolved problem."

The astronomical theory of ice age cycles originated in the 19th century and has evolved over the past century and a half. Quasi-periodic variations in the Earth's orbital parameters change solar energy input to higher latitudes with periods of multiple tens of thousands of years. The fact that solar inputs to high latitudes and data on past climate variations are both subject to quasi-periodic variations over similar time periods suggests that the two may be coupled. Spectral analysis supports this viewpoint. According to the astronomical theory, this variability of solar input to higher latitudes has a significant effect on the ability of surface and sea ice at higher northern latitudes to withstand the onslaught of summer. It has been theorized that during time periods when peak solar energy input in summer to higher northern latitudes is lower than average, the lower solar input may trigger feedback processes that lead to the spread of ice cover and the start of ice ages. Conversely, time periods with high peak solar energy input in summer to higher northern latitudes might trigger feedback processes that cause melting, leading to deglaciation. Thus, according to this theory, variability of the Earth's orbit about the Sun is a primary factor in determining the timing of glacial–interglacial cycles.

M&M asserted that a persuasive reason to think that astronomy is responsible (at least to some extent) for the observed glacial–interglacial variations is that over long periods ($\sim$800,000 years) these oscillations remain coherent (i.e., they maintain a relatively constant phase). However, as Figure 7.1 shows, the coherence is only approximate and there has been a systematic increase in the spacing of ice ages over the past 800,000 years. Even more important is the fact that coherence is still worse over a 2.7-million-year period. M&M further argued that the narrowness of the spectral peaks implies that glacial cycles are driven by a quasi-periodic astronomical force, regardless of the details of the actual driving mechanism—and that appears to be a strong argument.

It is not immediately obvious which measure of solar intensity is of greatest relevance in the astronomical theory. There is some reason to believe that ice ages originate at high latitudes in the Northern Hemisphere (NH) because that is where the great ice sheets grew during ice ages and that land (rather than water) occurs at high northerly latitudes, providing a base for ice sheet formation. It also seems reasonable to guess that the onset of widespread glaciation at high northern latitudes would be enhanced if a greater preponderance of ice could survive the effects of higher regional peak solar irradiance in summer. Hence, most investigators have utilized midsummer solar irradiance in the NH as a measure of solar variability from year to year.

Alternatively, there is some evidence that suggests that the key site for solar-induced climate change might be the SH where variations in oceanic transport of heat link the two hemispheres with a time delay. A number of studies have provided evidence that terminations of ice ages might originate in the SH.

In attempting to compare the astronomical theory with data, one must first clarify what the data represent. Models suggest that isotope ratio data at Greenland and Antarctica represent local temperatures. These interpretations of isotope ratios are far from ironclad and involve a number of uncertainties. Nevertheless, even if we accept these assumptions regarding the interpretation of ice core data, we still face the problem of how to compare ice core data with the variability of solar intensity from year to year. If increased solar intensity raises temperatures, is there a time lag and does it depend on other factors as well? How much higher is Greenland temperature increase than global temperature increase? If the main driver for climate change is NH solar intensity, how does this relate to Antarctica climate and temperature? If we ignore these legitimate concerns and merely compare solar intensity variability with the temperature record from ice cores, the results will be as shown in Figures 10.1 and 10.2. These results are suggestive of a solar influence. Solar intensity varies (as always) with a ~22,000-year period due to precession of the equinoxes. These oscillations vary in amplitude over long time periods. The temperatures implied by ice core records do not oscillate with this frequency. However, there seems to be a significant correlation between the amplitude of solar oscillations and ice core temperatures. In many (but not all) cases, time periods with higher amplitude solar oscillations appear to be associated with increasing temperatures, and periods during which solar oscillations are weak seem to be associated with decreasing temperatures. This would be the case if (1) there were a fundamental tendency toward glaciation, and (2) ice sheets grow slowly and disintegrate rapidly. In that case ice sheets would disintegrate and not recover when solar oscillations were large, but would grow when solar oscillations were small. The fact that the frequency spectrum shows frequencies for eccentricity and obliquity—but not precession—suggests that it is the amplitude of solar oscillations that matters, that the precession frequency does not directly contribute to climate change, and that it is the eccentricity and obliquity that determine the amplitude of precession oscillations. There are problems with this interpretation: (1) the change from ~41,000-year spacing to ~100,000-year spacing of ice ages, and (2) the occurrence of an ice age around 400,000 YBP when solar oscillations were minimal.

In a similar manner, if we accept the proposition that isotope ratios in benthic sediments provide a measure of ice volume ($V$), how do we compare these data with variable solar intensity? In order to compare ice sheet volume with variable solar intensity at higher latitudes, we require models for ice sheet volume as a function of variable solar intensity. A few models have been proposed. However, they appear to this writer to be overly simplistic and fail to take account of the complexities of the Earth's ocean and atmosphere systems. Comparison of the

Imbrie model with SPECMAP ocean data (as shown in Figure 10.4) shows the agreement to be moderate at best—such a simple ice model is highly approximate. On the other hand, Roe (2006) showed that if the slope of the SPECMAP curve (the rate of change in ice sheet volume, $dV/dt$) is compared with the solar intensity curve over the past ~800,000 years, the agreement is quite remarkable. Even though the SPECMAP curve was tuned to the solar intensity curve, this agreement provides a strong indication that the astronomical theory of ice ages is inherently correct. Nevertheless, it is not clear how ice ages terminate or why they should do so in a sudden manner.

# 11

# Future prospects

## 11.1 THE NEXT ICE AGE (OR LACK THEREOF)

### 11.1.1 Introduction

The last ice age began to wane about 18,000 years ago. Path E in Figure 10.1 shows that there was a moderate increase in solar input to high northern latitudes starting about 18 KYBP which could be interpreted as contributing to the end of the last ice age, although this increase in solar input was not as great as it was in several previous cycles, and these previous increases in solar input did not result in an interglacial. Solar input to high northern latitudes has been decreasing since about 11 KYBP, but as yet there is no sign of any cooling effect. It remains far from clear whether and how much changes in solar input to high northern latitudes induce ice ages and interglacials. However, Stott *et al.* (2007) found evidence that the terminations of recent ice ages appear to have originated in the Southern Hemisphere. Ice age termination is discussed in Section 10.2.3.

Looked at simplistically, Figure 7.1, for example, might suggest that warm interglacial periods with temperatures corresponding to the Holocene typically do not last exceptionally long—perhaps 5,000 to 20,000 years. Since the Holocene has now been in effect for more than 10,000 years, one may wonder when the next ice age may begin. The answer may lie in the plethora of conjectures on this topic, both pro and con.[1]

One school of thought is that there is a natural periodicity to the Earth that goes beyond human influence and, when its time arrives, the next ice age will occur. Had there not been a significant impact on the Earth's heat balance and climate by anthropogenic activity (greenhouse gas emissions, production of atmospheric aerosols, changes in land use, deforestation, water use, urban heat

[1] If you insert "the next ice age" into Google, you obtain over 100,000 responses.

D. Rapp, *Ice Ages and Interglacials: Measurements, Interpretation, and Models*, Springer Praxis Books,
DOI 10.1007/978-3-642-30029-5_11, © Springer-Verlag Berlin Heidelberg 2012

islands, etc.) the same forces that produced previous ice ages would likely be prevalent and, sooner or later, a new ice age would develop. Based on Figure 10.1, it would seem likely that a new ice age could begin almost any time within the next several thousand years in this scenario.

An alternative school of thought, held by a number of climatologists, is that the natural order of ice age cycles will be interrupted in the future due to global warming from increased $CO_2$ concentrations via the greenhouse effect, and projected further increases in $CO_2$ concentration during the 21st century will either delay or entirely prevent the next ice age. Dr. James Hansen has been quoted as saying:

> "Another ice age cannot occur unless humans become extinct. Even then, it would require thousands of years. Humans now control global climate, for better or worse."

A number of blogs have predicted, on the contrary, that global warming will induce the next ice age.

### 11.1.2 Orthodoxy in climatology

Before discussing the prospects of a new ice age occurring in the future, it is worthwhile to first discuss the degree to which objective neutral analysis is available in climatology and the degree to which institutionalized orthodoxy has taken hold of the field and produced biased perceptions. This is important at the outset because it suggests a degree of caution and skepticism is needed in interpreting the climatological literature.

Lindzen (2008) wrote an excellent article on this topic, and the book by Rapp (2008) is also relevant. Lindzen perceives that over the past four decades or so the fear of enemies or calamities has become the primary driving force for funding scientific research. The key to retain funding is then to perpetuate problems that require solving. Just as earthquake specialists repeatedly warn us that "the big one is coming," climatologists continually preach that the world faces a disaster due to global warming. Lindzen suggested that this might be a major factor in the lack of progress in many areas of science.

Lindzen (2008) described the politicalization of climate science:

> "All such organizations, whether professional societies, research laboratories, advisory bodies (such as the national academies), government departments and agencies (including NASA, NOAA, EPA, NSF, etc.), and even universities are hierarchical structures where positions and policies are determined by small executive councils or even single individuals. This greatly facilitates any conscious effort to politicize science via influence in such bodies where a handful of individuals (often not even scientists) speak on behalf of organizations that include thousands of scientists, and even enforce specific scientific positions and agendas. The temptation to politicize science is over-

whelming and longstanding. Public trust in science has always been high, and political organizations have long sought to improve their own credibility by associating their goals with 'science'—even if this involves misrepresenting the science."

The emergence of the *consensus* as the essence of *reality* in science has replaced scientific skepticism, and "simulation and programs have replaced theory and observation, where Government largely determines the nature of scientific activity." As Lindzen (2008) emphasized, "the bulk of the educated public is unable to follow scientific arguments; 'knowing' that all scientists agree relieves them of any need to do so." Taking issue with the consensus "serves as a warning to scientists that the topic at issue is a bit of a minefield that they would do well to avoid."

There are a number of scientific topics of great interest that are not amenable to resolution because of their complexity and because they deal with phenomena not accessible to current measurements. Benestad (2005) discussed the scientific method which requires that (1) hypotheses can be proven wrong (if they are wrong), (2) that they are based on objective tests, and (3) that the results must be repeatable. Most work in climatology and almost all work in paleoclimatology fail this test. Incidentally, so does almost all the work on the search for life in the solar system. There are scientific questions that are beyond our ability to answer. In such instances, scientists do not seem to be able to shrug their shoulders and admit that they just don't know the answers. They formulate hypotheses and a consensus develops around the most favored one. The consensus acquires legitimacy in proportion to the number and prominence of the scientists who subscribe to it. As the consensus becomes firmly imbedded in the culture, it acquires the respect usually accorded to fact. As Crichton (2003) said:

> "Let's be clear: the work of science has nothing whatever to do with consensus. Consensus is the business of politics. Science, on the contrary, requires only one investigator who happens to be right, which means that he or she has results that are verifiable by reference to the real world. In science consensus is irrelevant. What are relevant are reproducible results. The greatest scientists in history are great precisely because they broke with the consensus. There is no such thing as consensus science. If it's consensus, it isn't science. If it's science, it isn't consensus. Period."

Crichton (2003) provided several historical examples of scientific consensus gone wrong. Three examples where an unwarranted consensus currently prevails in science are:

(1) The belief that given liquid water, $CO_2$, and other basic chemicals for a few hundred million years life will evolve on any planet. This in turn has led to the investment of many billions of dollars by NASA in the search for life on Mars and elsewhere in the solar system and beyond. What is more, this policy has

spawned hundreds of conjectural papers and press releases based predominantly on supposition and little or no data (Rapp, 2007). Most of these papers and press releases are heavily laden with phrases such as "there might be" or "it is possible that". The preoccupation with the search for life has become so rampant that it has become common practice to "seed" any proposal to NASA on almost any topic with allusions to the search for life; otherwise, there is little likelihood of receiving NASA funding. Yet, there is no basis at all for believing that life forms easily and repeatedly; on the contrary, there are good reasons for believing that the evolution of life from inanimate matter is an extremely rare and fortuitous event. Crichton (2003) disparaged the futile efforts in the search for extra-terrestrial intelligence (SETI) as another outgrowth of the unfounded belief that life is widespread in the universe. The search for life in the solar system is almost sure to be a losing effort (Rapp, 2007).

(2) The belief that rising $CO_2$ levels were entirely or predominantly responsible for global warming in the 20th and 21st centuries. This belief is stated as proven fact by government agencies, professional societies, and various other bureaucratic organizations. It is taught in schools and our whole society has been indoctrinated with this belief even though very few have any knowledge of the fragile technical basis for the belief (Idso, 2008; Rapp, 2008). Oreskes *et al.* (2008) wrote a 70-page treatise on $CO_2$ as the cause of global warming in which the entire argument is based on a comparison of the credentials of those who believe it vs. the credentials of those who oppose it.

(3) The belief that the astronomical theory explains the occurrence and timing of ice ages and interglacial cycles. There are literally thousands of websites, books, pamphlets, and papers that proclaim this belief as fact. Most of the authors have never bothered to delve into the details of this topic but have merely adopted the view of the consensus.

In late 2009 and early 2010, an extensive set of emails between principal figures in the *paleoclimatological cabal* was made public. These emails revealed a deeply imbedded agreement amongst these climatologists to promulgate their orthodoxy that the Earth's climate has hardly wavered over the past 2,000 years and that $CO_2$ was the principal cause of unprecedented global warming in the 20th century. As Mosher and Fuller (2010) pointed out, they:

> "... ruthlessly suppressed dissent by insuring that contrary papers were never published and that editors who didn't follow their party line were forced out of their position. When Freedom of Information requests threatened to reveal their misbehavior, the emails showed them actively conspiring to delete emails to frustrate legitimate requests for information. Worst of all, one scientist threatened to delete climate data rather than turn it over, and that data is still missing."

Some of the worst gaffes were committed by Phil Jones, who said (amongst other things):

> "And don't leave stuff lying around on anonymous download sites—you never know who is trawling them. McIntyre and McKitrick have been after the Climatic Research Unit . . . data for years. If they ever hear there is a Freedom of Information Act now in the United Kingdom, I think I'll delete the file rather than send it to anyone."
>
> "I've just completed Mike's *Nature* trick [Michael Mann's publication in *Nature* where he replaced tree ring proxy data with measurement data because the tree ring data went in the 'wrong' direction[2]] of adding the measured temperatures to each series for the last 20 years (*i.e.* from 1981 onwards) and from 1961 for Keith's to hide the decline."
>
> "We have 25 or so years invested in the work. Why should I make the data available to you, when your aim is to try and find something wrong with it?"

They refereed each other's papers before submitting them to journals, communicated improperly in a mutual back-scratching environment subverting the peer review process, pressured journal editors not to publish papers contrary to the orthodoxy, conspired to write rebuttals to any papers that did slip through their barrier to publication of contrary views, and conspired to act in partnership to disparage and ridicule anyone with contrary findings. Several books present excerpts from the emails and provide interpretations of their implications, which are generally referred to as "Climategate" (e.g., Mosher and Fuller, 2010). In response to the many charges of malfeasance by the cabal members that appeared on the blogs, several reviews were carried out by vested interests (e.g., the so-called "Russell Report").[3] These generally provided a whitewash that was only to be expected.

The entire set of pirated emails provides strong evidence that there is indeed a cabal of climatologists, including both paleoclimatologists who seek to show that the Earth's climate has been relatively constant for thousands of years prior to the 20th century and climate modelers who seek to use climate models to infer that most of the 20th century warming was due to greenhouse gas buildup. The members of this cabal are dedicated to their preconceived beliefs, conspire with one another to prevent publication of dissenting views, conspire with one another to oppose and rebut dissenting papers that slip through their net of referees for major journals, and make frequent alarmist press releases to win over the public. It seems likely that the motivation for all this is to create a climate of fear so that governments will exponentially increase funding for climate research; in that respect they have been very successful.

[2] See *http://climateaudit.org/2009/11/20/mike%E2%80%99s-nature-trick/*
[3] *http://www.cce-review.org/*

One of the great achievements of the Internet is that any moron or any expert can voice his or her opinion. Indeed, there are plenty of both on the Internet, with a great preponderance of the former.

When searching for material on the Internet about any subject, one typically begins with Google. Google prioritizes its responses to any query in proportion to the number of links to any given site. It interprets links to a site as evidence of the site's importance and influence—a vote of confidence by the public. Thus, institutions and organizations tend to be at the top of the response list, while websites by individuals are often buried deep in the response list. As a result, the public is increasingly exposed primarily to orthodox institutional viewpoints.

As it turns out, the majority of paleoclimatologists accept the thesis widely promulgated by Al Gore, the U. N., NOAA, the National Academy of Sciences, and other predominant organizations that $CO_2$ emissions were the sole or major cause of global warming in the 20th century and this warming will increase in the 21st century in proportion to further emissions. Several noted climatologists have predicted that global warming will prevent the next ice age from occurring. This is the orthodox institutional viewpoint that is taught to schoolchildren and widely promulgated by academia. Similarly, the orthodox institutional viewpoint is that the astronomical theory explains the occurrence of ice ages, and you can find a thousand instances where this is stated as a proven fact. As institutions and organizations continue to dominate over individuals in these matters, a consensus builds up on each topic.[4] Furthermore, the global-warming alarmists proclaim their majority as evidence that they are correct. Oreskes (2004) built her entire argument in favor of anthropogenic global warming on the numbers and prestige of those who support the hypothesis, rather than the scientific basis for it. In fact, she does not appear to be familiar with the science underlying the belief. Furthermore, the degree of consensus has been exaggerated (Schulte, 2008), and the paleoclimatic cabal has managed to prevent publication of contrary views. For example, a major work that rebuts the $CO_2$ thesis is only available on the Internet as a blog (Idso, 2008).

As Lindzen (2008) pointed out, the field of climatology is a rather "small weak field" and the sub-field of paleoclimatology is even smaller and weaker. Both fields have been co-opted by the environmental movement, which exploits the fear of natural disaster. The earthquake specialists who continue to warn "the

[4] An anecdote illustrates the point. At the NSF workshop *Reversing Global Warming: Chemical Recycling and Utilization of $CO_2$* I presented a talk showing why the hockey stick representation of past temperatures was incorrect. A representative of the NSF, Jennifer Grasswick, raised a question at the end of my talk. She asked: "Why should I believe you when the National Academy of Sciences says otherwise?" She was relying on the institution over the individual. Ignoring the data that I presented, she fell back on reliance on the consensus. The issue was no longer whether my data and analysis were accurate but, rather, whether more prestigious organizations took a contrary position. Ayn Rand must be turning in her grave! While I was giving my talk, one attendee of the alarmist persuasion stomped out the meeting hall audibly cursing.

big one is coming" know full well that continued funding requires an atmosphere of fear.

Benestad (2005) discussed the tension between those who study the variability of the Sun as a source of climate change vs. those who are dedicated to $CO_2$ as the major driver of climate change. Benestad (2005) said:

> "I must admit that I have encountered entrenched positions on the subject and some prejudice, as the issue of whether solar activity may affect terrestrial temperatures appears to be laden with political and personal agendas .... Various hypotheses of solar regulation of our climate have sometimes been presented as a scientific challenge to the established view that human emissions of greenhouse gases represent a disrupting influence on our climate. Scientifically speaking, such a challenge would be sound and the best thing that could happen for further progress."

However, he did not feel safe leaving it at that but felt compelled to pay lip service to the consensus by saying it would be "unfortunate" if the claim that anthropogenic climate disruption can result in severe climate change proves to be real, and this challenge delayed response to this threat. He also knelt before the king by assuring that "solar influence on Earth's climate ... does not represent an antithesis to the so-called enhanced greenhouse effect."

### 11.1.3 Effect of $CO_2$ growth on global temperature

The question of interest here is whether projected $CO_2$ emissions in the 21st century will produce enough global warming to prevent or seriously delay future ice ages. Thus, we are concerned with the putative connection between $CO_2$ and global warming.

As Figure 4.16 shows, the $CO_2$ concentration in the Earth's atmosphere in the past has tended to vary between about 190 ppm during glacial maxima to about 280 ppm during interglacial periods. Because changes in the $CO_2$ concentration lag changes in global average temperature by perhaps 1,000 years, it seems likely that such changes are primarily the effects rather than the causes of ice ages. Nevertheless, such changes in the $CO_2$ concentration undoubtedly provide additional positive feedback to contribute to trends in climate change during glacial–interglacial cycles. Furthermore, there is evidence that previous interglacials reached higher temperatures than those of today; yet their $CO_2$ concentrations remained under 300 ppm. This seems very strange. The $CO_2$ concentration in the Earth's atmosphere has increased rapidly in the 20th and 21st centuries, well beyond the expected range for glacial–interglacial cycles (see Figure 11.1). During the time the $CO_2$ concentration has increased, the Earth has also undergone warming. Many climatologists believe that the rising $CO_2$ concentration has been the primary cause of this global warming. Figure 11.2 shows the alarmist view of rising global temperatures in the 20th century compared with rising $CO_2$ concentrations. However, there are difficulties with this interpretation.

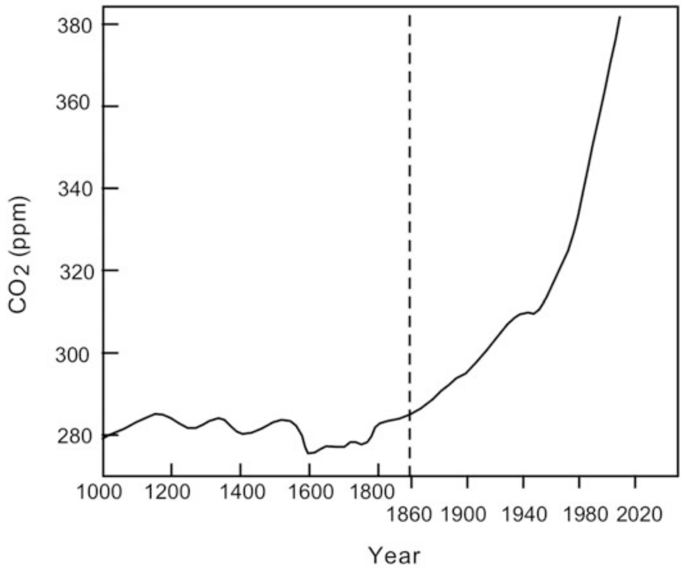


**Figure 11.1.** Carbon dioxide concentration over the past 1,000 years. Note the break in the time scale at 1860.

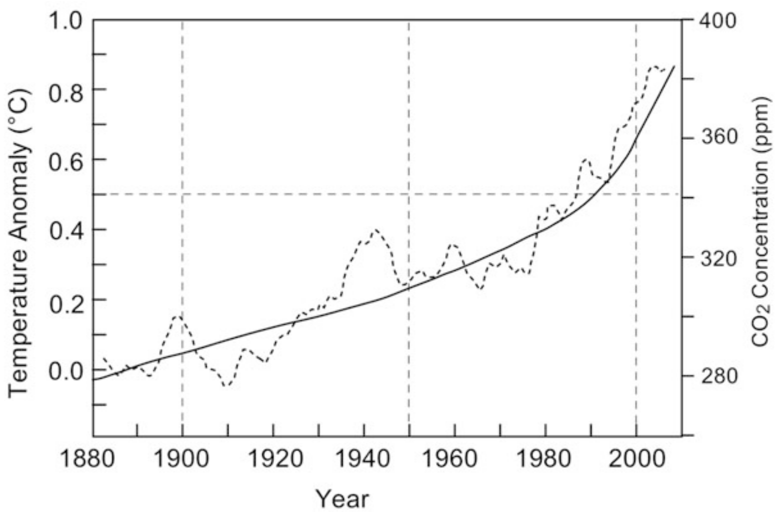


**Figure 11.2.** Comparison of global temperature (dashed curve) (from Hansen *et al.*, 2010) with buildup of $CO_2$ in the 20th century (solid curve).

The first difficulty is in defining the average temperature of the Earth.[5] Most estimates of the Earth's average temperature are based on land and ocean surface measurements around the globe and the application of some sort of averaging scheme. However, as Rapp (2008) showed in some detail, the global network of temperature measurement stations that have amassed 100 years of data is not only sparse but also mainly centered in the U. S. and Western Europe. Furthermore, the number of stations has been decreasing at an alarming rate late in the 20th century. In addition to the lack of long-term temperature data from around the globe, there are numerous problems associated with many of the measurement stations. These include poor siting because of local obstructions or reflectors; urban heating effects; changes in the environment of the station, the instrument used, or its location over the years; changes in observing practices and the method used to calculate mean temperature; and lack of maximum–minimum temperature capability at most sites. The problem of urban heat islands is particularly important. Hansen *et al.* (2010) carried out an extensive review and analysis of the adequacy of the global temperature measurement network. They claimed that the network was adequate and when they made corrections for urban areas these corrections were small. However, Imhoff *et al.* (2010) and Zhang *et al.* (2010) reported that urban heat effects are far greater than had previously been supposed, as much as 7°C higher in many cases. In addition, there are uncertainties in the calibration of long-term sea temperature records.

Rapp (2008) quoted some leading experts in the field of Earth temperature monitoring who said (amongst other things):

> "Climate researchers have used existing, operational networks because they have been the best, and sometimes only, source of data available. They have succeeded in establishing basic trends of several aspects of climate on regional and global scales. Deficiencies in the accuracy, quality, and continuity of the records, however, still place serious limitations on the confidence that can be placed in the research results."
>
> "It's very clear we do not have a climate observing system ... This may come as a shock to many people who assume that we do know adequately what's going on with the climate but we don't."

An alternative to surface measurement stations is the use of satellite observations to assess global temperatures. Douglass and Christy (2009) presented evidence that past problems with calibration have been solved and they presented the latest tropospheric temperature measurements. They argued that satellite measurements of temperature are superior to ground-based measurements because they provide a global view and do not suffer from boundary layer effects or

[5] The author's book *Assessing Climate Change*, Praxis Publishing, Second Edition, 2010 provides an in-depth discussion of the procedures used to estimate global temperatures and the results obtained so far.

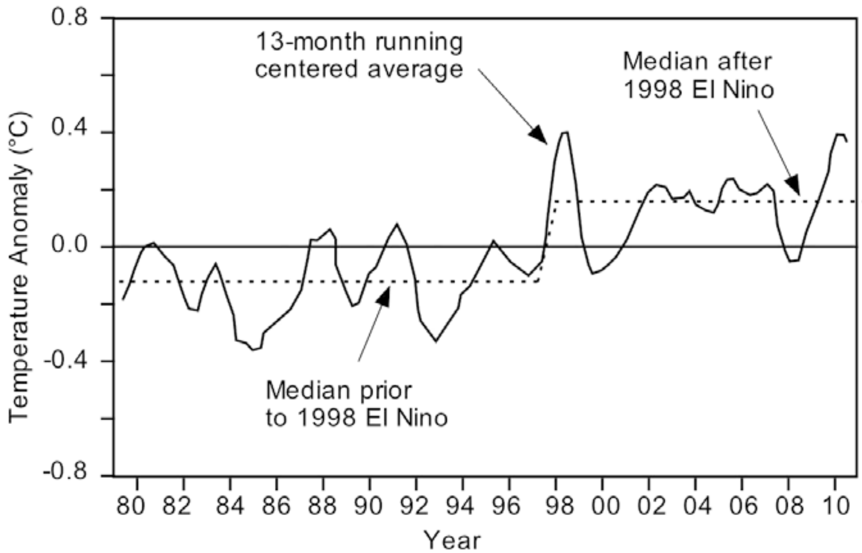


**Figure 11.3.** UAH globally averaged satellite-based temperature measurements of the lower atmosphere.[6]

other aberrations from human activity. However, the availability of satellite data only goes back as far as 1979 and, therefore, has only limited implications for understanding the long-term effects of $CO_2$. Contrary to the picture presented by Hansen *et al.* (2010) in Figure 11.2, the measurements on tropospheric temperature provide a very different picture (as shown in Figure 11.3). These results suggest that temperatures were stable from 1980 until the advent of the giant El Niño of 1998, after which a new temperature plateau was reached about 0.3°C higher than prior to the 1998 El Niño.

Temperature data of the Earth based on surface measurements suggest that over the past ~120 years, temperatures have risen the most in northern latitudes, with a smaller rise in the tropics, and an even smaller increase in southern latitudes. There was an initial temperature rise from about 1890 to 1940, a temperature dip from 1940 to about 1978, and a sharper rise after 1978 (see Figure 11.4).

The dip from 1940 to 1978 was seized upon by global-warming naysayers as evidence of a lack of connection between $CO_2$ growth and temperature rise. However, several studies have concluded that sulfate aerosols and particulates reflect incident sunlight, producing a cooling effect. Global-warming alarmists then argued that the cooling observed from 1940 to 1978 was due to an increase in aerosol production from power plants that overwhelmed the greenhouse effect, but that the cleanup of power plants starting around 1978 reduced aerosol production after that. This was challenged by naysayers, and there remains uncertainty

[6] *http://www.drroyspencer.com/*

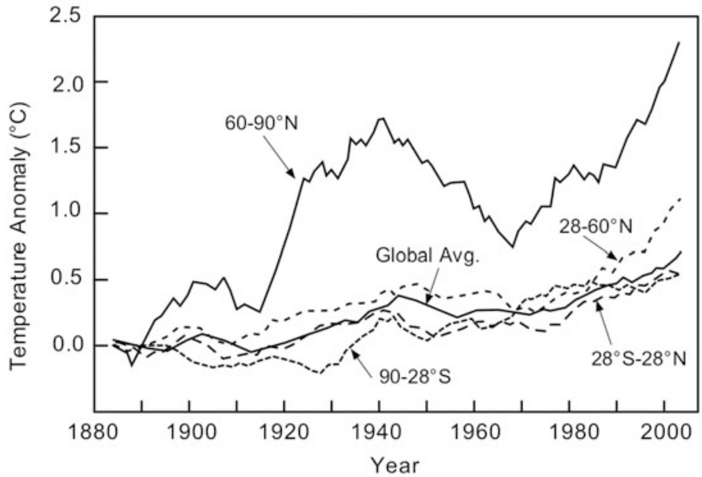


**Figure 11.4.** Area-weighted mean observed temperatures over the latitude bands indicated. The values are 9-year running means relative to the 1880–1890 mean (Shindell and Faluvegi, 2009).

regarding the impact of aerosols on global temperatures in the mid- to late 20th century. It is difficult to resolve this important issue at this time.

There is an interesting correlation between temperature rise after 1978 and the so-called El Niño–Southern Oscillation (ENSO) phenomena, as measured by the Southern Oscillation Index (SOI). The SOI is a measure of large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific during El Niño and La Niña episodes. In general, the SOI corresponds to changes in ocean temperatures across the eastern tropical Pacific. Prolonged periods of negative SOI values coincide with abnormally warm ocean surface waters across the eastern tropical Pacific typical of El Niño episodes. Prolonged periods of positive SOI values coincide with abnormally cold ocean waters across the eastern tropical Pacific typical of La Niña episodes. Estimates of the SOI have been made that date back to the mid-19th century. These results indicate roughly equal positive and negative fluctuations for many years. However, in the last ~25 years of the 20th century, the trend of the SOI has been overwhelmingly negative. It may well be that surface warming in the NH since 1978 has been heavily influenced by abnormally warm surface waters across the Pacific (Rapp, 2008). Douglass and Christy (2009) found almost perfect coincidence between oscillations in satellite-measured global temperature and the ENSO index since about 1978 (see Figure 11.5). This would seem to suggest that warming since 1978 has been heavily influenced by the Pacific Ocean, rather than by increasing $CO_2$.

Satellite measurements indicate that the global average temperature of the lower atmosphere oscillated in a narrow range after 1978 until the great El Niño of 1998 which drove temperatures up sharply. In the aftermath of the 1998

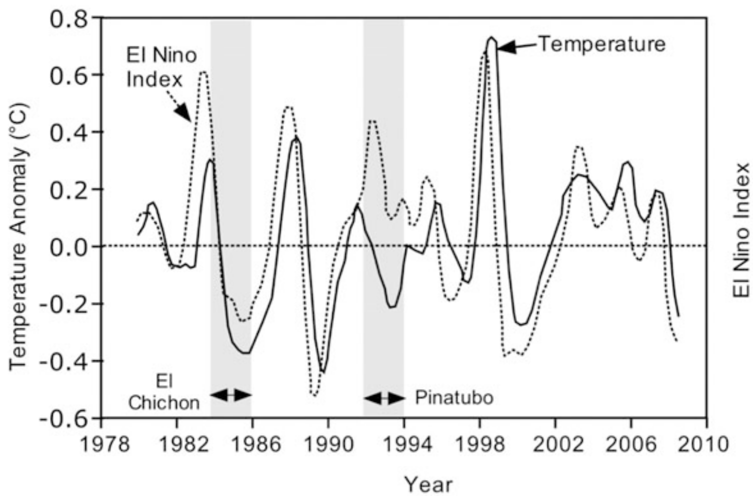


**Figure 11.5.** Comparison of the global temperature anomaly (measured from space) with an El Niño index (Douglass and Christy, 2009).

El Niño, temperatures oscillated around a new plateau about 0.3°C higher than pre-1998.

It should be kept in mind that the climatology cabal often provides biased public announcements regarding global warming. One minor example was in the January 4, 2009 *New York Times* weather report issued by the National Weather Service which said: "2008 was the 36th warmest year in the US since 1895." But we only exited the Little Ice Age in 1895, and the warmest years in the U. S. have all been after 1980. Since there have only been 28 years since 1980 and the weather report, the fact that 2008 was the "36th warmest since 1895" suggests that 2008 was colder than any year after 1980. But since U. S. temperatures actually dropped from 1940 to 1980, this would further imply that 2008 was the coldest year since 1940.

Aside from the fact that $CO_2$ concentrations and global temperatures have both risen over the past 100 years or so, the principal reason many climatologists believe that rising $CO_2$ has led to global warming is that global climate models predict increased $CO_2$ will produce a heating effect for the Earth. There is no doubt that atmospheric $CO_2$ produces a greenhouse effect by absorbing some of the outgoing radiation emitted by the Earth. Figure 11.6 shows forcing as a function of $CO_2$ concentration.

Carbon dioxide absorbs outgoing IR radiation primarily in the absorption band between wavelengths of about 13 and 17 μm. The absorption of any wavelength in the atmosphere is dependent on the integral of absorptivity × concentration on a vertical path through the atmosphere. This integral is called the absorption factor. Since the absolute amount of absorption depends on the exponential function of the absorption factor, an absorption factor of ~3 corresponds to about 99% complete absorption. As Figure 11.7 shows, with the

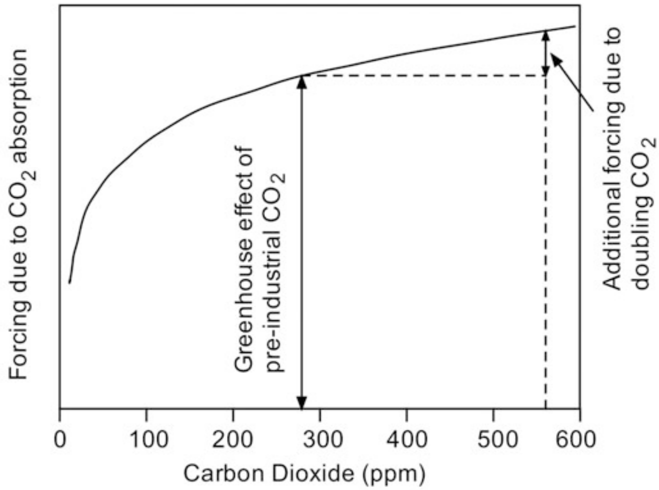


**Figure 11.6.** Schematic representation of forcing due to $CO_2$ greenhouse effect as a function of $CO_2$ concentration.

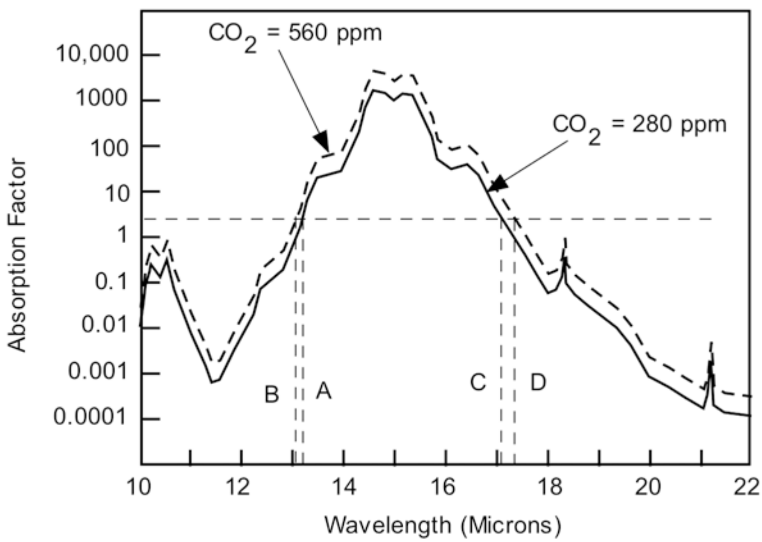


**Figure 11.7.** Absorption factor (absorptivity × concentration integrated over a vertical path through the atmosphere) for $CO_2$ vs. wavelength. The horizontal dashed line corresponds to an absorption factor of 3 (essentially total absorption along a vertical path through the atmosphere).

pre-industrial level of 280 ppm of $CO_2$, the entire absorption band from 13 to 17 μm is fully saturated.

Adding more $CO_2$ to the atmosphere does not increase absorption within the saturated region significantly. Only at the "wings" of the absorption band is there any significant increase in absorption by the atmosphere when the $CO_2$ concentration is increased. Thus, with a $CO_2$ concentration of 280 ppm, absorption is saturated between the vertical dashed lines labeled A and C in Figure 11.7.

If the $CO_2$ concentration doubles (from the pre-industrial value) to 560 ppm in the future, the absorption curve moves up by a factor of 2 on the log scale and the saturated region expands to the region between vertical lines B and D, producing a net heating effect. However, the additional heating effect (from absorption in the regions between A and B and between C and D) is much smaller than the original heating effect in going from 0 to 280 ppm (region between A and C). Thus, we see that as increasingly more $CO_2$ is added to the atmosphere the heating effect decreases per unit amount of $CO_2$ added. This is shown in Figure 11.6. However, the above description is overly simplistic. The actual effect of additional absorption by $CO_2$ is a change in the vertical profile of temperature through the atmosphere, which results in a change in outward radiant emission from the atmosphere (Lindzen *et al*., 1982; Lindzen, 1997, 2007).

A number of climatologists have addressed the problem of estimating future global average temperature rise resulting from doubling of the $CO_2$ concentration from the pre-industrial level of 280 to about 560 ppm sometime later in the 21st century. The reasons for choosing the benchmark of 560 ppm for the future relate to projections of future world population growth, increasing industrialization of developing nations, and expected increase in the use of coal as the 21st century progresses. The Inter-government Panel on Climate Change (IPCC) has developed a number of alternative scenarios for future $CO_2$ emissions, depending on economics, technology, and policy changes. A widely used middle-of-the-road business-as-usual scenario from the IPCC is shown in Figure 11.8 as "IS92a". In this scenario, annual $CO_2$ emissions continue to increase through the 21st century. Two other hypothetical future scenarios are shown in this figure. In one scenario, the $CO_2$ emission rate is held constant at the 2010 rate (estimated to be about 8 Gt/yr of carbon which is equivalent to $\sim 8 \times 44/12 = 29$ Gt/yr of $CO_2$) for the remainder of the 21st century.[7] In the other scenario, there is a downward ramp to lower emission rates as the 21st century wears on. It should be noted that the latter two scenarios require draconian modifications to the way that industrialized societies produce and consume energy. These three scenarios lead to the buildup of $CO_2$ in the atmosphere as shown in Figure 11.9 and assume that half of the $CO_2$ emitted ends up in the atmosphere.[8] In the business-as-usual scenario, the $CO_2$ concentra-

[7] The 8 Gt/yr of carbon emissions consists of about 2 Gt/yr from land clearing and about 6 Gt/yr from fossil fuel burning and cement production. The expectation in the business-as-usual scenario is that the land use figure will not change markedly but the fossil fuel combustion will increase significantly in this scenario.

[8] While this 50% assumption is representative of the past, it is not clear whether it will hold in the future. One model predicts that the 50% distribution will continue through at least 2040: F. T. Mackenzie, A. Lerman, and L. M. B. Ver, "Recent past and future of the global carbon cycle," in L. C. Gerhard, W. E. Harrison, and B. M. Hanson (Eds.), *Geological Perspectives of Global Climate Change*, pp. 51-82.

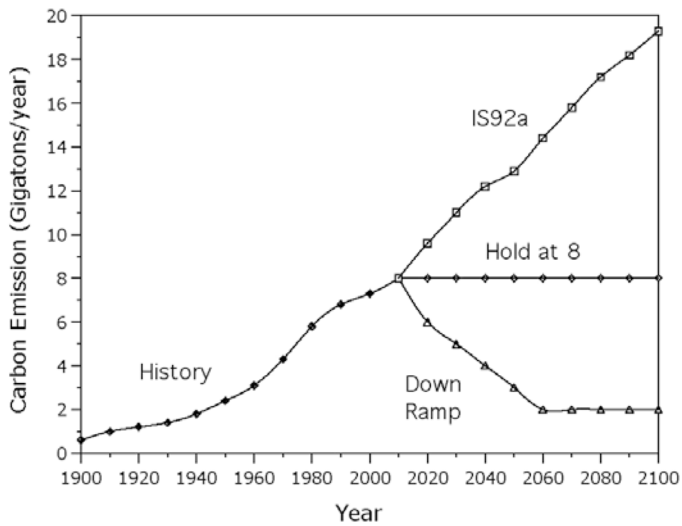


**Figure 11.8.** Annual emissions of carbon for three future scenarios in the 21st century.

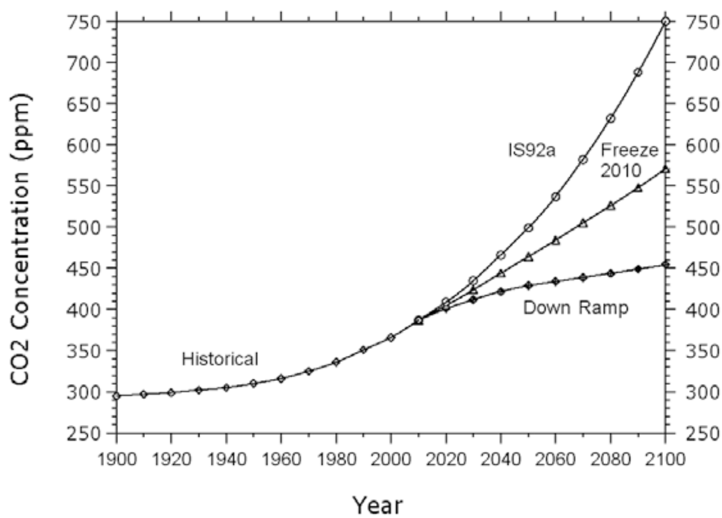


**Figure 11.9.** Buildup of $CO_2$ in the atmosphere corresponding to the three scenarios in Figure 11.8.

tion reaches 750 ppm by the end of the 21st century. If the $CO_2$ emission rate is frozen at the 2010 level, the $CO_2$ concentration roughly doubles the pre-industrial level by the end of the 21st century. Even the downward ramp leads to some elevation of atmospheric $CO_2$ concentration. Hence, it seems likely that the $CO_2$

concentration in the atmosphere will likely reach 560 ppm before the end of the 21st century.

Thus, with the likelihood that the $CO_2$ concentration will rise to 560 ppm (or more) during the 21st century, the question now becomes: What is the expected global temperature rise due to the greenhouse effect from this change? Climatologists have attempted to answer this question by means of global climate models (GCMs). In these models, scientists first estimate the greenhouse heating effect due to doubling of the $CO_2$ concentration as an equivalent amount of downward heat flow called a "forcing". Forcing units are measured in power per unit area ($W/m^2$). Having estimated the forcing produced by doubling the pre-industrial level of $CO_2$, they next estimate the rise in global average temperature produced by that forcing. This involves a complex computerized analysis of the coupled atmosphere–ocean–landmass Earth system. In the following we denote the forcing due to $CO_2$ as $\Delta F_C$ and the change in global average temperature as $\Delta T_C$ (the additional heating due to $CO_2$ in Figure 11.6).

The relation between these quantities is

$$\Delta T_C = \lambda \, \Delta F_C$$

where $\lambda$ is the so-called "climate sensitivity parameter". We use the subscript $C$ to denote that this is entirely due to the carbon dioxide greenhouse effect, ignoring the secondary effects due to this warming. According to the GCMs, the global warming ($\Delta T_C$) produced by the $CO_2$ greenhouse effect increases evaporation from the Earth's bodies of water and, hence, the global average humidity of the atmosphere. Since water vapor is a powerful greenhouse gas (much more so than $CO_2$) this increase in water vapor produces an additional forcing ($\Delta F_W$) which in turn produces an additional temperature rise ($\Delta T_W$). In addition, as the humidity of the atmosphere increases so does the degree of cloudiness of the Earth's atmosphere resulting in a change in the Earth's albedo. This will produce yet another change in temperature ($\Delta T_{\mathrm{Cl}}$). Depending on the nature and distribution of clouds, this term can in principle be positive or negative. Quite a few estimates have been made of the cloud feedback factor by various investigators. In general, those of the alarmist persuasion find that clouds amplify temperature changes, while skeptics find the opposite. If cloud feedback is negative, it will reduce the temperature rise induced by increased water vapor. Thus, we see that $\Delta T_W$ depends on $\Delta T_C$ but these quantities affect the $\Delta T_{\mathrm{Cl}}$ which provides the (probably negative) feedback. The total temperature change due to $CO_2$, water vapor, and changes in cloudiness can be expressed as

$$\Delta T_{\mathrm{tot}} = g\lambda \, \Delta F_C$$

where $g$ is the gain factor due to water vapor, cloudiness, and any other climatological factors that change as $CO_2$ builds up.

Climate models have been used by a number of investigators to estimate $\Delta F_C$. A value of about 3.7 $W/m^2$ seems to be representative of a doubling of $CO_2$ from the pre-industrial level of 280 ppm. Estimates of $\lambda$ in the literature range from about 0.3 to 0.8°C per $W/m^2$, although some estimates exist outside this range.

What is interesting is that those modelers with high values of $\lambda$ seem to choose low values of $g$ and vice versa. This keeps $\Delta T_{\rm tot}$ typically in the range $3 \pm 1.5°C$.

Huybers (2010) provided a very insightful review of climate models. He suggested that:

> "Inter-model compensation between climate sensitivity and radiative forcing underscores that the models are not based purely on theory but are also conditional upon observations and, possibly, expectations."

Huybers (2010) showed that the treatment of clouds was the "principal source of uncertainty in models". Indeed, his Table I shows that the variation of net feedback varied only from 0.49 to 0.73 (a narrow range) whereas the response of the climate system to clouds by various models varied from 0.04 to 0.37 (a wider spread). He then examined several possible sources of compensation between climate sensitivity and radiative forcing. He concluded:

> "Model conditioning need not be restricted to calibration of parameters against observations, but could also include more nebulous adjustment of parameters, for example, to fit expectations, maintain accepted conventions, or increase accord with other model results. These more nebulous adjustments are referred to as 'tuning'."

He gave an example of possible tuning: "reported values of climate sensitivity are anchored near the $3 \pm 1.5°C$ range initially suggested by the Ad Hoc Study Group on Carbon Dioxide and Climate (1979) and that these were not changed because of a lack of compelling reason to do so."

He went on to say:

> "More recently reported values of climate sensitivity have not deviated substantially. The implication is that the reported values of climate sensitivity are, in a sense, tuned to maintain accepted convention.
>
> Convergence between model results, if not truly driven by a decrease in model uncertainty or clearly understood as a result of calibration, could have the unfortunate consequence of lulling us into too great a confidence in model predictions or inferences of too narrow a range of future climates. To the extent that it occurs, tuning the models based on expectation or convention renders the modeling process a partially subjective exercise from which it is very complicated to derive a statistical interpretation."

Translated into simple terms, the implication is that climate modelers have been heavily influenced by the early (1979) estimate that doubling of $CO_2$ from pre-industrial levels would raise global temperatures $3 \pm 1.5°C$. Modelers have chosen to compensate their widely varying estimates of climate sensitivity by adopting cloud feedback values countering the effect of climate sensitivity, thus keeping the final estimate of temperature rise due to doubling within the limits preset in their minds. Had they not done this, the spread in estimates of temperature rise would be much greater. Thus, they have imposed their preconceived notions of expected temperature rise on the models to make them come out "right". In Section 11.2 we discuss an estimate of climate sensitivity based on paleoclimatic data.

Unfortunately, the topic of global warming has to some extent degenerated into a quasi-religious belief system. There are those on the left (alarmists) who believe that the end of the world is at hand and, like Old Testament prophets, warn the populace of impending climatological disaster. The IPCC required over 1,000 pages to describe all the supposed negative impacts of global warming in the 21st century. Extravagant claims have been proposed, most of which are unsubstantiated. In opposition to the alarmists are the naysayers, who dispute some or many of these claims, sometimes with cogent arguments and data. However, the far right cadre of naysayers (in addition to serious scientists) also includes creationists, religious nuts of several varieties, and others with little concern about desecration of the environment. At both ends of the spectrum, the matter seems to rest on faith rather than facts, and even scientists seem to have lost objectivity in many instances.

An important analysis of the effect of $CO_2$ on climate was made by Lindzen (1997). Many aspects are covered in his paper, but only a brief report on some parts is given here. He answered the question posed by the title of his paper ("Can increasing carbon dioxide cause climate change?") with tongue in cheek by saying nothing is impossible. But the real question is "By how much and is it discernible?".

Lindzen emphasized:

> "Water vapor, the atmosphere's main greenhouse gas, decreases in density rapidly with both height and latitude. Surface radiative cooling in the tropics, which has the highest concentration of water vapor, is negligible. Heat from the tropical surface is carried upward by cumulus convection and poleward by the Hadley circulation and planetary-scale eddies to points where radiation can more efficiently transport the heat to space. Where radiation can more efficiently carry the heat depends on the radiative opacity and the motions themselves. In point of fact, without knowing the dynamical heat fluxes, it is clear that one cannot even calculate the mean temperature of the Earth. It is interesting, in this regard, to look at model intercomparisons of meridional heat flux, and their comparison with observationally based estimates .... Such differences [are] roughly equivalent to differences in vertical fluxes of about 25 W/m$^2$—much larger than the 4 W/m$^2$ change that a doubling of $CO_2$ is expected to produce."

There are two points here: (1) the tropics lose heat by processes other than radiation and (2) meridional heat transfer is much greater than putative $CO_2$ forcing.

As we discussed previously, the prevailing view amongst climatologists is that global warming due to increased $CO_2$ is amplified by increased water vapor content in the atmosphere. Lindzen provided a detailed discussion of several aspects of the regional distribution of water vapor in the atmosphere and its relationship to global warming induced by increased $CO_2$. Most climate models make the assumption that relative humidity does not change with global warming and, since warm air can hold more water vapor than cool air, a constant relative humidity implies an increase in absolute humidity as the Earth warms. The basis for the assumption that relative humidity does not change with global warming lies in some rather old radiosonde data that indicate that the average distribution of relative humidity (when plotted on altitude vs. latitude axes) does not change much from winter to summer. The argument then goes that relative humidity would also not change over the smaller temperature change characteristic of global warming. However, Lindzen raised serious questions about the accuracy of the radiosonde data. Clearly, the assumption of constant relative humidity rests on a weak foundation, and that assumption is critical to the alarmist position that the doubling of $CO_2$ produces unacceptable global warming due to increased absolute humidity.

But Lindzen went further than this. He emphasized that the degree of water vapor feedback as a heating force in any region depends on absolute humidity. In desert regions with very low absolute humidity, an increase in humidity provides a significant heating force. However, in regions with high absolute humidity, an increase in humidity provides a very modest heating force (e.g., an increase in relative humidity from 10 to 20% produces a forcing of $1.5\,W/m^2$, whereas an increase in relative humidity from 50 to 60% produces a forcing of only $0.15\,W/m^2$). Tropical regions that already have high humidity do not gain much additional heating from an increase in humidity. Moreover, as Lindzen pointed out:

> "Given the nonlinearity of the radiative effect of water vapor, the average radiative response to water vapor is not equal to the response of the average water vapor."

As already noted, a doubling of $CO_2$ implies forcing at the tropopause of about $3.7\,W/m^2$. The question of climate sensitivity amounts to asking how much must the Earth's surface warm to compensate for this forcing. This requires globally integrated total radiative flux at tropopause levels to be estimated. A global change in the distribution of moist and dry regions can lead to a change in outgoing long-wavelength radiation (OLR) even in the absence of change in mean temperature. Changes in circulation and changes in temperature can both play a role in the moisture budget. Lindzen suggested:

> "... the interesting possibility that the primary feedback process might consist in the change in areal coverage of the very dry regions. Presumably, natural variations include a full range of such possibilities so that observed ratios of average temperature variations to variations in total OLR would show a significant scatter."

According to Lindzen, global climate models are not good at estimating the coupling between tropical and extratropical regions and, therefore, do not allocate the global distribution of water vapor accurately; this has a profound effect on the putative heating effect of increased $CO_2$. It seems possible that global warming might decrease the humidity of air descending above the desert areas of the Earth and, since these regions are by far the most sensitive to changes in humidity, they would counterbalance the smaller heating effect of increased humidity in regions where the humidity is higher. The regional effects of changes in humidity far outweigh the effects of changes in net global humidity. The expansion of already dry regions is more important than net humidifying of the globe. Net moistening of the Earth could have a negative water vapor feedback if most of that moistening occurs in already moist regions. Climate models that employ average humidity for the whole Earth are overly simplistic.

The effect of water vapor feedback in amplifying global warming produced by the $CO_2$ concentration increasing requires an understanding of the distribution of humidity changes resulting from warming; global average humidity change is not good enough. Of course, one must still cope with the problem of changes in cloudiness, despite being armed with a thorough understanding of the regional dependence of humidity change. Lindzen *et al*. (2001) and Lindzen (2007) studied this and came up with four major points: (1) cloud and water vapor feedbacks are intimately connected; (2) feedbacks are primarily associated with changing areas of moist and cloudy regions vs. regions that are dry and cloud free (as opposed to mean humidity); (3) models must have spatial and temporal scales (5–10 km and hours) characteristic of clouds in order to evaluate feedbacks; and (4) the effect of cumulus activity must be included. A simplistic model that merely treats humidity as a global average which increases when surface temperatures rise, which ignores regional changes in humidity, and which treats clouds crudely will always overestimate the temperature rise due to increased $CO_2$.

While most climate models deal with such elements as clear sky humidity, average humidity, or differences between regions of high and low humidity, Lindzen and co-workers studied feedback involving changes in the relative areas of high and low humidity and cloudiness. Their results suggest that cloudy moist regions contract when the surface warms and expand when the surface cools. In each case the change acts to oppose surface change and, thus, presents a strong negative feedback to climate change like a sort of Le Chatelier's principle. They concluded that the relevant feedbacks are negative rather than positive and very large in magnitude. Spencer *et al*. (2007) studied the effect of changes in clouds on changes in temperature in tropical regions and found a negative feedback of $-6\,W/m^2$ per degree of temperature rise. This provides some support for Lindzen's hypothesis.

Dessler *et al*. (2008b) attempted to derive water feedback sensitivity by comparing data on global temperature and humidity during the winter months of 2006–2007 and 2007–2008. However, Douglass and Christy (2009) demonstrated a strong correlation between global temperature and an El Niño index since 1978, and particularly for 2006–2008 (see Figure 11.5). Dessler *et al*. (2008b) also found a good correlation between global temperature and an ENSO index for 2006–2008. Hence, it seems clear that global temperature changes for 2006–2008 were driven primarily by changes in the oceans, and changes in humidity during that period were not a cause of global temperature change—but an effect. The effect of changing $CO_2$ concentration and a putative water vapor greenhouse effect are buried in the noise of a much stronger signal due to El Niño variability during these years. Therefore, it is physically impossible to derive water feedback sensitivity from data limited to these two winters. Yet, the authors claim that they have done so and quote a value in agreement with climate models. This seems impossible to this writer. They then reach the rather incredible conclusion:

> "The existence of a strong and positive water-vapor feedback means that projected business-as-usual greenhouse gas emissions over the next century are virtually guaranteed to produce warming of several degrees Celsius."

This conclusion is utterly unsupportable from the analysis of two winters' data controlled by El Niño activity.

Dessler *et al.* (2008a) analyzed one month's data in 2005 to infer clear sky top-of-atmosphere outgoing long-wavelength radiation (OLR) and its relationship to humidity. As to whether this paper sheds any light on water feedback sensitivity is not clear to this writer.

Gettleman and Fu (2008) analyzed the changes in humidity produced by temperature changes from 2002 to 2007. As before, temperatures during this period appear to have been determined by El Niño variability, and changes in water vapor content appear to be effects of this temperature change. There is little or no connection to heating produced by $CO_2$ and water feedback sensitivity does not seem to be derivable from this work.

It is now becoming apparent that the high temperatures experienced by the Earth in the late 1990s, and particularly in 1998, were related to the prevalence of El Niño conditions and, with the advent of the La Niña in 2007–2008, world temperatures dropped. Temperatures rose again with the El Niño of 2009, and then faded with the La Niña of 2010. While it is possible that growth in $CO_2$ contributed to global warming during the 20th century, it is clear that large fluctuations dictated by ocean conditions, aerosol emissions, and unknown factors have masked the putative $CO_2$ effect, making it very difficult to unravel the contribution of rising $CO_2$. As Kondratyev *et al.* (2003) concluded: "The principal conclusion to be drawn ... is that studies of such a complicated problem as global carbon dynamics are still at an early stage of development ...."

Perhaps the most amazing thing about the debate on global warming and greenhouse gases is that both sides (alarmists and naysayers) are so self-righteous and certain they are right while the systems are so complex and poorly understood.

### 11.1.4 Other evidence on the role of $CO_2$

#### *11.1.4.1 Temperatures over the past two millennia: the "hockey stick"*

Obviously, one of the great issues facing humankind is the question of how much global warming is to be expected from increased emission of $CO_2$ in the 21st century. The primary basis for the argument that increased $CO_2$ was the most significant factor in 20th century global warming rests upon climate modeling, which up until now has shown itself to be of uncertain veracity. In addition, there are other circumstantial inferences that may be relevant.

If after due consideration and analysis it turns out that the expected global temperature rise from increased $CO_2$ emissions in the 21st century is injurious to a critical extent, draconian changes in world energy production and consumption may be needed to mitigate the situation. Many alarmist organizations have already prematurely leapt to this conclusion.

While some alarmists have claimed that current $CO_2$ concentrations are unprecedented, we pointed out in Section 2.2 that hundreds of millions of years ago the $CO_2$ concentration may have been as high as hundreds of times greater than the present atmospheric level. It is widely believed that over the course of geological history, $CO_2$ levels have periodically been much higher than those that prevail today.

Turning our attention to the more recent past, a relevant issue is whether there have been climate fluctuations during the past few thousand years of magnitude comparable or greater than recent global warming. Since these fluctuations occurred prior to large-scale human impact, they probably reflect the range of natural variation, at least during the very recent past in the Holocene. If that range of natural variation exceeds the current trend, it would imply that the current trend could possibly be just another natural fluctuation. On the other hand, if the range of natural variation prior to large-scale human impact is much smaller than the current trend, that would seem to imply that current climate trends probably originate from industrialization and land use. The problem here is knowing how far back in time one should look for climate variability. Climate alarmists have emphasized the magnitude of current global-warming trends by making elaborate and exaggerated claims that current warming far exceeds anything the Earth has known for thousands (or even millions) of years—which is of course nonsense. Figure 4.15a shows data that indicate that the previous three interglacials were considerably warmer than the Holocene. Yet, the data do not indicate that $CO_2$ levels were higher than Holocene $CO_2$ levels. The $CO_2$–temperature connection seems to be weaker than the alarmists assume. As Figure 4.7 shows, significant temperature fluctuations may occur during an interglacial independent of the activities of humans. There is no reason to expect temperatures during an interglacial to remain constant and benign.

Of particular note is the temperature history of the past 1,000 to 2,000 years. There have been many studies of past climate variations over this time period which were based on a variety of proxies (tree rings, corals, ice cores, pollen, etc.). Realizing that there exist many local, regional, and hemispheric proxies, with variable spatial and temporal extent, Mann *et al.* (1998, 1999) and Mann and Jones (2003) attempted a comprehensive analysis of the history of global average temperatures over the past 1,000 to 2,000 years using a multi-proxy network consisting of "widely distributed high-quality annual-resolution proxy climate indicators, individually collected and formerly analyzed by many paleo-climate researchers." This was intended to integrate as many proxy sources as possible into a single comprehensive view of how a single global average temperature (or NH average temperature) varied over the past millennium or two. A number of closely related studies were also published by other paleoclimatologists, all of the alarmist persuasion. The final result was a reconstruction of a single NH or global average temperature over the past one or two millennia that took on a so-called "hockey stick" structure: a rather flat profile for most of the past two millennia with a significant rise in the 20th century.

The papers by Mann, Bradley, and Hughes (MBH) are compact, full of jargon, and difficult to follow. However, this is a characteristic shared by many papers that deal with large datasets for historic Earth temperatures. The reference period for calibration of proxies with actual temperature data was from 1902 to 1980. The various proxies were more numerous in recent times and much less so in the more distant past. Each of the proxy datasets had variable geographical and temporal distribution, and the quality of the data probably varied enormously. The task was to combine these into a uniform function that best expressed the putative single global average temperature over a long time span. The process used for data reduction is too complex to discuss in any detail here. However, it should be kept in mind that the data were very sparse and contained mostly noise. MBH used principal component analysis (PCA) to process the data. The end result of this work was the discovery that global temperatures were basically unchanged (with small fluctuations) for the past 2,000 years, and then there was a sudden turn upward in the 20th century. This is often referred to as the hockey stick result because it has the shape of a hockey stick lying on the ground with the blade pointing upward at about 45°. According to this result, one would conclude that there was no Medieval Warm Period (MWP) centered around 900 AD, and no Little Ice Age (LIA) in the period 1500 to 1850. This diagram became the rallying point of alarmists who argued that warming in the 20th century was unprecedented in recent history and must be due to human impact. Millions of copies of reports containing this result have been widely disseminated. Subsequently, Stephen McIntyre and Ross McKitrick found a fundamental flaw in the data-processing procedure used by Mann *et al.* (1998, 1999) and Mann and Jones (2003) which had the effect of skewing the apparent result to produce the hockey stick configuration when, actually, the data do not support this result. However, McIntyre and McKitrick were thwarted in their attempts to get this information published, and ended up disseminating their analysis mainly from their website.[9] In addition to McIntyre and McKitrick, others reviewed the methods of MBH. The U. S. Congress asked a noted expert,

[9] See the Climate Audit website at *http://www.climateaudit.org*

Professor Edward J. Wegman, to perform an independent examination of the hockey stick controversy. His result is available at Wegman *et al.* (2006).

According to Wegman *et al.* (2006):

> "The controversy of Mann's methods lies in that the proxies are centered on the mean of the period 1902–1995, rather than on the whole time period ... Principal component methods are normally structured so that each of the proxy data series are centered on their respective means and appropriately scaled .... In the MBH approach the authors make a simple seemingly innocuous and somewhat obscure calibration assumption. Because the instrumental temperature records are only available for a limited window, they use instrumental temperature data from 1902–1995 to calibrate the proxy data set. This would seem reasonable except for the fact that temperatures were rising during this period, so that centering on this period has the effect of making the mean value for any proxy series exhibiting the same increasing trend to be de-centered low. Because the proxy series exhibiting the rising trend are de-centered, their calculated variance will be larger than their normal variance when calculated based on centered data, and hence they will tend to be selected preferentially as the first principal component. Thus, in effect, any proxy series that exhibits a rising trend in the calibration period will be preferentially added to the first principal component."

Wegman *et al.* (2006) went on to say:

> "The centering of the proxy series is a critical factor in using principal components methodology properly. It is not clear that the MBH Team even realized that their methodology was faulty at the time of writing the MBH paper. The net effect of the de-centering is to preferentially choose the so-called *hockey stick* shapes. While this error would have been less critical had the paper been overlooked like many academic papers, the fact that their paper fit some policy agendas has greatly enhanced their paper's visibility. Specifically, global warming and its potentially negative consequences have been central concerns of both governments and individuals. The *hockey stick* reconstruction of the temperature graphic dramatically illustrated the global warming issue and was adopted by the IPCC and many governments as the poster graphic. The graphic's prominence together with the fact that it is based on incorrect use of PCA puts Dr. Mann and his co-authors in a difficult face-saving position."

The findings of Wegman *et al.* (2006) are quite lengthy and only a very brief summary is given here:

1. In general, they found the papers by MBH somewhat obscure and incomplete. (This writer found the same.)
2. In general, they found the criticisms by McIntyre and McKitrick to be valid and their arguments to be compelling.

3. Use of the temperature profile in the 1902–1995 time span for centering leads to misuse of principal component analysis. However, the narrative in MBH on the surface sounds entirely reasonable and could easily be missed by someone who is not extensively trained in statistical methodology.
4. The cryptic nature of some of the MBH narratives requires outsiders to make guesses at the precise nature of the procedures being used.
5. Generally speaking, the paleoclimatology community has not recognized the validity of the McIntyre and McKitrick criticisms and has tended to dismiss their results as being developed by biased amateurs. The paleoclimatology community seems to be tightly coupled and has rallied around the MBH position.
6. Widely quoted assessments that the 1990s were the hottest decade in a millennium and that 1998 was the hottest year in a millennium cannot be supported by a proper rendition of the MBH analysis ... The paucity of data in the more remote past makes hottest-in-a-millennium claims essentially unverifiable.
7. The use of bristlecone pine proxies are inappropriate because they were probably $CO_2$ fertilized. Therefore, it is not surprising that this important proxy in MBH yields a temperature curve that is highly correlated with atmospheric $CO_2$. There are clearly confounding factors for using tree rings as temperature signals.

The ruling paleoclimatic cabal, all ardent alarmists, used their influence to gain support for their basically untenable position by the United Nations, the National Academy of Sciences, and other influential institutions. The details of this entire saga are described in some detail by Rapp (2008). As a result, MBH acquired widespread support for bad science via the consensus route. As it turns out, the criticism heaped upon the hockey stick did not go unnoticed. While Mann and co-workers never acknowledged the existence of McIntyre and McKitrick (or other critics of the hockey stick) they did respond to a suggestion of the National Research Council and revisited the subject via Mann *et al*. (2008). This paper, like its predecessors, is basically unreadable except perhaps to a handful of narrow specialists. While the paper purports to respond to criticism regarding the use of tree ring proxy data, it does not seem to respond to the fundamental flaw (reported previously by M&M and Wegman) of basing anomalies on the average value over the standardization period. The mathematical procedures used in the process are so abstruse as to hide the original data completely. But when the original proxy data are examined[10] the overwhelming majority of these proxies show no hockey stick trend at all, and it is clear that the report of an even more extreme hockey stick (than previously) represents a mathematical artifice—not a true averaging of the data. Furthermore, there is no basis for treating all proxies as equally valid. The Mann *et al*. (2008) results are in conflict with a large amount of their own data. It seems likely that the combination of mathematically averaging large amounts of democratically treated noisy proxy data will tend to cancel

[10] Graphs for all the 1,209 proxies are available at *http://www.climateaudit.org/data/images/mann.2008/*

out variations in the past, while use of recent unreliable terrestrial temperature data, biased by urban heating and other aberrations, will exaggerate the temperature rise of the past century relative to the past. Indeed, their finding that global temperature increased by 1.0°C since 1900 is considerably greater than what has been widely reported by others. What is more, Mann *et al.* (2008) found themselves faced with a problem: their tree ring proxies did not rise in the late 20th century when most of the temperature rise is claimed to have occurred. So, they were crafty enough to use what Phil Jones referred to as Mann's "trick" in which they did not show the proxy data late in the 20th century and, instead, put in the alarmists' view of the rising global temperature measured in the late 20th century. However, as Figures 11.2a and 11.3 show, global temperatures have not risen continuously upward in the past 30 years as MBH would have you believe. Nevertheless, the far right of their graphs for the last 30 years show a red line zooming upward.

Recently, McShane and Wyner (2010) (M&W) reviewed the hockey stick from the point of view of statistical analysis. They claimed that the hockey stick is a clever piece of public relations but it does not have the valid implications that a naive reader might suppose. The apparent agreement between the model and the data in the period after 1850 was forced by tuning the model to the data. The estimated implicit uncertainty in the data is optimistic but, even so, is so wide as to encompass almost any past temperature profile.

M&W went on to say:

> "... the task [of analyzing past proxy data to infer global average temperature history] is highly statistical [and] extremely difficult. The data is spatially and temporally auto-correlated. It is massively incomplete. It is not easily or accurately modeled by simple autoregressive processes. The signal is very weak and the number of covariates greatly outnumbers the number of independent observations of instrumental temperature."

There are two points here. One is that, by implication, MBH changed the rules of the game to achieve a desired result in an unscientific unprofessional manner. The other is that by doing this the hockey stick shape was relegated to the fourth level of principal component analysis, which infers low credibility. Michael Mann, in his rebuttal testimony before Congress, continued to stubbornly defend his turf, which is understandable since his whole scientific reputation depended on it? He claimed that many subsequent peer-reviewed studies confirmed his findings, but all of these studies used variants of his approach and were peer-reviewed by the paleoclimatic cabal. In particular, they all used skew-centering, as evidenced by the fact that the data were not spread across the zero line roughly equally. Furthermore, as Climategate has revealed, peer review in paleoclimatology is mainly a mutual affirmation by members of the club. This was the backdrop for the study by M&W to reexamine the issues involved in reconstructing past global climates from proxy data.

The precision of various proxies at representing temperature and only temperature remains a mystery. One thing is certain: not all proxies are equally credible. M&W were concerned with the statistical processing of data, assuming the data were adequate. More likely, the data were poor in quality, such that even the best statistical analysis would result in garbage in–garbage out (GIGO).

As Steve McIntyre (*climateaudit.org*) pointed out:

> "The fundamental problem in paleoclimate is not the need for some novel multivariate method, but better proxies and reconciliation of discordant existing 'proxies' .... Team reconstructions use highly stereotyped proxies over and over again in different guises ...."

The details of the statistical analysis in M&W (and the 13 commentaries that followed it) are quite complex and are only intelligible to specialists. One possibility raised by M&W was:

> "... it is possible that the proxies are ... too weakly connected to global annual temperature to offer a substantially predictive (as well as reconstructive) model over the majority of the instrumental period. This is not to suggest that proxies are unable to detect large variations in global annual temperatures (such as the differences that distinguish our current climate from an ice age). Rather, we suggest it is possible that natural proxies cannot reliably detect the small and largely unpredictable changes in annual temperature that have been observed over the majority of the instrumental period."

This appears to be the truth of the matter. Proxies seem able to detect very large excursions in temperature, such as occur in transitions between ice ages and interglacials, but probably are not able to resolve small temperature changes within an interglacial. The problem of backcasting historical temperatures from proxy measurements calibrated during a limited period of overlap between temperature measurements and proxy measurements is very complex and requires very sophisticated statistical analysis which might be beyond the capability of climate scientists. M&W attempted to bring such a sophisticated statistical analysis to bear on the problem:

> "... we conclude unequivocally that the evidence for a 'long-handled' hockey stick (where the shaft of the hockey stick extends to the year 1000 AD) is lacking in the data. The fundamental problem is that there is a limited amount of proxy data which dates back to 1000 AD; what is available is weakly predictive of global annual temperature. Our back-casting methods, which track quite closely the methods applied most recently in Mann *et al.* (2008) to the same data, are unable to catch the sharp run up in temperatures recorded in the 1990s, even in-sample .... Consequently, the long flat handle of the hockey stick is best understood to be a feature of regression and less a reflection of our knowledge of the truth.

> The final point is particularly troublesome: ... the number of truly independent observations (i.e., the effective sample size) may be just too small for accurate reconstruction. Climate scientists have greatly underestimated the uncertainty of proxy-based reconstructions and hence have been overconfident in their models .... Proxy based models with approximately the same amount of reconstructive skill produce strikingly dissimilar historical back-casts: some of these look like hockey sticks but most do not. Natural climate variability is not well understood and is probably quite large. It is not clear that the proxies currently used to predict temperature are even predictive of it at the scale of several decades let alone over many centuries."

Thirteen independent groups or individuals wrote commentaries on the M&W paper. These commentaries demonstrated there is very little objectivity in paleoclimatology as evidenced by the facts that the establishment alarmist climatologists vigorously defended Mann *et al.*, statisticians made abstruse mathematical comments, and several climatologists exterior to the paleoclimatological cabal indicated support for M&W.

One aspect of this controversy is the use of principal component analysis (PCA). Before applying PCA one starts with a set of data from various proxies at various locations over various time periods. If one adds these up and apportions them equal weight, one obtains mainly mush—a smear of sparse data with no apparent direction or structure. Then, PCA is applied. While one might naively treat all proxies equally, PCA assigns weights to the various proxies on the basis that those proxies with the least tendency toward a trend are given low weight and those proxies with the greatest tendency toward a trend are given greater weight. As M&M and Wegman showed, MBH gave some proxies hundreds of times the weight of other proxies in the extreme case. The dataset was very sparse to begin with, and PCA further reduces the dimensionality of the dataset by placing a microscopic focus on those few proxies that demonstrate a strong trend, some of which were suspect tree ring proxies. How can a weak sparse dataset be improved by throwing out most of the data? Statisticians might respond by saying they have identified the proxies that generate the trend for the whole set but, considering the uncertainty and unreliability of all proxies, this seems like a very biased counter-productive approach. PCA gives climatologists and statisticians fodder to play with, but the whole process seems to add up to GIGO. In short, this writer thinks the use of PCA as a method in this application is highly suspect.

M&W's rebutted the various commentaries by the 13 authors on their paper in some length. M&W concluded by characterizing the assumptions made by the hockey stickers (linearity, stationarity, data quality, etc.) as "questionable, perhaps even indefensible". They also said: "we reiterate our conclusion that 'climate scientists have greatly underestimated the uncertainty of proxy-based reconstructions and hence have been overconfident in their models'." They closed with: "Finally, and perhaps most importantly, the NRC assumptions of linearity and stationarity outlined in our paper are likely untenable and we agree with Berliner in calling them into question."

### *11.1.4.2 The Medieval Warm Period and the Little Ice Age*

Evidence for the existence of the MWP and the LIA in the last 1,100 years has been observed in various datasets. For example, Figure 4.2 shows evidence of the existence of the MWP and the LIA in the GISP2 ice core record. Idso (2008) provides extensive evidence in favor of the existence of both.[11] Grove (1988) provides 1,000 pages of evidence of the existence of the LIA. Moreover, there were numerous temperature excursions comparable with or greater than current global warming prior to the MWP.

Thorsteinsson showed evidence for the MWP and LIA in the Camp Century ice core.

Dansgaard (2005) claimed that the MWP and the LIA "were recognizable" and "stand out clearly" in the Camp Century ice core. He also presented Figure 11.10. Dahl-Jensen *et al.* (1998) presented essentially the same data. The Woods Hole Oceanographic Institute website points out that both the LIA and MWP show up in ice core records. So does Wally Broecker in his book *The Glacial World*.

Shindell (2007) studied paleoclimatic data from a number of sources and concluded:

> "Historical data spanning the past millennium show substantial variations in aridity in the dry bands of the subtropics .... Palaeoclimatic records from a variety of sources and subtropical locations suggest that the MWP was generally marked by drier conditions, including prolonged droughts, which became less prevalent during the LIA. These records are supported by additional sediment and lake level records, including some showing wetter conditions near the equator, as well as fire residue and cultural records."

Keigwin (1996) estimated sea surface temperatures in the Sargasso Sea over the past few thousand years from isotope ratios of the remains of marine organisms in sediments at the bottom of the sea (see Figure 11.9).

Esper *et al.* (2002) started out by repeating the mantra of the global-warming alarmists:

> "... the MBH reconstruction indicates that the 20th century warming is abrupt and truly exceptional. It shows an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time. The magnitude of warmth indicated in the MBH reconstruction for the MWP, 1000–1300 is uniformly less than that for most of the 20th century."

Esper *et al.* (2002) used data manipulation in much the same way as MBH, but this led to a hockey stick that was somewhat different from that derived by

[11] Evidence in favor of the existence of the MWP and the LIA is collated at *http://co2science.org/data/mwp/mwpp.php*

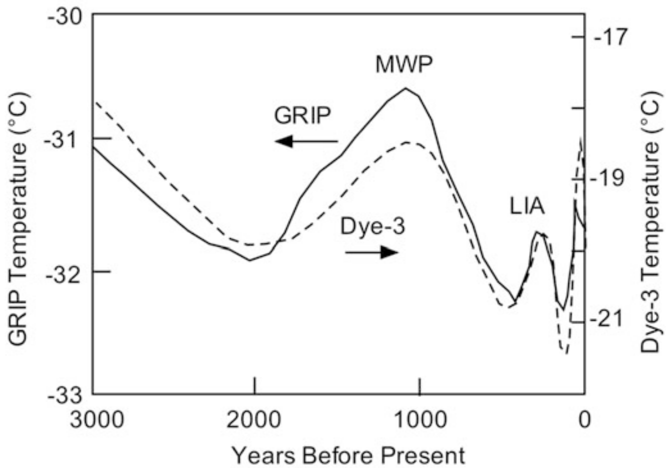


**Figure 11.10.** Ice core records showing the LIA and MWP.

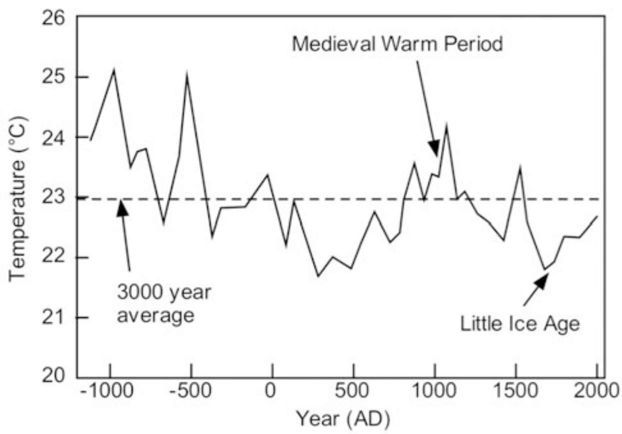


**Figure 11.11.** Sea surface temperatures in the Sargasso Sea (Keigwin, 1996).

MBH. While they intended to support MBH, the large differences between their results and those of MBH seem to lead to the opposite conclusion. This brings into doubt whether any reconstruction based on proxies is credible. McIntyre examined the data in Esper *et al.* (2002) in considerable detail and wrote at length on their analysis. The actual proxies examined by McIntyre are shown in Figure 11.12, which could be described as a spaghetti diagram. McIntyre took a simple average of all the proxies in Esper *et al.* (2002) and obtained Figure 11.13.

Richey *et al.* (2007) used Mg/Ca analyses of the white variety of the planktic foraminifera delta, which were obtained from the northern Gulf of Mexico as a measure of historical sea surface temperatures. The results are shown in Figure

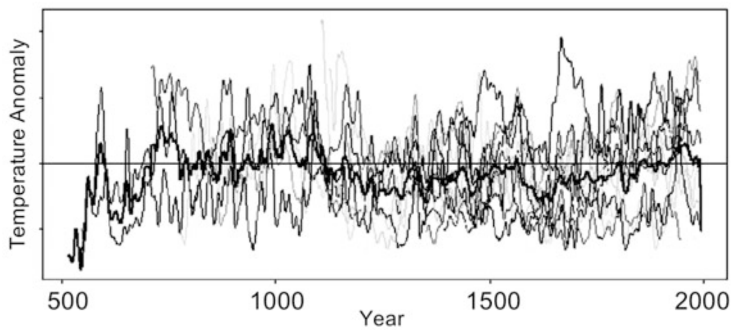


**Figure 11.12.** Individual proxies used by Esper *et al.* (2002).

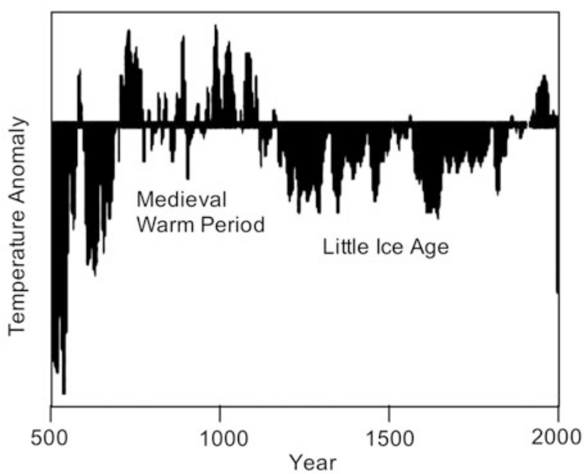


**Figure 11.13.** Simple average of proxy data from Esper *et al.* (2002) (adapted from McIntyre, 2007).

11.14. These results suggest MWP temperatures were warmer than current temperatures.

Mangini *et al.* (2005, 2007) measured stable isotope concentrations in Holocene stalagmites from central Germany which were dated very precisely with Th/U. They found strong evidence of the existence of a substantial MWP and of the existence of the LIA.

Frisia *et al.* (2005) measured stable isotope levels ($\delta^{18}O$ and $\delta^{13}C$) in a stalagmite in a cave in the European Alps. It is believed that this stalagmite started to grow about 16,600 YBP and has grown continuously right up to the present. Dating along the stalagmite was accomplished by U/Th techniques. From their $\delta^{18}O$ data, they found an LIA (~1500–1880), two MWPs separated by a colder period (~750–1300), and a Roman warm period (400–100 BCE).

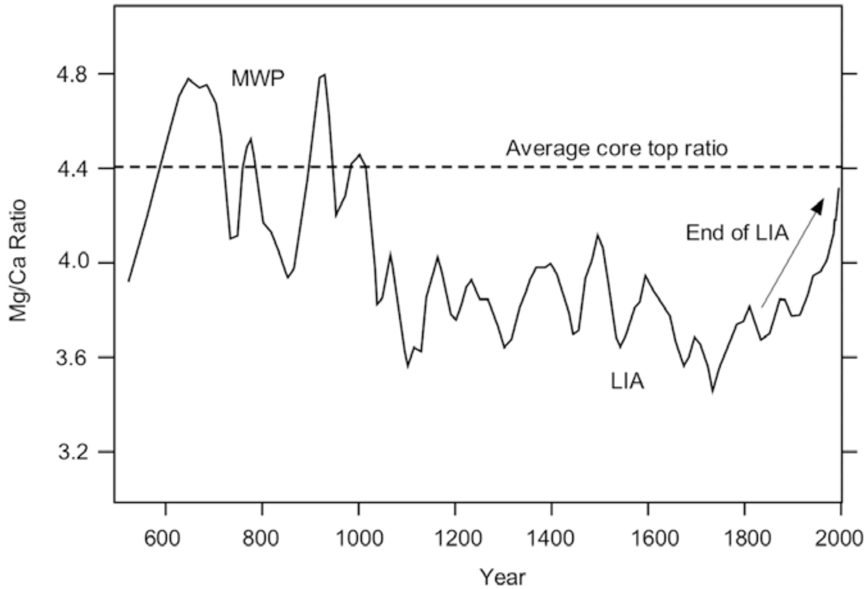


**Figure 11.14.** Mg/Ca analyses of the white variety of the planktic foraminifera delta, which were obtained from the northern Gulf of Mexico as a measure of sea surface temperatures (Richey *et al.*, 2007).

Rorvik *et al.* (2009) examined sediment cores from a Norwegian fiord to infer temperature changes over the past thousand years. They found that "The periods from c. AD 500 to 790 and c. AD 1500 to 1940, stand out as cold periods."

Kobashi *et al.* (2010) derived Greenland temperatures over the past thousand years using nitrogen and argon isotope data, rather than oxygen isotope data. Their procedure is complex and appears to involve a number of assumptions. Nevertheless, they addressed these issues in considerable detail. Their conclusion was: "The data show clear evidence of the Medieval Warm Period and Little Ice Age in agreement with documentary evidence."

The degree to which the current global warming trend is due to industrialization and land clearing remains to be determined but, clearly, the range of past climate variability is large enough that it is possible—at least in principle—that we are simply witnessing another natural fluctuation.

### *11.1.4.3 Retreat of mountain glaciers*

Holzhauser *et al.* (2005) discussed the advance and retreat of mountain glaciers as climate indicators. As they pointed out:

> "Glaciers in mountain areas are highly sensitive to climate changes and thus provide one of nature's clearest signals of warming or cooling and/or dry and wet

climate periods. Thus, in a simplified manner, one can say that the [periodic] fluctuations of Alpine glaciers were driven by glacier-hostile (warm/dry) and glacier-friendly (cool/wet) periods."

However, they emphasized: "a detailed examination of historical data suggests a rather more complex situation." They provided examples where "specific and varying temperature and precipitation courses during winter and summer" were responsible for glacier advance and retreat. In particular, they claimed: "the LIA between 1300 and 1850 coincided with wetter summers and colder winters, i.e., two factors favorable to glacier extension and higher lake levels." They also suggested the NAO index could well influence glacier advance and retreat, and indicated this may have initiated "the impressive loss of the alpine glaciers since the last glacial maximum c. 1850/60."

Evidence is also available from mountain glacier retreat records. The question here is whether mountain glacier retreat began before the buildup of $CO_2$ in the atmosphere or whether the retreat of glaciers conforms in time with $CO_2$ buildup. In the former case, it would appear that glacier retreat might be a natural phenomenon as the LIA waned. In the latter case, it may be due to global warming induced by greenhouse gases. Kotlyakov (1996) in his extensive survey of glaciers showed that the rate of mountain glacier retreat did not change substantially from 1900 to 1982. A number of other studies of mountain glacier retreat are summarized by Rapp (2008). The claim made by Al Gore in his film *An Inconvenient Truth* that the loss of glaciers on Mt. Kilimanjaro was due to global warming induced by greenhouse gases has been proven false by Mote and Kaser (2007). Mote and Kaser (2007) said:

"... warming fails spectacularly to explain the behavior of the glaciers and plateau ice on Africa's Kilimanjaro massif, just 3 degrees south of the equator, and to a lesser extent other tropical glaciers. The disappearing ice cap ..., which gets a starring role in *An Inconvenient Truth*, is not an appropriate poster child for global climate change. Rather, extensive field work on tropical glaciers ... reveals a more nuanced and interesting story."

Mote and Kaser went on to point out:

"Another important observation is that the air temperatures measured at the altitude of the glaciers and ice cap on Kilimanjaro are almost always substantially below freezing (rarely above $-3^\circ C$). Thus the air by itself cannot warm ice to melting by sensible-heat or infrared-heat flux ..."

The mass balance of ice cover on Kilimanjaro is primarily determined by precipitation vs. solar-induced sublimation. The reason that Kilimanjaro has been losing ice cover is that precipitation has decreased and sunlight increased; it has nothing to do with global warming. It may be possible that changing wind patterns resulting in lower precipitation and cloudiness might be related to global warming, but that is only speculation. As Mote and Kaser conclude:

> "If the Kibo ice cap is vanishing or growing, reshaping itself into something different as you read this, glaciology tells us that it's unlikely to be the first or the last time."

Hall and Fagre (2003) studied the glaciers at Glacier National Park in Montana. They pointed out:

> "Since its establishment in 1910, Glacier Park has lost most of its glaciers. Over two-thirds of the estimated 150 glaciers existing in 1850 had disappeared by 1980. Furthermore, over that same time period, the surviving glaciers were greatly reduced in area."

In the course of their description Hall and Fagre (2003) pointed out: "nearly all the ice masses in Glacier National Park had been undergoing rapid recession since the turn of the century" and that "many of the glaciers in the western United States that formed during the Little Ice Age began retreating about 1850 to 1855." They indicated that mountain glaciers in the park retreated at a modest rate from 1917 to 1926, retreated at a rapid rate from 1926 to 1942, retreated at a slower rate after 1942, stopped retreating from 1950 to 1975, and began retreating again after 1975. In particular, they showed that the Grinnell Glacier has retreated at a steady pace since 1890, and the Sperry Glacier retreated most between 1910 and 1930. Neither of these retreats can be attributed to greenhouse gases.

Dyurgerov and Meier (1999) estimated the historical retreat of a number of mountain glaciers during the 20th century. For most glaciers, the data were restricted to the period 1961–1997. However, eight glaciers were traced back to 1890. They concluded:

> "One can conclude that the present-day wastage of glacier volume is, on the average, part of a continuous process started in or before the 19th century, after the end of *Little Ice Age* maximum. Climate became warmer, and glaciers continued losing volume in response to this change. However, the rate of loss has been accelerating recently; this suggests that it is not just a simple adjustment to the end of an 'anomalous' *Little Ice Age*, as some have claimed."

Zemp *et al.* (2009) reported on six decades of annual mass balance data compiled by the World Glacier Monitoring Service:

> "In total, there have been 3,480 annual mass-balance measurements reported from 228 glaciers around the globe. However, the present dataset is strongly biased towards the Northern Hemisphere and Europe and there are only 30 'reference' glaciers that have uninterrupted series going back to 1976. The available data from the six decades indicate a strong ice loss as early as the

1940s and 1950s followed by a moderate mass loss until the end of the 1970s and a subsequent acceleration that has lasted until now.''

They also emphasized ''the shortcomings of the available dataset'' and ''the relatively small set of current long-term observations with a strong bias towards the Northern Hemisphere and Europe.''

Braithwaite (2009) echoed Zemp *et al.* in emphasizing the sparsity of the mountain glacier dataset. He also pointed out that the 30 glaciers that have 30 years of data ''are biased towards wetter conditions than are typical for global glacier cover.'' They went on to say: ''The mass-balance variations for these glaciers are therefore not representative of the global glacier cover'' and ''these 30 glaciers must be showing larger mass-balance changes than the global average.'' They concluded:

> ''Current estimates of the glacial contribution to sea-level rise ... may therefore be too large. There is already a discrepancy between observed sea-level rise and estimated contributions from the different sources, and the discrepancy will increase if the contribution from glaciers is really overestimated.''

Haberli and Hoelzle[12] reviewed data on several mountain glaciers. Of particular interest is the Aletsch Glacier in Switzerland. These authors present pictures of this great glacier taken in 1856 and 2001, showing the great retreat of the glacier. The 20th century history of Aletsch Glacier retreat shows that (i) the retreat began before the buildup of $CO_2$ concentrations and (ii) there have been alternating advances and retreats for two millennia. On the other hand, the retreat seems to have accelerated in the late 20th century as $CO_2$ built up.

*Nature Magazine* commented on glacier retreat in its June 10, 2010 issue. The issue's editorial was based on a recent Swiss study (Huss *et al.*, 2010)[13] that involved over 10,000 *in situ* observations of 30 Swiss mountain glaciers. The results suggest that Swiss glacier retreat was due to a combination of factors: (1) changes in precipitation patterns, (2) cyclic changes in North Atlantic sea surface temperatures (60-year cycle?), and (3) increased air temperatures. Since *Nature* is highly biased toward the extreme alarmist view, it is not surprising that the editorial ended with some dire predictions for the remainder of the 21st century. Huss *et al.* concluded ''Strong glacier retreat is very likely in the 21st century!'' Extrapolating forward from the 20th century, this seems to be a fairly safe prediction. The next several decades should provide a test of this prediction.

Holzhauser *et al.* (2005) reported on glacier and lake level variations over the last 3,500 years. Their results clearly show the MWP and the LIA. However, the retreat of glaciers in the most recent period appears to be sharper than previous retreats and reflects global warming in the 20th century. This may be linked to

[12] *http://www.zamg.ac.at/ALP-IMP/downloads/session_haeberli.pdf*
[13] M. Huss, G. Jouvet, and M. Funk, *C2SM Climate Change Scenario Workshop*, ETH Zurich, March 2, 2010.

rising $CO_2$. It is noteworthy that they claim a strong correlation between glacier advance and retreat with atmospheric residual $^{14}C$ which, according to some theories, is a measure of the activity of the Sun. Yet, this correlation appears to lie more in the eye of the beholder than in the data.

#### *11.1.4.4 Sea level rise*

IPCC (2012) is a 1,000-page report describing the putative impacts of global warming on humanity. While many of these impacts ranged from dubious to ridiculous, one potential impact stood out as a serious concern: sea level rise. Hansen (2004) said: "The dominant issue in global warming, in my opinion, is sea-level change and the question of how fast ice sheets can disintegrate."

However, the issues involved in ascertaining the effect of global warming on sea level rise illustrate the complexity and uncertainty involved in predicting the future. Kolker and Hameed (2007) said:

> "Determining the rate of global sea level rise (GSLR) during the past century is critical to understanding recent changes to the global climate system. However, this is complicated by non-tidal, short-term, local sea-level variability that is orders of magnitude greater than the trend."

Fjeldskaar (2008) echoed this viewpoint, saying that "relative sea level changes are not the same as eustatic changes" and "it is difficult to imagine where a eustatic change can be measured realistically."

Douglas and Peltier (2002) pointed out that the measurements of relative sea level (RSL) at any location have large annual and decadal fluctuations that tend to obfuscate long-term trends as a result of noise. Consequently, only very long-term records have the potential to accurately provide the underlying trend. A CNES analysis showed that the use of only four decades of data at tide gauge sites led to an overestimate of GSL rise. Other studies showed that the extreme dependence of trend on record length is real—not an artifact of the tide gauge.

Specific measurements of sea level rise have been made by means of tide gauges and satellite observations. Cazenave and Nerem (2004) found that sea level rise for the decade 1993–2003 was $2.8 \pm 0.4$ mm/yr, as determined from TOPEX/Poseidon and Jason altimeter measurements, rising to 3.1 mm/yr if the effects of post-glacial rebound are removed. This rate is significantly larger than the historical rate of sea level change measured by tide gauges.

Lombard *et al.* (2005) found large oscillations in decadal changes in sea level due to the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), and cautioned against extrapolating short-term sea level data from satellite measurements.

Sea level rise as measured by tide gauges provides a different picture. Holgate and Woodworth (2004) estimated sea level rise from 1952 to 1997 (45 years) based on 177 tide gauges from 13 regions with near-global coverage, and then used a glacial isostatic adjustment model to correct for land movements. Sea level rise over these 45 years was estimated to have averaged $1.7 \pm 0.2$ mm/yr, although the curve showed periodic oscillations. Furthermore, the curve of sea level vs. time seemed to be accelerating upward in the 1990s. In a more recent study, Holgate (2007) chose nine long and nearly continuous sea level records from around the world to explore rates of change in sea level for 1904–2003. The lack of high-quality long-life gauge records was circumvented by finding representative gauges that matched the data for 1952 to 1997 when more data were available. These records were found to capture the variability found at a larger number of stations over the last half-century which was studied in their 2004 paper. The addition of new data not only extended the time period back to 1904 but also the time period forward to 2003. The new results indicated that the apparent acceleration noted in the 1990s tailed off and now appears to have been just another oscillation, while the extended curve indicated that the rate of rise of sea level was slightly higher early in the century than it was later in the century. According to Holgate (2007):

> "Extending the sea level record back over the entire century suggests that the high variability in the rates of sea level change observed over the past 20 years were not particularly unusual. The rate of sea level change was found to be larger in the early part of last century ($2.03 \pm 0.35$ mm/yr 1904–1953), in comparison with the latter part ($1.45 \pm 0.34$ mm/yr 1954–2003). The highest decadal rate of rise occurred in the decade centered on 1980 (5.31 mm/yr) with the lowest rate of rise occurring in the decade centered on 1964 ($-1.49$ mm/yr). Over the entire century the mean rate of change was $1.74 \pm 0.16$ mm/yr" (see Figure 11.15).

Jevrejeva *et al.* (2008) found that sea level rise began well before large-scale $CO_2$ emissions (see Figure 11.16) This would suggest that the relationship between global warming and $CO_2$ emissions may be weak. According to this study, the pace of sea level rise has oscillated about an upward trend line during the 20th century even though a serious rise in sea level began near the beginning of the 19th century. The rate of sea level rise from 1992 to 2002 was the highest recorded. This might suggest a relationship to $CO_2$; however, the rate of sea level rise dropped from about 1955 to 1975.

According to Singer and Avery (2007) the initial rapid rise of sea level was about 200 cm per century when the great ice sheets began to melt at the end of the last period of glaciation. This gradually changed to a slower rate of rise (15–20 cm per century) about 7,500 years ago, once the large ice masses covering North America and North Europe had melted away. But the slow melting of the West Antarctic Ice Sheet continued and will continue, barring another ice age, until it has melted away perhaps 6,000 years from now. This means that the world will continue to endure a sea level rise of about 18 cm per century (1.8 mm per year), just as it has been in previous centuries. What is more, it is likely that there is nothing we can do about it. Thus, Singer and Avery (2007) attribute continuing slow sea level rise to natural consequences of the post-glacial period but make no allowance for anthropogenic global heating.

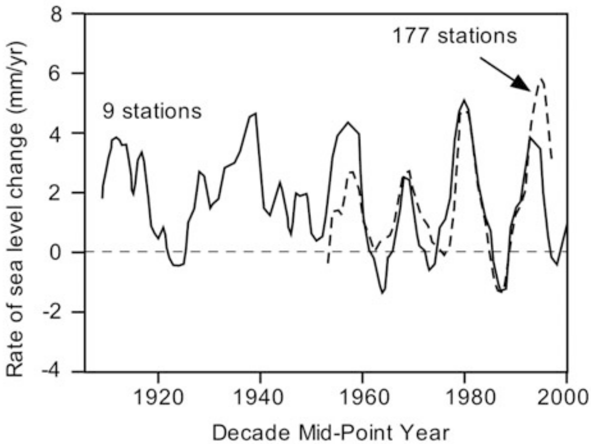


**Figure 11.15.** Decadal variation of sea level (Holgate, 2007).

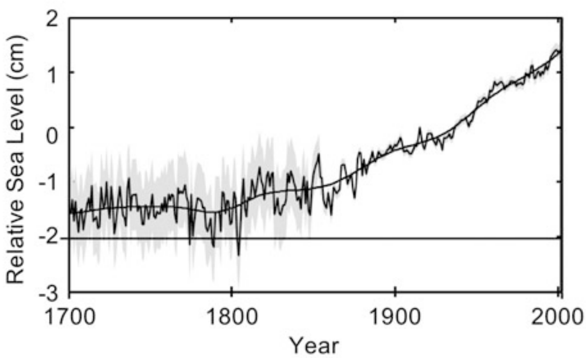


**Figure 11.16.** Yearly global sea level with 30-year windows. Gray shading represents standard errors (Jevrejeva *et al.* 2008).

Wunsch *et al.* (2007) estimated the regional patterns of global sea level change from a 1° horizontal resolution general circulation model based on about 100 million ocean observations and many more meteorological estimates between 1993 and 2004. Regional variability was found to be significant. They estimated a global mean of about 1.6 mm/yr, of which about 70% is from the addition of freshwater. They concluded, however: "Useful estimation of the global averages is extremely difficult given the realities of space–time sampling and model approximations. Systematic errors are likely to dominate most estimates of global average change: published values and error bars should be used very cautiously".

Wopplemann *et al.* (2008) claimed that tide gauge records at Brest, France were stable between 1889 and 2007. They found that the rate of sea level rise at Brest was constant over that period. This would suggest that rising $CO_2$ levels did not play a role in this case.

In a recent study, Rignot *et al*. (2011) reported that they had resolved the disparities between two approaches to estimating ice sheet mass balance in Greenland and Antarctica over the past eight years. The surface mass balance (SMB) method utilizes "the sum of snowfall minus surface ablation reconstructed from regional atmospheric models with perimeter loss calculated from a time series of glacier velocity and ice thickness to deduce the rate of mass change," whereas "the gravity method employs a monthly time series of time-variable gravity data from the Gravity Recovery and Climate Experiment (GRACE) to estimate the relative mass as a function of time." However, their procedures are not only very complex and detailed, they also appear to require many assumptions of uncertain veracity. From this, they estimated mass loss rates from the Greenland and Antarctica ice sheets over the past 18 years based on the SMB method. Over this period, the annual rate of mass loss has oscillated about a trend that accelerated at both sites. Annual loss in 2010 was about 250 Gt/yr of ice at each site, totaling about 500 Gt/yr for both sites. This corresponds to a rise in sea level of about 1.5 mm/yr, which seems a bit high when compared with independent estimates of sea level rise by direct measurement. Rignot *et al*. (2011) also noted that the annual rate of heat loss had accelerated over the 18-year period. They estimated that acceleration put the sum of both sites at about 36 $Gt/yr^2$. If this acceleration persists into the future, it would imply that total sea level rise would be 15 cm by 2050 and 56 cm by 2100. However, there is some alarmist chartsmanship in this conclusion. There are large oscillations in the data, and the mass gain in 1992–1993 skews the slope of the acceleration lines. Furthermore, the large positive loops in Antarctica since 2005 do not seem to be adequately considered. A strong case can be made for much flatter acceleration lines. In addition, the measurements of sea level suggest that there are long-term oscillations, and extrapolations of short-term data are not justified.

#### *11.1.4.5 Will global warming prevent or initiate the next ice age?*

The *First International Conference on Global Warming and the Next Ice Age*[14] took place in August 2001. More than 100 scientists from 13 countries attended. The conference seems to have reaffirmed the differences between alarmists and skeptics on the degrees and causes of climate change, with very few attendees (if any) changing their positions as a result of the discussions. "The predictions of the timing of the next ice age varied between 5,000 and 50,000 years. It was also suggested that due to the increased levels of carbon dioxide and other greenhouse gases, the next ice age might never come (a blessing for Canada)."

The *Second International Conference on Global Warming and the Next Ice Age*[15] was held in July 2006. Just like the first conference, most of the discussion focused on human contributions to recent climate change—not on ice ages:

[14] *http://www.mscs.dal.ca/HalifaxClimateConference/sumup.htm*
[15] *journals.ametsoc.org/doi/abs/10.1175/2008BAMS2359.1*

> "The 'Next Ice Age' conference theme often manifested itself in animated discussions based on widely varying interpretations of observational data, its meaning, and future implications. One interpretation is that a natural pattern of low orbital obliquity exists where the dark tropical oceans warm at the expense of the polar regions, thereby increasing meridional vapor transport and glaciations. Based on an interglacial period ~400,000 years ago, another interpretation estimated that the current interglacial period will persist for another 14,000 years in the absence of anthropogenic forcing."

In order to predict the onset of the next ice age, we need to know why and how ice ages begin and evolve. Since we only have incomplete inferences as to their causes, it is difficult (if not impossible) to predict whether and when the next ice age will begin. It would be difficult enough to predict the putative emergence of the next ice age were the Earth unperturbed by large-scale intervention by humans. But, with the great increase in $CO_2$ concentration in the past 100 years or so, and the possibility that this has contributed to the global warming we have recently observed, the problem is made even more complex in trying to understand the impact of putative human-induced global warming on the natural evolution of the climate.

As usual, there are many blogs on both sides of the question. There are blogs that purport to show that the climate is actually cooling in preparation for the next ice age. The cold fluctuation of 2007–2008 was a great boon to these enthusiasts.[16] There are also blogs that deny the next ice age will ever come.

Basically, there are three considerations regarding the next ice age. One is the natural turn of events which assumes that ice ages are driven by variations in the Earth's orbit. As we show below, the expectation of low eccentricity in the future suggests that, in the natural order of things, solar oscillations will have low amplitude implying that another ice age may be likely. A second consideration is that warming may interfere with thermohaline circulation leading to a new ice age as a consequence of the reduced delivery of heat to higher latitudes.[17] A third consideration is the longevity of excess $CO_2$ in the Earth's atmosphere and the role it may play in heating the Earth, thereby preventing future ice ages.

Berger and Loutre (2002) showed that the Earth's eccentricity, presently around 0.016, will decrease in the future, bottoming out ~25,000 years from now at around 0.004 and remaining at 0.015 or less over the next 100,000 years. As a consequence, the amplitude of oscillations in solar input to high latitudes will remain extremely low for the next 25,000 years and will remain moderately low over 100,000 years. These are historically low values; eccentricity has reached the range 0.04 to 0.05 in the past. As Berger and Loutre (2002) emphasized, "The small amplitude of future insolation variations is exceptional." They pointed out

[16] For example, *http://www.iceagenow.com/Record_Lows_2008.htm* and *http://www.citeulike.org/tag/ice-age*

[17] However, as pointed out earlier, Wunsch (2002) insists (correctly) "The upper layers of the ocean are clearly wind-driven."

that a similar trend for solar oscillations occurred around 400,000 years ago (see Figure 10.3) when there was an exceptionally long interglacial period. Hence, they suggested that we might expect a similarly long interglacial period in our future. However, Figure 10.3 shows that the period of low-amplitude solar oscillations began about 450 KYBP and continued to about 340 KYBP. During that period there occurred both a long interglacial and a major ice age (which began to develop around 395 KYBP). Thus, the period from about 450 KYBP and continuing to about 390 KYBP is supportive of the notion that the amplitude of solar oscillations at high latitudes is the controlling force in determining glacial–interglacial cycles, but the period from 390 to 340 KYBP provides a contrary trend.

Several significant papers by leading experts suggested that global warming could interrupt the thermohaline circulation of the Atlantic Ocean and lead to a variety of consequences, one of which might be premature evolution of the next ice age (e.g., Broecker, 1997b). Broecker (1999) mentioned that there were suggestions that the ongoing greenhouse buildup might induce a shutdown of the ocean's thermohaline circulation, raising questions as to how Earth's climate would change in response. Thornalley *et al.* (2011) found evidence that thermohaline circulation has played a role in climate change since the Last Glacial Maximum. Broecker argued that an extreme scenario is unlikely, because models suggest that Earth would have to undergo a 4 to 5°C greenhouse warming in order to force an ocean conveyor shutdown. Broecker also lamented the lack of an atmospheric model that would lead (from first principles) to the observed large and abrupt changes in the climatic state of Earth's atmosphere. Broecker summed up his doubts about climate models succinctly:

> "No one understands what is required to cool Greenland by 16°C and the tropics by $4 \pm 1$°C, to lower mountain snowlines by 900 m, to create an ice sheet covering much of North America, to reduce the atmosphere's $CO_2$ content by 30%, or to raise the dust rain in many parts of Earth by an order of magnitude. If these changes were not documented in the climate record, they would never enter the minds of the climate dynamics community. Models that purportedly simulate glacial climates do so only because key boundary conditions are prescribed (the size and elevation of the ice sheets, sea ice extent, sea surface temperatures, atmospheric $CO_2$ content, etc.)."

Rahmstorf (2004) said:

> "Threatening scenarios of a breakdown of the Atlantic thermohaline circulation, a collapse of northern European agriculture and fisheries, and of glaciers advancing on Scandinavia and Scotland have captured the popular imagination in recent years, with a number of newspaper reports, magazine articles and television documentaries covering this topic with a widely varying degree of accuracy. The risk of critical thresholds in the climate system being crossed where some irreversible qualitative change sets in (such as a major ocean

> circulation change) is taken increasingly seriously in the discussion on anthropogenic climate change.''

Rahmstorf (2004), relying principally on models, then went on to discuss some aspects of the effects of global warming on thermohaline circulation assuming that rising $CO_2$ induces global warming. He concluded that warming would have to be extreme (4–5°C) to cause such a shutdown.[18]

*The Day After Tomorrow* was a 2004 apocalyptic science fiction film that depicted the catastrophic effects of global warming leading into a new ice age via the shutdown of thermohaline circulation. The poster for the film shows New York City engulfed in a mountain of ice and snow (it is on sale at a number of websites). This film grossed over $500 million. Weaver and Hillare-Marcel (2004) stated this film was based to some extent on scientific studies that posed the possibility that global warming could lead to an ice age. A brief summary of the concept is that enhanced freshwater discharge into the North Atlantic from warming would shut down the AMO (the North Atlantic component of the overturning circulation of the global ocean). This would produce downstream cooling over higher northern latitudes, leading to onset of the next ice age. Alley[19] also referred to the film. He said:

> ''Are overwhelmingly abrupt climate changes likely to happen anytime soon, or did Fox Studios exaggerate wildly? The answer to both questions appears to be yes. Most climate experts agree that we need not fear a full-fledged ice age in the coming decades. But sudden, dramatic climate changes have struck many times in the past, and they could happen again. In fact, they are probably inevitable.''

However, Weaver and Hillaire-Marcel (2004) asserted that only during periods of extreme glaciation are there sources of freshwater at high latitudes that can provide the required flows to shut down thermohaline circulation. They concluded: ''... it is safe to say that global warming will not lead to the onset of a new Ice Age.''

Clark *et al*. (2002) pointed out that most GCM projections of the 21st century climate show a reduction in the strength of the overturning circulation of the Atlantic as a result of increasing concentrations of greenhouse gases, and ''if the warming is strong enough and sustained long enough, a complete collapse cannot be excluded.'' They concluded:

> ''... although the possibility of a reduced Atlantic thermohaline circulation

[18] However, as pointed out earlier, C. Wunsch (pers. commun., December 2008) insists (correctly) ''The sinking of high latitude water does not sustain the Gulf Stream. The Stream is a wind-driven feature and a result of the torque exerted on the ocean by the wind. It would exist even in a constant density fluid with zero convection.''

[19] *Abrupt Climate Change*, see *http://www.chicagocleanpower.org/alley.pdf*

in response to increases in greenhouse-gas concentrations has been demonstrated in a number of simulations, ... it remains difficult to assess the likelihood of future changes in the thermohaline circulation, mainly owing to poorly constrained model parameterizations and uncertainties in the response of the climate system to greenhouse warming."

Archer (2005) used a climate model to study the long-term fate of $CO_2$ in the atmosphere amounting to anywhere from 300 to 5,000 Gt of carbon as a result of emissions over the next 150 years. In each case, $CO_2$ concentration spikes after 150 years with a peak concentration ranging as high as 1,700 ppm for 5,000 Gt of emissions and 800 ppm for the (more likely) 2,000 Gt emissions of carbon. As the ocean absorbs ever more $CO_2$ from the atmosphere, it becomes more acid and so dissolves more calcium carbonate from the shells of marine organisms. This in turn reduces the oceans' ability to absorb more $CO_2$, leaving more greenhouse gas in the atmosphere. At first, the $CO_2$ concentration rapidly declines from the peak (dropping to less than half the peak value in about a century or two), but then it declines slowly over several tens of thousands of years, returning ultimately to pre-industrial levels. Archer made the point that this slow decline would result in elevated $CO_2$ levels (albeit well below the peak) for a very long time. Tyrrell *et al.* (2007) carried out a similar study.

Whether such enhanced levels of $CO_2$ influence the probability of occurrence of the next ice age remains uncertain.

Crowley and Hyde (2008) hypothesized that the Earth's climate has been transitioning from non-glacial to glacial over the past ~50 million years. Notably, the transition to longer period higher amplitude fluctuations about a million years ago was viewed as a "climate bifurcation point" leading to a transition period over the past million years to a second climate bifurcation point that will lead the Earth into permanent deep glaciation in the next 20,000 years or so. They employed a coupled energy balance/ice sheet model to support this interpretation. This paper was criticized by a number of notable and prominent climatologists.[20] Some of the critics argued that such untestable predictions based on simplistic models are not science. Crowley responded: "this is science—you might not like it, but it is science." However, in Section 11.2.1 we emphasize that the scientific method requires (1) that hypotheses can be proven wrong (if they are wrong), (2) that they are based on objective tests, and (3) that the results must be repeatable. The Crowley and Hyde (2008) model (like most climate models) fails this test.

Another factor that may affect climate is the activity of the Sun. As we pointed out in Section 8.7.2, there is some evidence to suggest that when the Sun is inactive (e.g., as evidenced by a lower-than-normal incidence of sunspots) cosmic ray flux into the atmosphere will increase, leading to greater cloud formation and potential climate cooling. The transition from sunspot cycle 23 to sunspot

[20] "More on whether a big chill is nigh," *http://dotearth.blogs.nytimes.com/2008/11/13/more-on-whether-a-big-chill-is-nigh/*

cycle 24 was characterized by a long period of very low sunspot count, suggesting that the cosmic ray mechanism may produce some cooling if sunspot cycle 24 has a relatively low sunspot count. Climate models do not take this into account.

## 11.2 WAYS OF IMPROVING OUR UNDERSTANDING

### 11.2.1 The need to depoliticize climate change

The topic of ice ages is associated with the allied topic of climate change which is currently dominated by interest in global warming and its putative relationship to increased $CO_2$ in the atmosphere due to industrialization and land use. While looking backward to better understand historical climate variations such as ice ages is of academic interest, looking forward to predict future climate change as a function of future carbon emissions by human activity is of great economic and political interest.

Humanity has become addicted to fossil fuels and, with growing world population and the industrialization of many developing countries, the demand for fossil fuels will continue to increase in the 21st century in the business-as-usual scenario. This, in turn, will produce continually increasing carbon emissions and rising atmospheric $CO_2$ concentrations. As oil production tops out, there will likely be more dependence on coal, which produces more $CO_2$ than hydrocarbons per unit energy generated. The majority of climatologists are convinced that rising $CO_2$ concentrations in the atmosphere are primarily responsible for global warming over the past $\sim$100 years, and many of them believe that continuation of the business-as-usual policy for generating energy in the 21st century will produce catastrophic global warming with severe economic and environmental consequences. These climatologists have a controlling influence on environmental issues in professional societies, research laboratories, advisory bodies (such as national academies), government departments and agencies (including NASA, NOAA, EPA, NSF, etc.), universities, and the U. N. As a result, government agencies at state, federal, and international levels are actively planning legislation to cut back severely on carbon emissions in the remainder of the 21st century. In October 2007, Chairman Dingell's Energy and Commerce Committee of the U. S. Congress proposed: "The United States should reduce its greenhouse gas emissions by between 60 and 80 percent by AD 2050."[21] President Obama proposed an 80% reduction in emissions.[22] As part of his plan, he would increase the use of coal and use a cap-and-trade system for emissions. The cap-and-trade system would allow those who can afford it to continue to emit. Thus, the percentage reduction for those not buying the right to emit would be even higher than 80%. Obama plans the use of "clean coal". But, coal pollutes in the mines, in the runoff from the mines, in the desecration left behind, in the railroads that transport the coal, in

[21] *http://energycommerce.house.gov/Climate_Change/White_Paper.100307.pdf*

[22] *Los Angeles Times*, November 19, 2008.

the power plants that burn the coal, in the emissions from the power plants, and in the ash left over. Coal produces a lot more $CO_2$ per unit energy produced than petroleum or natural gas. In the process of cleaning up coal for combustion, a considerable amount of $CO_2$ is emitted. The economic impact of such policies will be measured in many trillions of dollars, and the technical and economic challenges in implementing such policies have generally been underestimated (Pielke *et al.*, 2008). Thus, if one accepts the alarmist view that continued use of fossil fuels will produce unacceptable global warming, humanity is caught between the proverbial rock and a hard place. According to this belief, we cannot accept the consequences of continuing business as usual; however, we have neither the technical nor economic capability to do otherwise without creating great financial and operational dislocations. But how solid is the alarmist view? As we have shown, the alarmist view rests on shaky foundations. As Lindzen (2008) has so eloquently pointed out, the science of climatology has been thoroughly politicized, and scientific skepticism has taken a backseat to adherence to belief systems. Alarmists have so infiltrated funding agencies that expressing contrary views is not conducive to career progress in climatology. There are some published papers in journals that found results not necessarily supportive of orthodoxy; nevertheless, the authors usually cannot resist a gratuitous remark to the effect that "this result does not mean we shouldn't be concerned about $CO_2$-induced global warming." The paleoclimatic cabal has managed to prevent contrary views from being published and they have perpetrated erroneous scientific conclusions (e.g., the hockey stick) as facts.

There is also a widespread belief system regarding the cause of ice ages which, though not necessarily political, nevertheless represents adherence to orthodoxy. It is widely believed that the astronomical theory explains the occurrence of ice ages and, indeed, one can find literally hundreds (maybe thousands) of books, websites, and other references that express this view as if it were proven fact. As we have shown in this book, there are aspects of the astronomical theory that are suggestive of ice age cycles but the astronomical theory falls short in some respects.

As discussed in Chapter 10, the world of science seems to have lost its foundation of skepticism and very few of the recent crop of climatologists appear to come from Missouri.[23] Instead of doubt and dialectic opposition, science has adopted orthodoxy and consensus. Three examples where this is particularly widespread are: (1) the belief that global warming over the past 100 years was primarily due to increased $CO_2$, (2) the belief that the astronomical theory explains the occurrence of ice ages, and (3) the belief that life evolves easily and repeatedly on planetary bodies with liquid water. There are undoubtedly others. Scientists, like the public at large, seem unable to shrug their shoulders and simply admit that we just don't know the answers. The fierce competition for funding in an environment dominated by orthodoxy pressures scientists to bias

[23] For example, *http://www.trivia-library.com/b/origins-of-sayings-im-from-missouri-youve-got-to-show-me.htm*

their viewpoints. We note a significant rise in the number of news releases and papers by scientists with phrases such as "there might be ..." or "it is possible that ...." What science cannot seem to do these days is accept that:

> "Sometimes there is no alternative to uncertainty except to await the arrival of more and better data" (Wunsch, 1999).

It seems likely that scientific (or economic) progress in climatology will be impeded by the fact that data and models are routinely biased to adhere to a belief system. The IPCC has led the way with a plethora of conclusions and predictions regarding the role of $CO_2$ emissions on the Earth's climate and the potential impact on humanity. These represent mainly political conclusions—not scientific ones. The majority of recognized climatologists have aligned like weather vanes to the prevailing wind, making it all but impossible to get contrary views published in journals. As a result, there has arisen a blogopolis in which contrary views are available on websites but not in the literature. While many of these blogs are populated by moronic entries, a few are full of detailed analysis and data. One example of an excellent study in the blogs is the 830-page detailed rebuttal of the IPCC position written by Idso (2008). The most important thing to do now is to depoliticize climatology, in general, and paleoclimatology, in particular. However, with the entrenched power structure in these fields, it is not clear how to accomplish this. We may be in the position of the proverbial mice desiring to put a bell around the cat's neck.

As we have seen, repeated climate variations in the past have been severe and, in some cases, rapid. Wild gyrations of the Earth's climate occurred long before large-scale activity by humans. There is some reason to believe that over the past million years the natural state of the Earth has been the repeated buildup of ice ages interspersed by relatively brief interglacial periods. While $CO_2$ concentrations varied from glacial to interglacial periods, the variability of $CO_2$ was not the cause of climate change in these cycles, although it undoubtedly contributed a secondary amplification. Superimposed on this long-term variability, there have been many sudden and intense short-term fluctuations ("flickering") of the Earth's climate. These could not possibly be tied to variability of the Earth's orbit which varies much too slowly. Lacking an adequate understanding of what phenomena produced past climate changes, we are in a weak position to predict future climate change.

### 11.2.2 Technical progress

***Additional ice cores and sediment cores*** Except for the WAIS Divide project (see next paragraph) there does not appear to be a great deal to be gained from boring additional ice and sediment cores at this point, although more data may be helpful to some degree.

***North–south synchrony*** One important issue that requires further study is the relationship between climate change in Greenland and climate change in Antarctica, or, more generally, climate change in the NH vs. climate change in the SH. The main problem in comparing climate data in the NH and the SH is achieving precise absolute chronologies. Because layers can be counted at Greenland, the chronology is much more precise and highly resolved, at least over the past 40,000 to 50,000 years. By contrast, the Antarctic chronology has less precision and resolution. In this connection, the West Antarctica Ice Sheet Divide (WAIS Divide) project will bore a deep ice core from the flow divide in central West Antarctica in order to provide Antarctic records of environmental change with the highest possible time resolution for the last ~100,000 years and will be the Southern Hemisphere equivalent of the Greenland GISP2, GRIP, and North GRIP ice cores. The most significant and unique characteristic of the WAIS Divide project will be the development of climate records with an absolute annual-layer-counted chronology for the most recent ~40,000 years. It is hoped thereby to determine (a) the role played by greenhouse gases in ice ages and (b) whether the initiation of climate changes occurs preferentially in the south or the north. Drilling was completed in 2011 and analysis is under way. Thus, it is of great importance that the WAIS project be pursued and completed as planned.

Stott *et al.* (2007) and Timmermann *et al.* (2009) found experimental and theoretical evidence that ice age terminations may originate near Antarctica—and not in the NH. This line of research may provide further advances in our understanding of the roles of the north and south in glacial–interglacial cycles.

***Role of oceans*** The role of the oceans in climate change and glacial–interglacial cycles has been discussed by a number of authors, particularly regarding abrupt climate change (see Section 8.6). However, much of this is based on modeling and conjecture. We need to collect more data on the past variability of ocean currents and temperatures. Extension of studies such as that of Piotrowski *et al.* (2004) to determine past ocean circulation will be very helpful.

Clark *et al.* (2002) concluded: "Although understanding the mechanisms behind abrupt climate transitions in the past is interesting in its own right, there is a pressing need to gain insight into the likelihood of their future occurrence." They suggested that "progress towards a mechanistic understanding of abrupt climate change ... can be expected from coupled models with higher resolution, that no longer require flux adjustments, and that include biogeochemical cycles."

Experiments such as the World Ocean Circulation Experiment can provide important information on heat transport by the oceans (Ganachaud and Wunsch, 2002). Schmidt *et al.* (2004) analyzed two Caribbean Sea sediment cores to reconstruct tropical Atlantic surface salinity during the last glacial cycle. They found that Caribbean salinity oscillated between saltier conditions during cold periods and lower salinities during warm periods, varying in consonance with the strength of North Atlantic Deep Water formation. Thornalley *et al.* (2011) found evidence that thermohaline circulation has played a role in climate change since the Last Glacial Maximum.

***Direct measurement of climate sensitivity*** One of the critically important unknowns in climatology is the current sensitivity of the climate to increasing $CO_2$ concentration. Lindzen (1997) suggested several possible approaches for direct measurement of climate sensitivity; however (as he admitted), none of them are straightforward.

According to Lindzen: "a very important consideration ought to be how dry and how large the areal coverage is of the very dry subsiding regions." Getting satellites to measure humidity over dry regions over a period of years during which $CO_2$ is increasing would provide the necessary relevant data.

Lindzen (1997) suggested "a proper observational determination of the sensitivity to global forcing." In this approach, one would attempt to measure the monthly average top-of-atmosphere (TOA) flux integrated over the whole Earth for several years along with surface temperature over the same period. One could then correlate TOA flux with temperature. A caveat raised by Lindzen is that OLR may change in response to changes in circulation without accompanying changes in mean temperature. This could make interpretation of the data confusing.

An indirect approach might be based on observations of the Earth's response following a major volcanic eruption. However, past attempts to do this had very large error bars.

***Cosmic rays as the forcing function for ice age–interglacial cycles*** Kirkby *et al.* (2004) proposed "a new model for the glacial cycles in which the forcing mechanism is due to galactic cosmic rays, probably through their effect on clouds" and suggested that "the model makes definite predictions that can be tested by further observations and experiments." They suggested the following program:

> "The first area to be tested concerns the paleo record of GCR flux, its orbital components and association with climate change. Further $^{10}$Be measurements in sediment cores are required, over longer time spans and with improved precision and dating. Parallel improvements are required for paleomagnetic intensity and direction in order to study the orbital components and to separate solar and geomagnetic effects in the $^{10}$Be record. Orbital influences on the geomagnetic field should be modeled. Further satellite data on GCR/solar wind characteristics in the heliosphere are required, both in and out of the ecliptic, and during different periods of solar magnetic activity. GCR transport in the heliosphere for a magnetically quiet Sun (e.g. Maunder Minimum) should be modeled to estimate the expected magnitude of orbital variations of the GCR flux.
>
> The second area to be tested concerns the interactions of GCRs with Earth's clouds and climate. Improved and extended satellite observations of clouds are needed. Investigations are required on the effects of GCRs on clouds and thunderstorms, including ion-induced cloud condensation nuclei production, electro-freezing of super-cooled liquid droplets and atmospheric electrical processes. The microphysics of GCR–cloud–climate interactions should be investigated in laboratory experiments under controlled conditions, and the results applied to models and field observations. Combined interdisciplinary efforts in these directions may quite quickly be able to establish whether or not the GCR model for the glacial cycles is further supported, and where more work is needed to quantify its physical basis."

***Orbiting Carbon Observatory*** The Orbiting Carbon Observatory (OCO) is a new Earth-orbiting mission. The OCO mission was designed to collect precise global measurements of carbon dioxide ($CO_2$) in the Earth's atmosphere which, it is hoped, will improve our understanding of the natural processes and human activities that regulate the abundance and distribution of this important greenhouse gas. This improved understanding will hopefully enable more reliable forecasts of future changes in the abundance and distribution of $CO_2$ in the atmosphere and the effect that these changes may have on the Earth's climate. Unfortunately, the launch vehicle for the OCO failed and the observatory fell into the ocean. This was followed by a similar failure in the launch of the Glory satellite which was supposed to monitor aerosols and the Sun. The Delta II launch vehicle has a long history of success, but it was retired in favor of the Orbital Sciences launch vehicle, which has now failed twice in a row.

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