ICE AGES AND INTERGLACIALS

Measurements, Interpretation and Models

Donald Rapp

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Preface

The typical description of the past million years would be that the Earth has experienced about ten 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 ten interruptions during which the climate resembled something like today's 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 in thickness. 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 treeline down by up to 700 m to 800 m. The temperature of Greenland was lower by up to 20°C, but the climate was only a few degrees colder than normal in the tropics.

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 the continents moved outward by a considerable distance. 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 latitudes to mid-latitudes, climates were semi-Arctic and the flora shifted to tundra. Humidity was reduced and many lands 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 with dust. This ice age began to wane around 15,000 years ago, and dissipated through a series of gyrating climate oscillations, ending in a comparatively benign period that has lasted for the past ~10,000 years, called the *Holocene*.

A few geologists of the 19th century were perceptive enough to read the signs in the rocks and formations, and concluded that the Earth must have once (or more) 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 wasn't 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 semi-periodic variability in the Earth's orbital parameters, which change relative solar energy input to higher latitudes. As the theory goes, when solar energy input to higher northern latitudes drops below a critical threshold range, ice and snow can survive the summer, and thus a runaway expansion of ice sheets develops over many millennia. James Croll formulated this concept in 1875. In the first several decades of the 20th century, Milutin Milankovitch quantified this theory by carrying out extensive calculations by hand in the pre-computer age. Nevertheless, in the absence of long-term data over many ice ages, astronomical theory remained an abstract concept. Furthermore, there were no credible mechanistic models that described how changing solar energy inputs to higher latitudes led to alternating ice ages and deglaciations.

With the advent of marine sediment data in the 1970s, it became possible to compare astronomical theory with data over many glacial cycles. John Imbrie was a pioneer in this regard. He created the SPECMAP "stack" of ocean sediment data from several sites to reduce noise, and devised models with which to compare climatic time series with solar variations. In doing this, he "tuned" the chronology of the SPECMAP using solar variability as a guide. He also used spectral analysis to show that some of the prominent frequency components of 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 ~650,000 years. However, there seems to be some circular reasoning involved, and one could construe his procedure to involve curve fitting as well as physics. More importantly, when a dispassionate comparison of data and theory is made today, the results are not so convincing.

As ocean sediment data were extended backward in time, it became apparent that some features of the sediment record did not fit astronomical predictions. Of greatest importance 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 about ~1 MYBP, climate cycles have increased in period and amplitude. By contrast, astronomical theory would not have predicted any such major shift in frequency and amplitude since there is no reason to believe that solar forcing to higher latitudes changed qualitatively during this time period. There were other problems with the theory as well; at some prominent 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 astronomical theory. A number 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 several parameters (obliquity, eccentricity, longitude of precession) acts separately over different eras to produce a changing data record. While there may indeed be strange and unusual non-linear effects in the way that climate reacts to orbital parameters (e.g., Rial, 1999) nevertheless within the scope of conventional astronomical theory, 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 astronomical theory.

Yet despite the problems with 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.

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 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, the eras with higher amplitude solar oscillations appear to be associated with increasing Earth temperatures, and the eras 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 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 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. The Imbries' model for comparing ocean sediment time series with 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 add confusion. There is some evidence that the termination of ice ages originates in the southern hemisphere, not the northern hemisphere. In addition, there are alternative theories that propose that ice age cycles are controlled by the penetration of cosmic rays into the Earth's atmosphere, which enhance cloud formation and produce a cooling effect.

Amid 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 book *The Great Ice Age* does a creditable job in some respects (Wilson, 2000). The closest that anyone has come to a thorough review is the book by Richard A. Muller and Gordon J. MacDonald: *Ice Ages and Astronomical Causes*, Springer/Praxis (2000). This book (denoted here as M&M) provides coverage of a good portion of the data that were available at the time of writing (late 1990s), and it provides quite a bit of discussion of models. The topic of spectral analysis was a dominant theme in this book, almost to the neglect of other aspects. It is 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. Nevertheless, ultimately, it is the time phasing of the two curves that is of greatest importance in establishing a cause–effect relationship. I have relied on the book by 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 in the future. This topic is discussed toward the end of this book. Some climatologists believe that global warming induced by CO_2 emissions will prevent future ice ages from occurring. However, the connection between CO_2 emissions and global warming is far from firm. Because the CO_2-warming connection has been heavily politicized, much of the literature on this topic is biased.

Throughout this entire study of ice ages and climatology, climatologists seem determined to draw a dollar's worth of conclusions from a penny's worth of 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."

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I would like to thank Clive Horwood and John Mason of Praxis Publishing for encouraging me to write this book. Their support was important to me throughout and I hope that I have produced a product worthy of this fine publishing house. I also want to thank Neil Shuttlewood of Originator Publishing Services for his usual exemplary job in setting this book into type.

Figures

Tables

Abbreviations and acronyms

ACP	Age Control Point
AM	Amplitude Modulated
AMO	Atlantic Meridional Overturning
AWS	Automated Weather Station
CAS	Central American Seaway
CLIMAP	Climate: Long Range Investigation, Mapping and Prediction
D–O	Dansgaard–Oeschger event
DEW	Distant Early Warning
EAIS	East Antarctic Ice Sheet
ECM	Electro-Conductivity Measurement
EEM	Eemian
ENSO	El Niño–Southern Oscillation
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
GISP	Greenland Ice Sheet Project
GRIP	Greenland Ice Core Project
GYBP	Billions of Years Before Present
H&W	Huybers and Wunsch (2004)
IPCC	Inter-government Panel on Climate Change
IRD	Ice Rafted Debris
ISI	Information Sciences Institute
KYBP	Thousands of Years Before Present
L&R	Lisiecki and Raymo
L&W	Landwehr and Winograd (2001)

L&W	Landwehr and Winograd (2001)
LGM	Last Glacial Maximum
LIA	Little Ice Age
LLS	Laser Light Scattering
M&M	The book by Richard A. Muller and Gordon J. MacDonald: *Ice Ages and Astronomical Causes*, Springer/Praxis (2000)
MOC	Meridional Overturning Circulation
MPR	Mid-Pleistocene Revolution
MWP	Medieval Warm Period
MYBP	Millions of Years Before Present
NADW	North Atlantic Deep Water
NGRIP	North Greenland Ice Core Project
NH	Northern Hemisphere
NHG	Northern Hemisphere Glaciation
OCO	Orbiting Carbon Observatory
OLR	Outgoing Long-wavelength Radiation
PAL	Present Atmospheric Level
PDB	Crushed belemnite (*Belemnitella americana*) from the Peedee formation (Cretaceous) in South Carolina
SETI	Search for Extraterrestrial Intelligence
SH	Southern Hemisphere
SMOW	Standard Mean Ocean Water
SOI	Southern Oscillation Index
SPECMAP	Spectral Mapping
SST	Sea Surface Temperature
TIMS	Thermal Ionization Mass-Spectrometric
TOA	Top-Of-Atmosphere
TSI	Total Solar Irradiance
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 Antarctic 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 were 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. Many 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, data from ice cores, and data from ocean sediments, we know that the Earth was immersed in an ice age over the past $\sim$100,000 years that peaked about 20,000 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 ago) was about 57×10^6 km^3. This huge volume of ice resulted in a lowering of sea level of about 110 m (Zweck and Huybrechts, 2005). Assuming that this ice sheet was built up over $\sim$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 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. Assuming that the temperature drop at high latitudes was far greater than the temperature drop in the tropics during ice ages, 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.

Barton *et al.* (2002) provide a window into the 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 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

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

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

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).

well-draining soil. The result was a land of grassy steppes. An array of tiny plants 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

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).

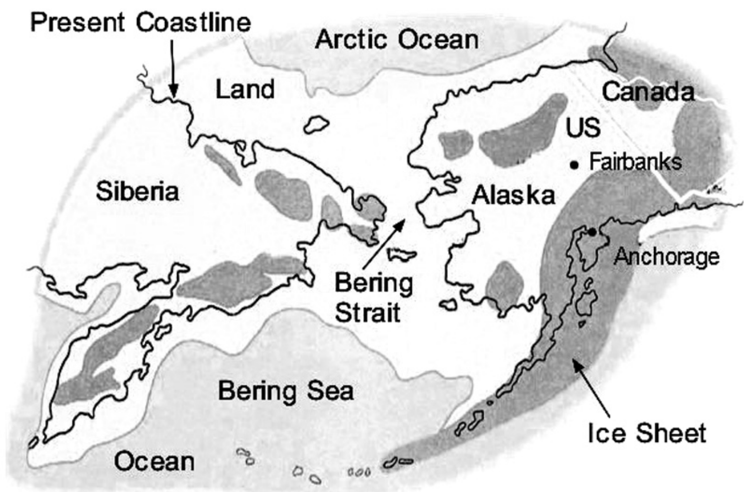

Figure 1.4. Beringia, the connecting link between Siberia and Alaska about 18,000 YBP (Barton *et al.*, 2002; reprinted by permission of Random House).

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 mammoth, horses, bison, and other mammals. Zazula *et al.* (2003) reported the discovery of macrofossils of prairie sage, bunchgrasses, 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 system, called ''mammoth steppe,'' would 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 the 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 subtle.

Paul 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. His 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, many 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 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 others 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.

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 an extinction of species about 12,900 years ago.

1.2 THE GLACIAL WORLD—ACCORDING TO WALLY

Wally Broecker (WB), a giant in the field of paleoclimatology, wrote a treatise on ice age climates.

According to WB:

> ''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.''

WB 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 ended.

WB 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 the 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 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. WB described the use of the past levels of lakes with closed drainage basins such as 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. WB discusses several complications but concludes: "despite these complications, the size of closed basin lakes is by far our best paleoprecipitation proxy." Finally, WB 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 treeline in the western United States descended by up to 700 m to 800 m. 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, long-legged and short-legged llamas, a giant condor-like vulture with a 15 ft to 17 ft wingspan, dire wolves, 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).

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 is 5.1×10^8 km^2, the rate at which energy is released from the interior of the Earth is 3.1×10^{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 1.7×10^{14} kW. Actually, only about 70% of 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 when 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 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

- 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 rate at which solar energy impinges on the Earth is 342 W/m^2 averaged over the whole Earth. Some fraction of this (called the albedo) is reflected back into space. The albedo depends on the state of the Earth. Ice and snow have high albedos (0.5 to 0.9) while land (0.3) and oceans (0.1) have lower albedos. Averaged over the whole Earth, the present albedo is a little over 0.3, so the net solar input to Earth, independent of the greenhouse effect is about $0.7 \times 342 \sim 239\ W/m^2$. 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 has passed through such a snowball state in its distant past.

The presence of greenhouse gases in the atmosphere acts as a barrier to the 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.

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) the 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. However, water vapor and methane are not as saturated, and increases in these concentrations produce significant heating. But 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, 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). CO_2 is also removed by the 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 the 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.

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. 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 (n.d.) 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 oceans average 3.7 kilometers deep. Most of the world's water is there too, of course, as are 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 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.

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.

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 the evolution of the Sun from its early beginnings indicate that solar luminosity has risen steadily over the past $\sim$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 billion years ago and global glaciation would have been the likely result.

The earliest rock records from western Greenland, dated approximately 3.8 billion years ago, provide a record of the waterborne processes of erosion, transport, and sedimentation. Liquid water must have existed at least locally. The earliest record of glaciation is 2.7 billion years ago. The temperature sensitivities of the diversity of life since 3.8 billion years ago 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 billion years ago. 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 billion years ago. 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).

If the Earth ever enters a warm state where the polar ice melts completely and the glaciers are all gone, it can remain in that state for a long period because (a) 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 the 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 melts completely 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 Myr 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 million years ago 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 in that era.

Around the same time that Harland publicized his theory, Mikhail Budyko 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, 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 30° south, the positive feedback became overwhelming, and once having passed through 30° the freeze becomes irreversible, yielding an entirely frozen Earth.

At first, Budyko's simulation was surrounded with controversy, because it was believed that such a catastrophe would extinguish all life, and also that once the Earth entered the frozen state, it would remain permanently in that state. However, it was later shown that some organisms could survive such an extreme climate. In addition, Kirschvink (1992) pointed out that during a global glaciation, shifting tectonic plates would continue to build volcanoes and supply the atmosphere with carbon dioxide. If the Earth were completely frozen over, the processes that remove carbon dioxide from the atmosphere would essentially cease, allowing carbon dioxide to build up in the atmosphere to extremely high levels, thus reversing the snowball Earth. Once melting begins, the ice–albedo feedback would be reversed and this, combined with the extreme greenhouse atmosphere, would drive surface temperatures 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. Calculations cited by Hoffman and Schrag 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.

As Hoffman and Schrag (2002) 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 million years ago.

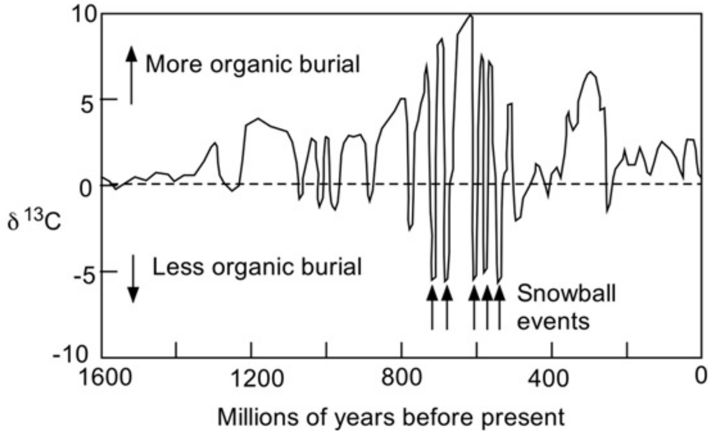

Figure 2.1. Variation in carbon isotope composition of shallow marine carbonates. $\delta^{13}C$ is measured in ‰ or parts per 1,000 (M. Purdy, 2003).

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. Lubick (2002) provides a good summary of arguments pro and con.

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 ~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 bar to 20 bar of CO_2, the oceans would have been even more stable at 85°C to 110°C with a vapor pressure of 0.6 bar 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 CONTINENTAL DRIFT AND CONTINENTAL GEOMETRY AS A FACTOR IN PALEOCLIMATE CHANGE

2.3.1 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. 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 areas, but clouds add significantly to 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, 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 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 Myr ago, and may have contributed to formation of a snowball Earth. This situation that 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 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 Myr to 200 Myr ago and made rough estimates of land distribution among deserts and forest, 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 factor in determining the global climate is the network of pathways for ocean currents to transport heat. When 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 the transport of heat to polar areas.

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 90° to 45°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 2.2. 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 subpolar position for a continent appears to be a necessary (but not sufficient) condition for widespread glaciation.

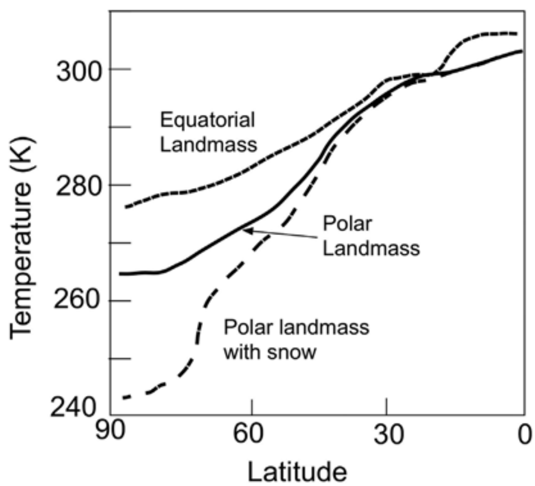

Figure 2.2. Dependence of temperature on latitude for three hypothetical distributions of landmass.

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 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 the 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 2.3. Two-thirds of the land area occurs in the northern hemisphere (NH). This undoubtedly explains why ice sheets form primarily in the NH during ice ages. The presence of

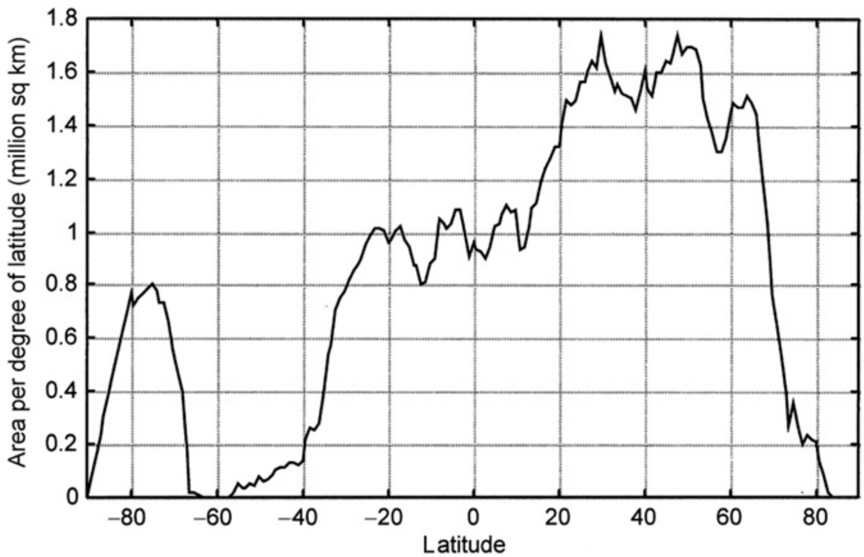

Figure 2.3. Land area vs. latitude on the Earth. Two-thirds of the landmass is north of the equator (Muller and MacDonald, 2000, p. 189 by permission of Praxis Publishing).

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

2.3.2 Evolution of glaciation near the south pole ~34 million years ago

Antarctica has been located over southern polar latitudes since about 150 million years ago, yet it is believed to have remained mostly ice-free, vegetated, and with mean annual temperatures well above freezing until about 34 million years ago. At about that time, 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. Temperature changes at the poles were probably twice the 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, n.d.).

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. The deep-sea cores prior to 34 Myr ago 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 Myr–55 Myr ago—Australia and Antarctica were joined.
— 55 Myr ago—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 Myr–38 Myr ago—the Southern Ocean was relatively warm and Antarctica largely non-glaciated.
— 38 Myr ago—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 Myr–22 Myr ago—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 Myr–11 Myr ago—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 seafloor 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, n.d.). 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 Myr ago to 600 ppm at 34 Myr ago) 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 paleogeography, 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 arbitrary and contrived.

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 Myr and 15 Myr 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."

2.3.3 The 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 year 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 the 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 million years ago, 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 Myr ago 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 freshwater vapor into the atmosphere. The Trade Winds carried the water vapor from east to west across the low-lying Isthmus of Panama and deposited freshwater 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 revealed that the salinity contrast between the Atlantic and Pacific had already started to develop by 4.2 million years ago. Thus Haug raised the question: ''If the salinity had already changed by 4.2 million years 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 million years ago? 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-to-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 Myr ago, 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 NHG?

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 NHG. 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-latitude and high-latitude ocean. After a transient precursor event at 3.2 million years ago, signals of large-scale glaciations suddenly started in the North Atlantic in two steps, at 2.92–2.82 Myr and 2.74–2.64 Myr ago. They also noted that the time period around 2.7 million years ago was the onset of ice-rafted detritus in the Pacific. Thus they described an irreversible "climate crash" that began from 2.74 Myr to 2.64 Myr ago. 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 Myr to 2.64 Myr ago was estimated at 45 m.

Bartoli *et al.* (2005) established the timescale 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 conducive 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".

Most recently, 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.

In an interesting related study, Cane and Molnar (2001) pointed out that global climate change around 3 Myr to 4 Myr ago 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 million years ago. 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 Myr to 4 Myr ago could be responsible for aridification of Africa and other climate changes. Their model indicated that the northward displacement of New Guinea, about 5 million years ago, may 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

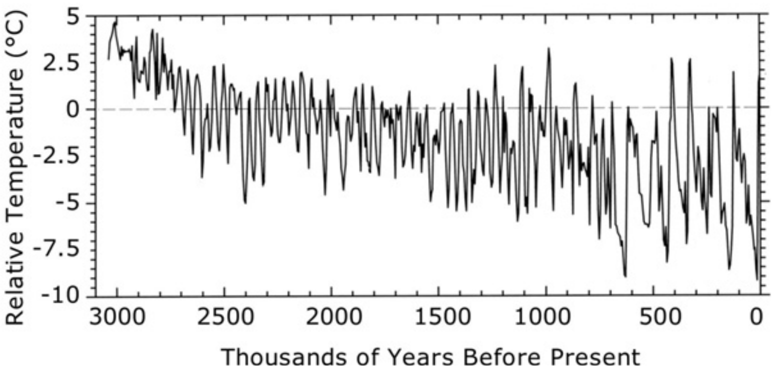

Figure 2.4. Global average temperature over the past 3 million years (Raymo, 1992).

the equatorial Pacific may have reduced atmospheric heat transport from the tropics to higher latitudes, stimulating global cooling and the eventual growth of ice sheets.

2.4 ICE AGES IN THE RECENT GEOLOGICAL PAST

As we shall demonstrate in the chapters of this book that follow, there is evidence that the climate of the Earth has undergone significant sharp oscillations over the past three million years. The Earth has vacillated between two endpoints.

At one endpoint the climate of the Earth is not unlike that prevailing today, give or take a degree or two. 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.

At the other endpoint, 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, global average temperatures drop significantly, and temperatures at high latitudes drop even more. Figure 2.4 shows an estimate of global average temperature over the past three million years. The data in this figure suggest that over the past few hundred thousand years, the duration and depth of 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 worldwide 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.

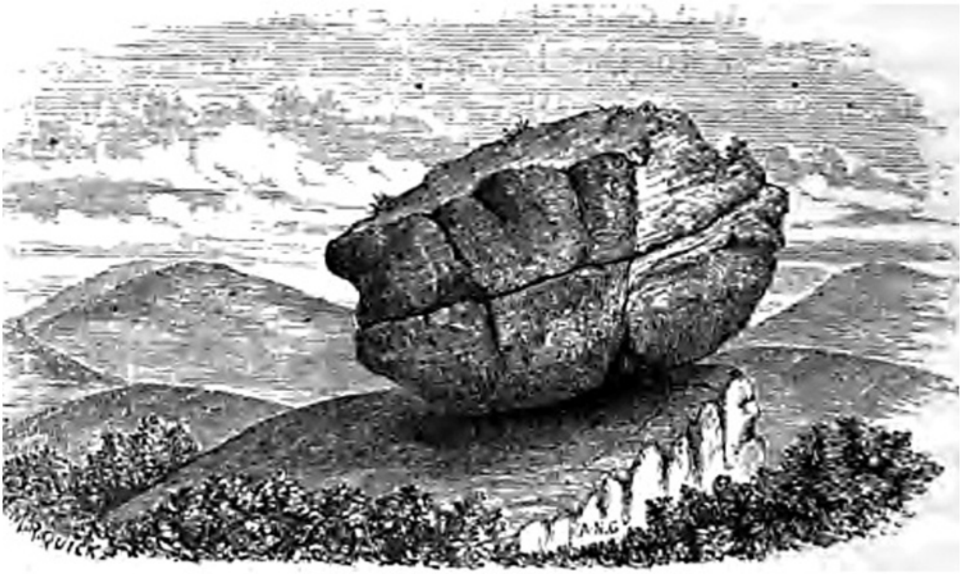

Figure 2.5. Erratic Stone (Geike, 1894).

2.5 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, as well as scratch marks on the walls of rock in mountains, and 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 end of the 19th century provide good insights into what was known prior to modern techniques for estimating historical temperatures. Wright (1920) is the source of Figures 2.5 and 2.6.

''Bubble Rock'' in Maine is a favorite subject for photographers (see Figure 2.7). 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

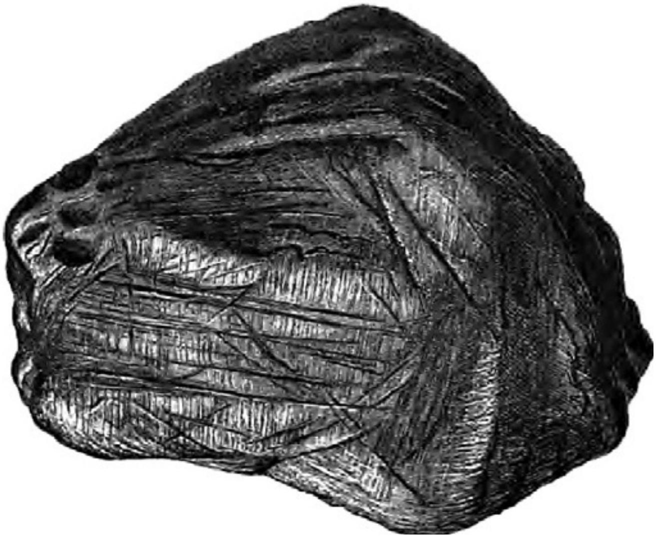

Figure 2.6. Scratched Stone (Geike, 1894).

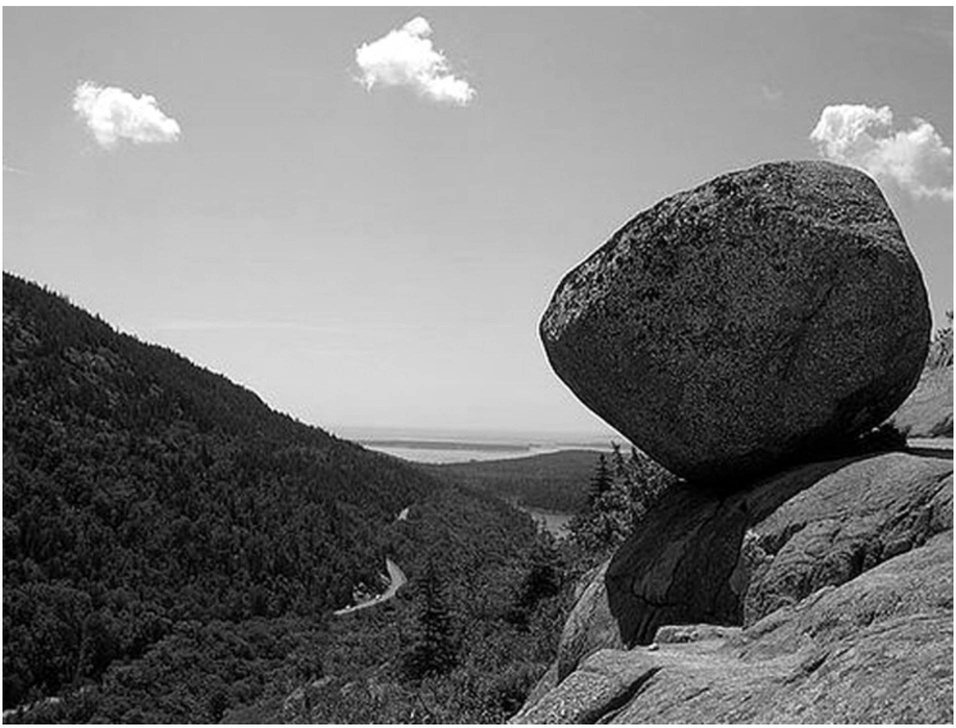

Figure 2.7. Bubble Rock, Acadia, Maine (*http://flickr.com/photos/iamtonyang/29259194/*).

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 stiff semifluid 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 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 must 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; only fine material is transported to the same distance during the lower stages of water; 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 he 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 distant regions. Moreover, the pebbles in this deposit are mostly polished and scratched after the manner of those which we know to have been subjected to glacial action."

Finally, Wright (1920) discussed the fact that the southern margin of the region where unstratified deposits containing striated stones and transported material was

Figure 2.8. Extent of the most recent ice age in North America (Geike, 1894).

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 character of its southern border that was of most significance. Wright emphasized that the southern border, with its indentations 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

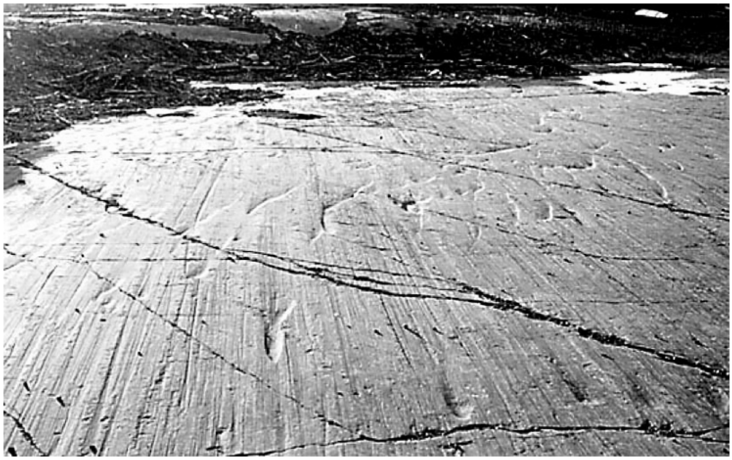

Figure 2.9. Glacial striations (UWESS, n.d.).

Figure 2.10. Example of polishing of bedrock by glacial silt (UWESS, n.d.).

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 (Wright, 1920) 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 the 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 2.8.

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.

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 2.9).

UWESS (n.d.) describes how glacier action can pluck large blocks leaving the characteristic scalloped terrain. Fine silts suspended in glacial melt water can polish underlying bedrock (see Figure 2.10).

In addition, the UWESS presentations provide 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 for probing temperature changes over 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 (the hydrogen can either be H or D, and the 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 ppm and 320 ppm (parts per million), respectively. When water evaporates, a higher concentration of the lighter form of water appears in the 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 ppm (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 delta symbol (δ). 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:

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

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 these units are 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 increased at which the rain formed. When a cloud produces rain, it loses more $H_2{}^{18}O$ than the corresponding concentration in the 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 the water- bearing clouds move inland, they cool ever more, and the depletion of ^{18}O continues. The snow that accumulates on the ice sheet above the 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 from CO_2 entrapped in air bubbles). However, analyses of the bubble air showed reduced contents of the most soluble gases that were more or less washed out by melt water. It

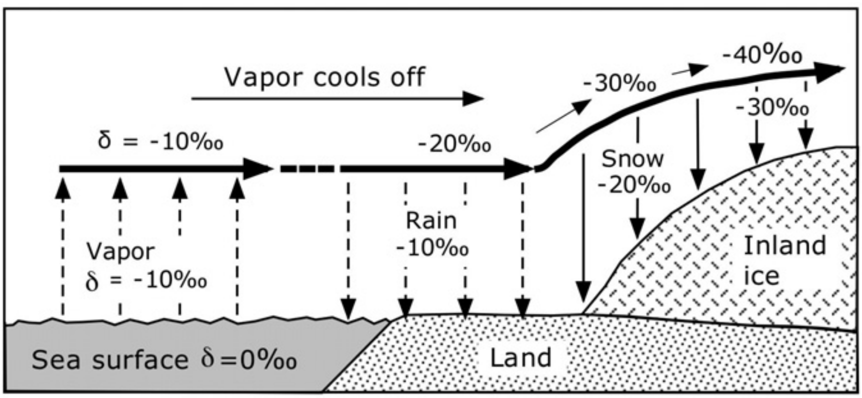

Figure 3.1. δ-changes (isotopic fractionation) in vapor and precipitation by evaporation from the sea and precipitation from a cooling airmass during its move towards higher latitudes and/or higher altitude (adapted from Dansgaard, 2005)

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 freshwater 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 icecap 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.

The 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 re-crystallize 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 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 the thickness of firn and ice. The firn–ice transition usually occurs at a depth of around 70 m to 100 m, typically deeper in Antarctica than in Greenland.

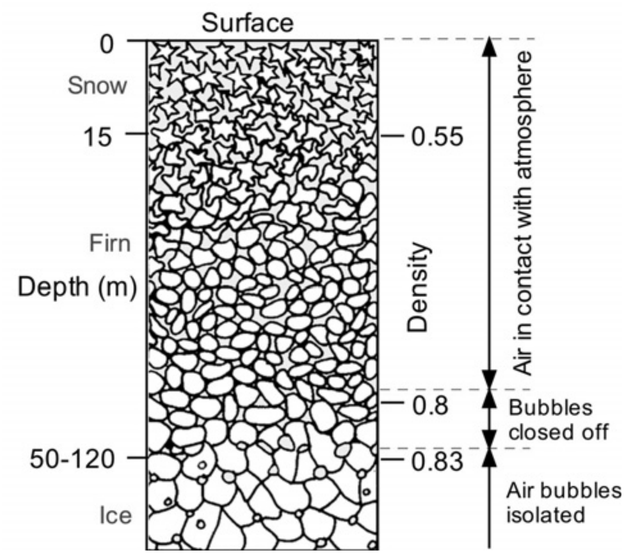

Figure 3.2. The sintering process as snow is converted to firn and then on to ice with bubbles of air entrapped (adapted from *http://www.csa.com/discoveryguides/icecore/review.php*).

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 contains 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 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 (2003):

> "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" (Soon and Baliunas, 2003).

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 distributed over several hundred (or more) years.

Michael Oard (2005) provided a good description of ice cores. Ice cores of length over 3,000 meters 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 ago. The results indicated an ice age from about 100,000 years ago to about 10,000 years ago, 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 years ago, a medieval warm period around 1,000 years ago, and a Little Ice Age from around 500 years to 100 years ago.

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 years.

One of the early ice core sites was the so-called *Dye 3* that 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, that involved eight nations (Belgium, Denmark, France, Germany, Iceland, Italy, Switzerland, and the U.K.). GRIP successfully drilled a 3,028-meter ice core to the bed of the Greenland Ice Sheet at Summit, central Greenland from 1989 to 1992 at (72°N).

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

There was also a follow-up U.S. *GISP2* project, which drilled at a geologically better location on the summit. This hit bedrock (and drilled another 1.55 m into bedrock) in 1993 after five years of drilling, producing an ice core 3,053 meters in depth.

The *North Greenland Ice Core Project (NGRIP)* site was near the center of Greenland (75°N). The core was 2,917 m long. The cores were cylinders of ice four inches in diameter that were brought to the surface in 3.5-meter lengths. The site was chosen for a flat basal topography to avoid the flow distortions that render 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, and these provide longer term records than Greenland, recently extended to about 800,000 years. 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 that 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°C and snow accumulation is 25 mm/yr. 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 NorthGRIP 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 improved time resolution and this small age offset will allow a study of interactions between climate variations and atmospheric composition with 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, with a greater level of detail than was 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 is not expected to be complete until well into 2011.

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-to-depth relationship that provides a chronology of the 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 the 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 the 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 crumpled.

However, visual resolution of annual layers is not feasible in Antarctica where annual precipitation is much less and the layers are more closely packed. The uncertainty in the Vostok (Antarctica) timescale 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 was done, what assumptions were implied, and how reliable these assumptions are. Many investigators have relied on a comparison of key transition points in the isotope ratio vs. depth curve to 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 rocesses 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 astronomical theory is greatly diminished because 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 astronomical theory, such circular reasoning can be counter-productive. But there seems to be a widespread bias in the community of paleoclimatologists to defend astronomical theory at all costs, using all manner of tinkering with the data to seek agreement. It is amazing that when disagreements are found between the data and the theory, 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, and 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 the 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 years ago. Zielinski *et al*. (1994) identified evidence of volcanic activity in a Greenland core that goes as far back as 9,000 years ago. 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 years and 5,279 years ago 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 Antarctica cores between the age of entrapped gas and the ice in which it is embedded. Models have been used to estimate δ(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 the ^{10}Be records in ice cores. The Greenland ice cores yield an age of about 41,200 years for this occurrence, and this age was assigned to the position in the Antarctic core where a similar peak occurred (Parrenin *et al*., 2007). Independent measurements of the age of this event from sources other than ice cores suggest an age in the range 40,000 years to 41,400 years ago.

Antarctic volcanic eruption. There is independent evidence of a large volcanic eruption from volcanic Mt. Berlin in Antarctica that occurred about 92,500 years ago. If the ash is located in the core, it can be attributed to that date.

Speleothems in caves. Speleothems are mineral deposits that are formed from groundwater within underground caverns. Stalagmites, stalactites, and other forms may be annually banded or contain compounds which 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 130,000 years ago (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 to around 130,000 years ago.

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 the 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*. reported on the "NorthGRIP VS" profile covering the depth interval 1,330 m to 3,085 m, which corresponds to the time interval 9,000 years to 123,000 years ago (Svensson *et al*., 2005). Their paper is the source of 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. The 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 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

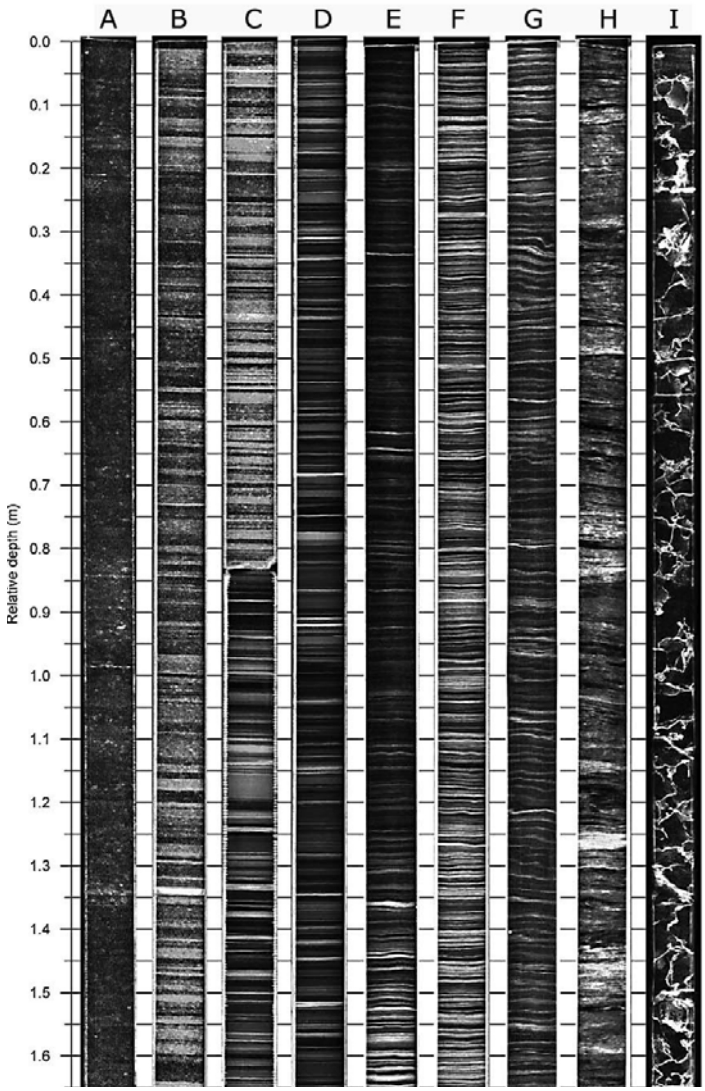

Figure 3.3. Examples of line scan images of ice cores from various depths. Each ice section is 1.65 m long, 3 cm thick, and 8 cm–9 cm wide. (a) Holocene ice, 1,354.65 m–1,356.30 m depth; white patches are most likely ice crystal interfaces within the ice. (b) Ice from the Younger Dryas, 1,504.80 m–1,506.45 m depth; the bright layer at 1.33 m relative depth is a volcanic ash layer. (c) 1,750.65 m–1,752.30 m depth. (d) Ice from around the last glacial maximum, 1,836.45 m–1,838.10 m depth. (e) Ice from a sharp climatic transition ("IS19") at 2,534.40 m–2536.05 m depth. (f) Ice from the cold period preceding "IS19" at 2,537.70 m–2539.35 m depth. (g) Microfolding starts to appear below 2,600 m at the 2,651.55 m–2,653.20 m depth. (h) 2,899.05 m–2,900.70 m depth; overall horizontal layering is still obvious, but individual cloudy bands are not distinguishable. (i) 3,017.30 m–3,018.95 m depth; visible grain boundaries of large crystals (Svensson *et al.*, 2005).

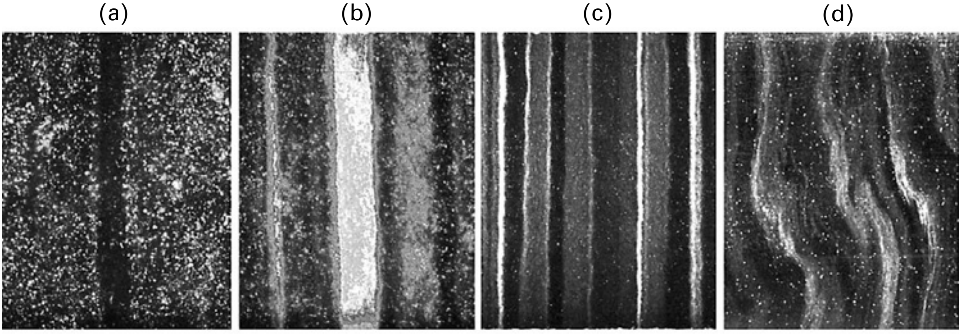

Figure 3.4. Close-up examples of line scan images (rotate 90° to compare with previous figure). The sections shown are 6 cm high and 7.5 cm wide. (a) 1,412.1 m depth; Holocene ice with visible air bubbles; the band of clear (dark) ice indicates a possible melt layer or ice where the air bubbles are converted into clathrate hydrates. (b) 1506.1 m depth, the visible "Vedde" volcanic ash layer in Younger Dryas. (c) 1836.9 m depth; there is 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).

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 the 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 cm to 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 rates (Parrenin *et al.*, 2007). However, layers can be discerned in the upper part of the core at Law Dome (on the coast) that receives a great deal more snow than the inland domes.

Over the most recent 110,000 years, 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 the visual stratigraphy further down in the core. The LLS method is based on the fact that the 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 is melted, because bubbles in the ice also scatter the light in the upper portion of the core. The bubbles disappear about 1,400 meters 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. 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 meters. In fact they believe they were able to count 50,600 more annual layers with an accuracy of 24% from 2,800 m to 3,000 m. The age at 3,000 meters was about 161,000 years ago. However, this lower layer was probably distorted by ice flow and the extension to 3,000 meters is likely to be invalid.

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

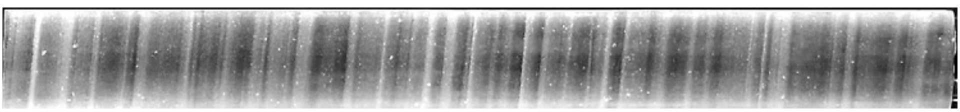

Figure 3.5. Section of the GISP2 ice core from 1,837 m–1,838 m deep in which annual layers are clearly visible. The appearance of layers results from differences in the size of snow crystals deposited in winter vs. summer and resulting variations in the abundance and size of air bubbles trapped in the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

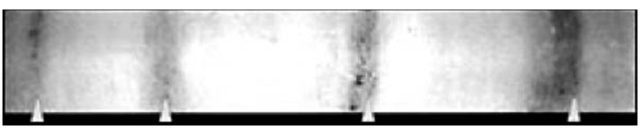

Figure 3.6. Section of an ice core drilled in the Kunlun Mountains of Western China. The thick, lighter bands indicate heavy snowfall during the monsoon season around the year 1167 AD, while the thinner, darker strips show layers of dust blown into the snowfield during the dry season (photo attributed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

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 the precipitation in the year of deposition. The decade from AD 1225 to 1235 was dryer 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 always straightforward and resolution of individual years can be a very subjective process.

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 δD and electrical conductivity measurements have also been used to discern yearly layers.

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,

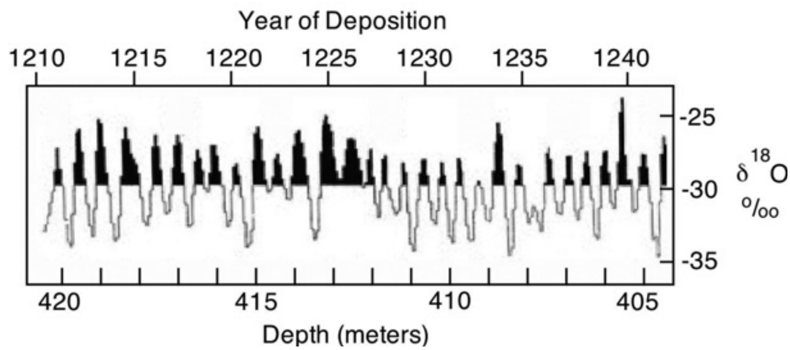

Figure 3.7A. Layering as evidenced by periodic variations in $\delta^{18}O$ (Dansgaard, 2005).

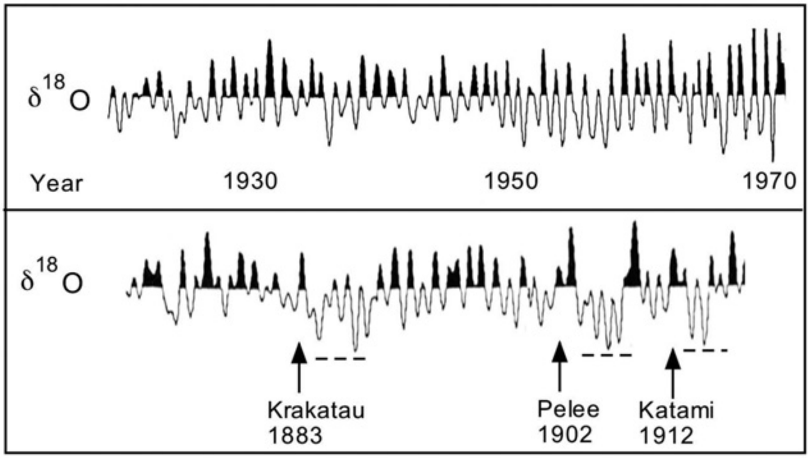

Figure 3.7B. Layering of $\delta^{18}O$ measurements at Station Crete, Greenland. The upper panel shows normal recent variation. The lower panel shows the effects of three large volcanic eruptions in the 19th century as the patterns underlined by dashed lines.

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 provided corroboration to visually observed layers.

3.2.5 Ice flow modeling

Ice sheets and glaciers are sedimentary deposits consisting of sequences of layers, deposited annually as snow accumulation. The snow layers sink into the icemass, 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 the 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 icemass.

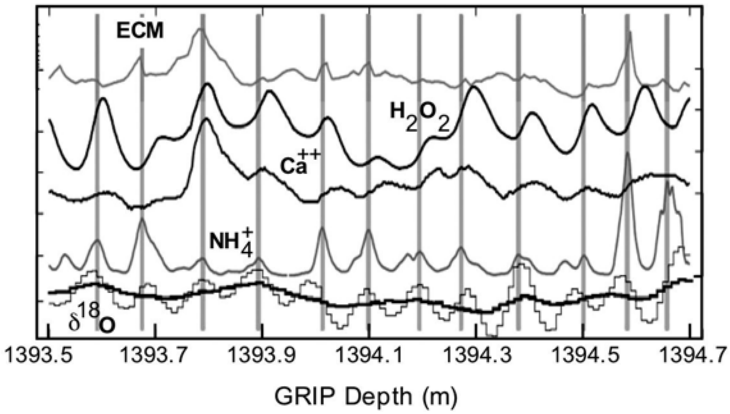

Figure 3.8. Example of a 1.2-meter segment of GRIP data from about 8,800 years ago. Visually determined annual layer markings are shown as gray vertical bars. The annual layers were also identified as matching pairs of spring and summer indicators: spring was characterized by high dust content leading 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)

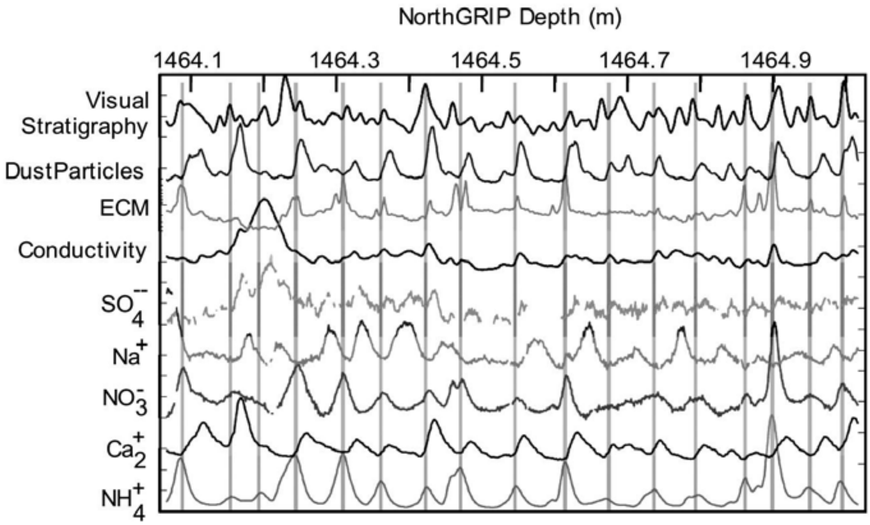

Figure 3.9. Example of data and annual layer markings (gray vertical bars) from visual stratigraphy during the early Holocene. A 0.95-meter long section of NGRIP data is shown. The annual layers are marked at the summer peaks, which are defined by high [NH_4^+] and [NO_3^-]. The spring is characterized 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 contains 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.

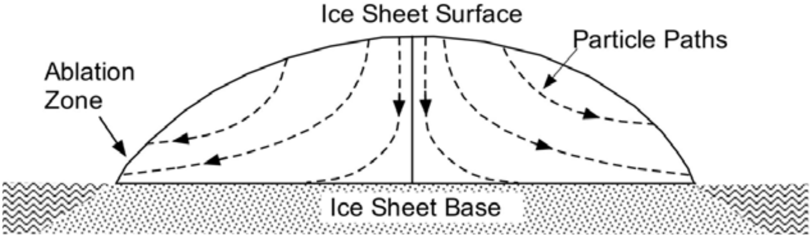

Figure 3.10. Ice particle flow paths.

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 icemass 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 for corrections 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 timescale.

The temperature of the ice varies with depth. The temperature of subterranean ice is typically fairly constant for a significant depth (down to ~1,500 m), but it becomes warmer at deeper depths and may rise to 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 in order 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:

$$\text{Age(depth)} = \int_0^{\text{depth}} \frac{dz}{\text{accumulation}(z) \times \text{thinning}(z)}$$

The accumulation function has been modeled for various localities but it depends on past temperatures, which in turn depend upon the chronology, so there is some circular reasoning 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.* (2007) 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 ± 0.19 mm/yr for basal melting at Dome C. The annual layer thickness as a function of depth was the primary result of this model. It was found that the 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 m 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 of 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.*, 2007).

3.2.6 Other dating methods

pH balances

Precipitation during ice ages is markedly alkaline. This is due to the fact that the extensive glaciation during an ice age lowers the ocean level by perhaps $\sim$100 meters, thus exposing a larger portion of the continental shelves. Huge clouds of alkaline dusts (primarily $CaCO_3$) from these shelves were 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.

3.2.7 Synchronization of 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 (Δ-age). 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 in depth intervals with elevated dust concentrations, hence in ice covering glacial time periods. CH_4 is of special 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 (Loulergue *et al.*, 2007; Blunier *et al.*, 2007).

3.2.8 GISP2 experience

Meese *et al.* (1997) described processes used for dating of 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 of visual stratigraphy, electro-conductivity measurement (ECM), laser light scattering from dust (LLS), oxygen isotopic ratios of the 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. (Hoar layers are porous, low-density snow layers.) 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. During the height of the Ice Age, the stratigraphic signal was not the characteristic depth–hoar sequence, but rather cloudy bands

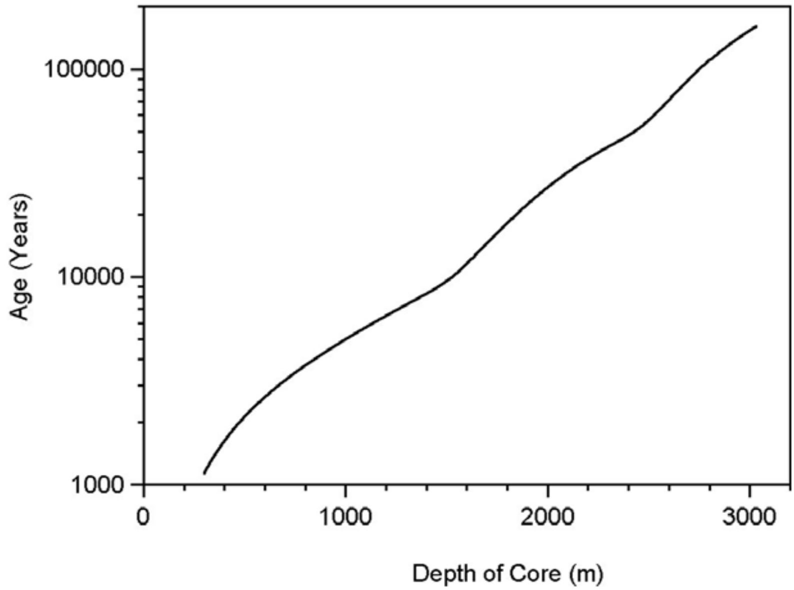

Figure 3.11. Depth–age relationship in GISP2.

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 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.

The resultant age–depth relationship is shown in Figure 3.11.

3.2.9 Tuning

The process of dating sediment cores by comparing patterns of isotope variability with patterns of solar variability, based on 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.* (2007):

> "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 non-linear 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 3.12.

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 the 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 autocorrelated) processes are particularly prone to generating oscillations that to the eye look related."

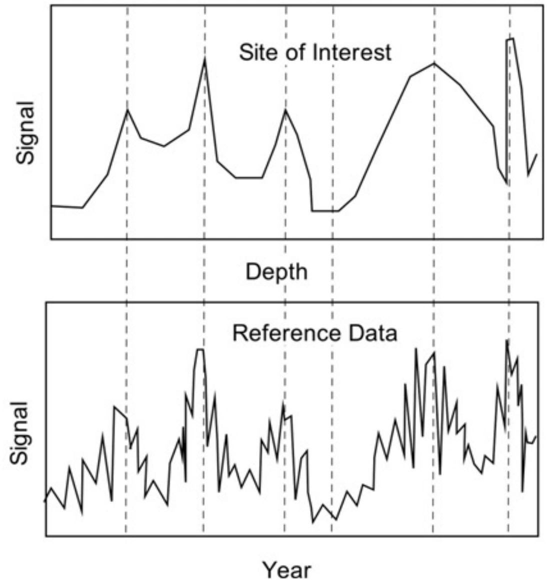

Figure 3.12. Comparison of features for site of interest with features in reference data.

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 insignificantly 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 timescales from various sources that it is often difficult to determine which solid ground (if any) timescales rest upon.

The first (and perhaps most influential) inference in 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 100,000 years ago, and this was used as a marker. This was later raised to 125,000 years ago. However, there is evidence that warming started as early as 140,000 years ago (see Figure 6.3 and discussions in Sections 6.1.4, 6.2, and 6.5.2).

A magnetic polarity change that is believed to have occurred some 780,000 years ago can sometimes be useful. But ocean sediment data date back to 3 Myr ago and comparison with 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 an ice sheet in the past is believed to be in some way proportional to δ^{18}O. The isotope ratio:

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

and its counterpart δ(D) are indicators of past temperatures that prevailed when snow was deposited at the site that 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 δ^{18}O at these sites (see Figure 3.13). Dansgaard also measured δ^{18}O—and δ(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 δ^{18}O—or δ(D)—held during the past few hundred thousand years (a rather large extrapolation), these straight line correlations between δ^{18}O—or δ(D)—and temperature can be used to infer past temperatures from measurements of δ^{18}O—or δ(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 δ are measured in units of ‰ (parts per thousand). This was the method of choice for converting isotope measurements to temperature for several decades.

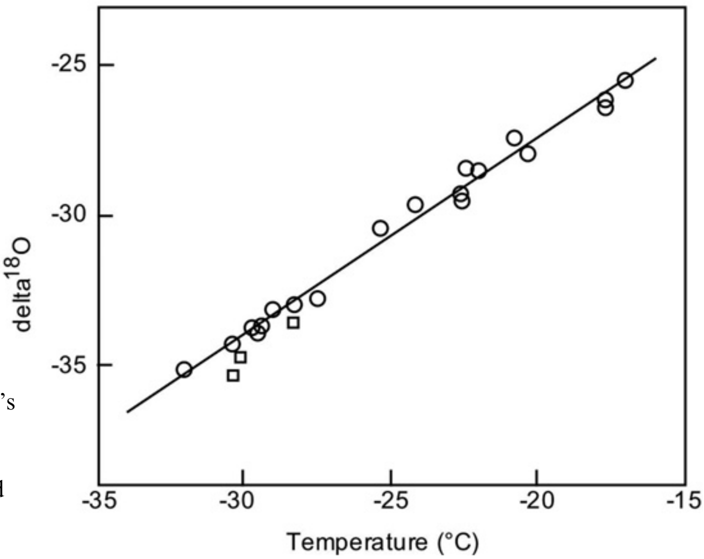

Figure 3.13. Dansgaard's correlation of $\delta^{18}O$ with temperature. The circles are south Greenland and the squares are north Greenland.

For example, according to Kotlyakov (1996):

> "The main method of paleotemperature estimation involves analysis of the stable isotope 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 δD measurements to temperature is far from straightforward due to a variety of confounding factors that may occur. While the 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 the isotope ratios during glacial periods include more extensive sea ice cover during glacial periods that increases the distance from the moisture source, and changes in the isotopic composition of oceans during glacial periods.

Ideally, records of both surface temperature and isotopic contents of the precipitation should span over a relatively long period at any site where an empirical relationship between δ 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 the 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

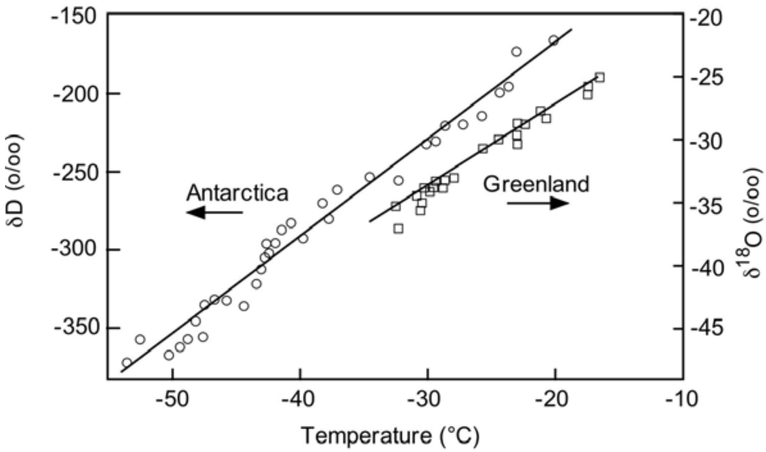

Figure 3.14. Present-day correlations of $\delta^{18}O$ or δD with temperature (Jouzel *et al.*, 1997).

from automated weather stations (AWSs) and satellite temperature sensors provide additional support for the linear relationship of δ 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 (δ stands for either δD 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 3.14. This does not necessarily validate the relationship under past conditions, particularly during extensive glaciation.

Jouzel *et al.* (1997) reviewed empirical estimates and theoretical models of the relationship between isotope ratios and temperature. They focused on polar areas and more specifically on Greenland where the GRIP and GISP2 drillings allowed empirical estimates to be obtained from paleothermometry and motivated modeling experiments (see Figure 3.15).

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 temperature can 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 from the parcel. With these assumptions, the isotope content of this precipitation is a unique

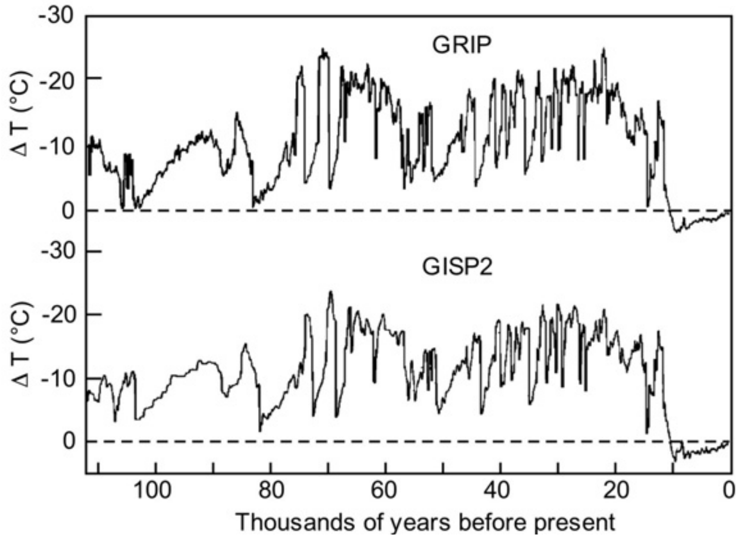

Figure 3.15. Comparison of estimated temperatures at two Greenland sites (Jouzel *et al.*, 1997).

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 3.14, 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 δD. 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 the 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" (Cuffey *et al.*, 1995).

Temperatures in the upper ~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 the ice flow in different regions of ice sheets. 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 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, the 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 3.16. 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 $\delta^{18}O$ vs. T, as shown in Figure 3.16. 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 and ice flow model. They then compared the modeled T vs. depth with the GISP2

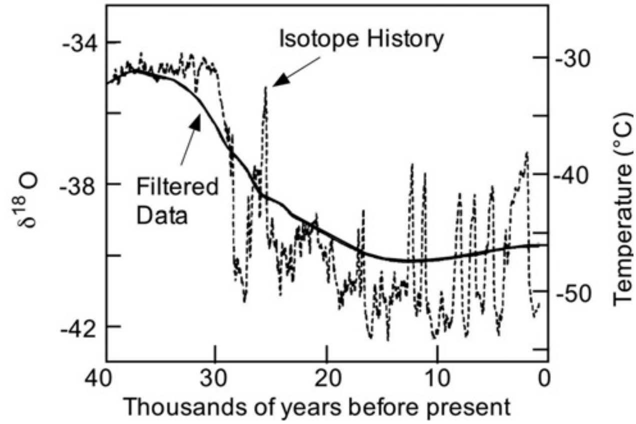

Figure 3.16. Filtered isotope data (Cuffey *et al.*, 1995)

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 δ^{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 δ^{18}O were considerably greater than had been supposed based on current data for δ^{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 timescale to 50,000 years ago (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 δ^{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 years ago. This was due to an increase in snow accumulation rate due to the availability of moisture in the nearby atmosphere as deglaciation proceeded (see Figure 3.17).

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

Use of climate models

An atmosphere general circulation model was used (Werner *et al.*, 2000) to estimate Greenland temperatures during the LGM about 20,000 years ago, and these results

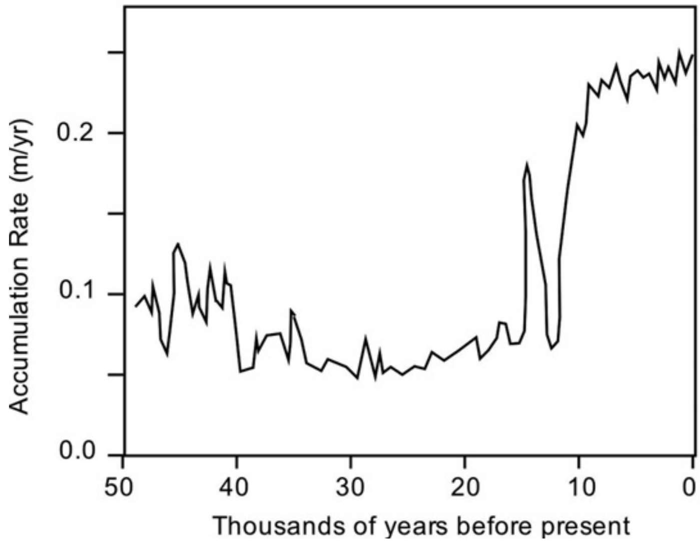

Figure 3.17. Rate of accumulation increase in the Holocene (Cuffey and Clow, 1997).

support borehole estimates rather than isotope correlations. This adds corroboration to the belief that the temperature difference from today during the LGM was about twice as great 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 3.18. As this diagram shows, summer precipitation produces a lower isotope ratio than the yearly average.

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).

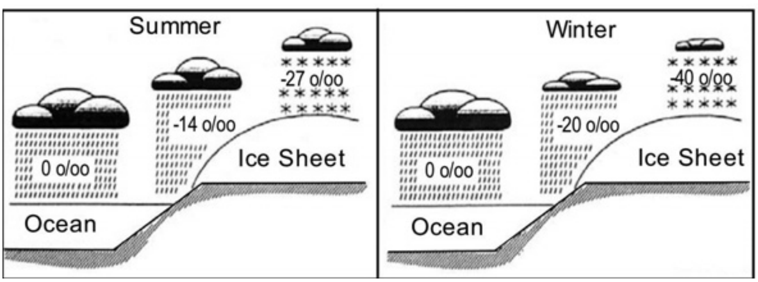

Figure 3.18. Difference between isotope ratios in summer and winter (adapted from Thorsteinsson, n.d.).

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, and 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) exposure of continental shelves due to lowering of 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 much 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 m to 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 m–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 freshwater 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/yr of water (equivalent) in the extreme south, to 30 cm/yr–50 cm/yr in the lower to mid-range, to 10 cm/yr–30 cm/yr in the north. At the highest point on Greenland, the annual mean temperature is −30°C, varying between −15°C in midsummer to −41°C in midwinter.

The Joint European Greenland Ice Core Project (GRIP) drilled a 3,029 m ice core to bedrock in Central Greenland from 1989 to 1992 at 72°N. The ice cores contained records of the 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 meters into bedrock in July, 1993 recovering an ice core 3,053 meters in depth, about 28 km from GRIP. This was the deepest ice core

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 of water per year)	32	19
Increase in height of oceans if completely melted (m)	7	68

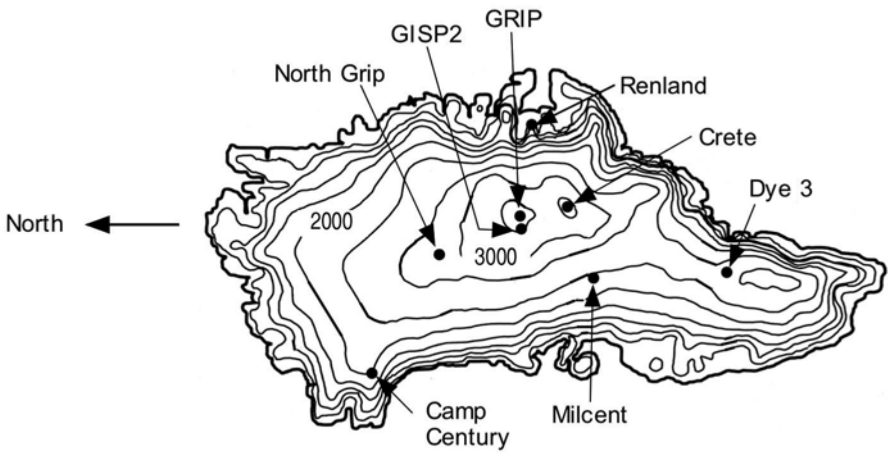

Figure 4.1. Greenland topographical map showing locations of several major ice core sites. Numbers are elevations in meters (adapted from M. Oard, *The Frozen Record*).

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 meters above sea level) on the "ice divide" of central Greenland. Here the ice moves 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 3.15).

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

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

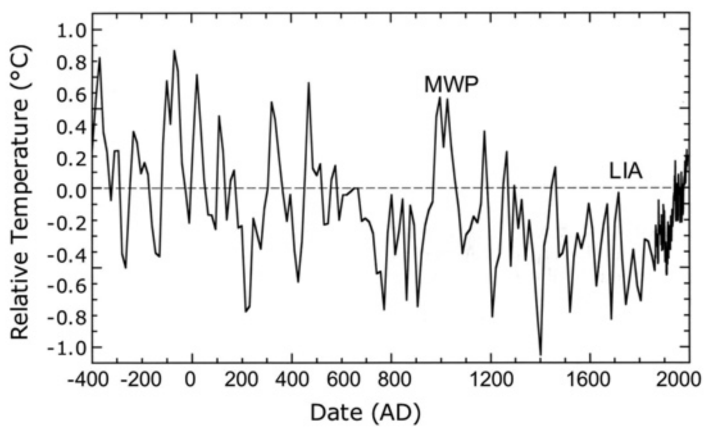

Figure 4.2. GISP2 estimates of global temperatures over the past two centuries. The Medieval Warm Period and Little Ice Age are evident (Muller and MacDonald, 2000, p. 3; Grootes *et al.*, 1993).

4.2 shows the GISP2 data for the past two centuries. There is good evidence for a so-called "Medieval Warm Period" around 1,000 AD and a "Little Ice Age" from about 1400 AD 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 years ago. 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

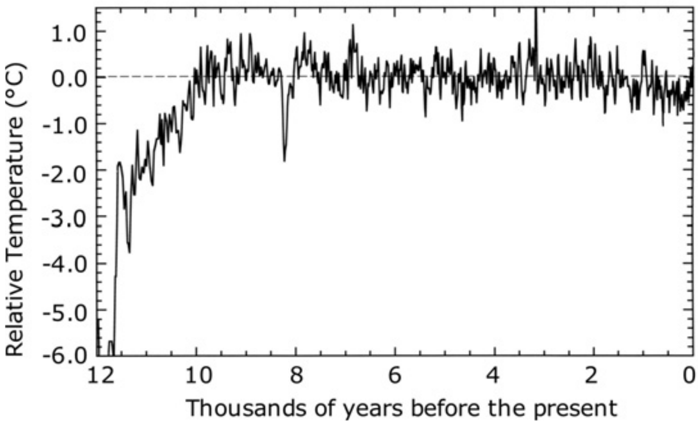

Figure 4.3. Ice core estimates of global temperatures during the past 12,000 years (Muller and MacDonald, 2000, p. 3).

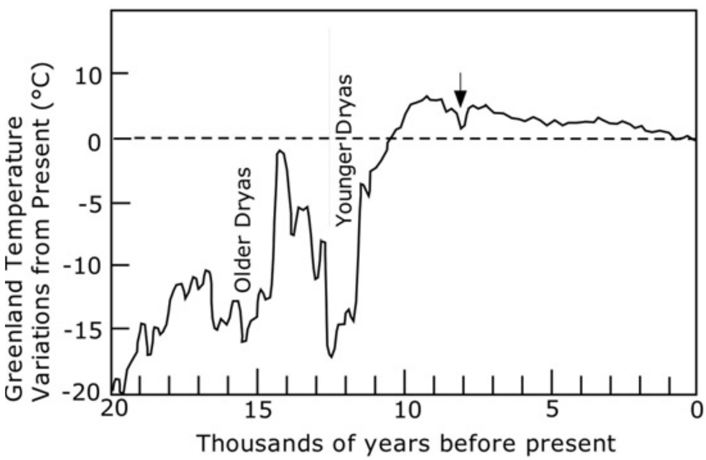

Figure 4.4. Greenland temperature history from GRIP over 20,000 years (smoothed data).

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 the 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 years ago may have contributed to the Younger Dryas (Kennett *et al.*, 2009). The 8,200 event is shown with an arrow. Figure 4.5 extends the data to 40,000 years. Two things stand out in this figure: (1) the 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

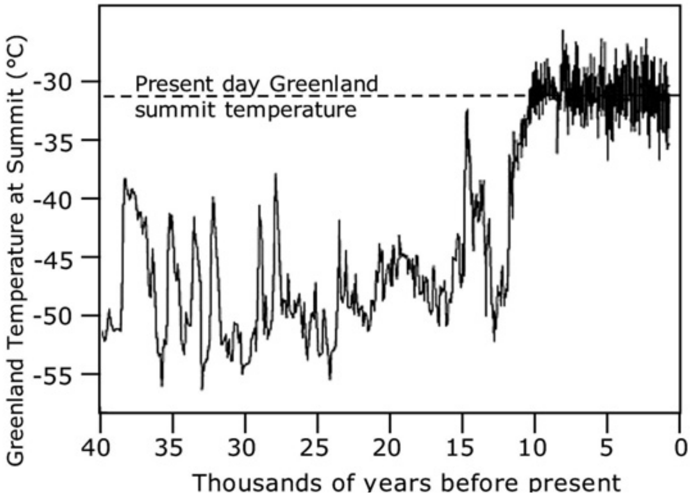

Figure 4.5. GISP2 ice core results taken at Greenland summit over 40,000 years (adapted from *http://www.mos.org/soti/icecore/studies.html*).

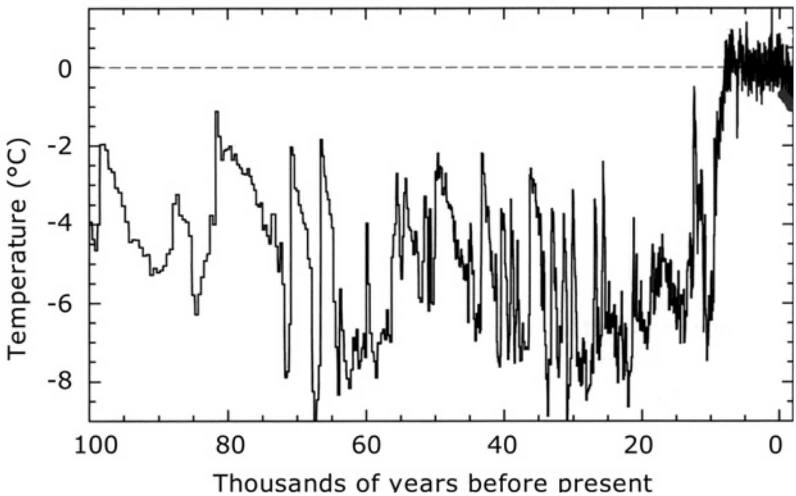

Figure 4.6. Global temperature estimates from GISP2 ice cores over 100,000 years (Muller and MacDonald, 2000).

shows the longest term data, dating back to the last interglacial prior to the most recent ice age.

4.2 ANTARCTICA ICE CORE HISTORICAL TEMPERATURES

4.2.1 Vostok and EPICA data

Antarctica is the coldest and windiest place on Earth. Antarctica sits over the Earth's southern pole and is covered by an ice sheet up to 4 km thick and over 4,000 km

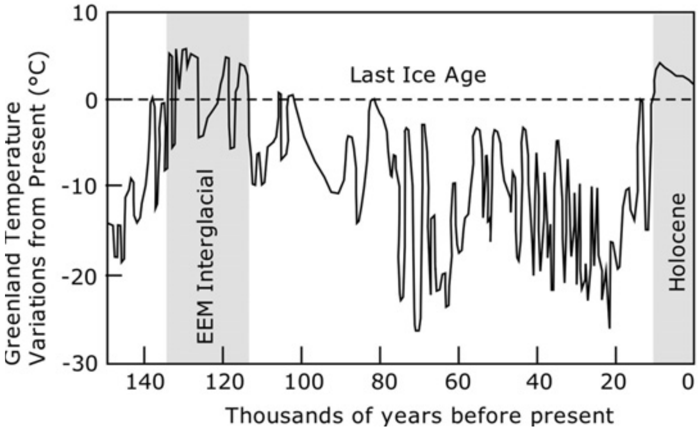

Figure 4.7. Greenland temperature history from GRIP (smoothed data) over 150,000 years. Interglacial periods are shown by gray shading.

across. It contains 70% of the Earth's freshwater and 90% of its ice, and has existed in roughly its present form for around 15 million years. The ice sheet is 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, n.d.).

Figure 4.8 provides a rough topographical map showing the locations of several major ice core sites at Antarctica. The characteristics of the various drilling sites are

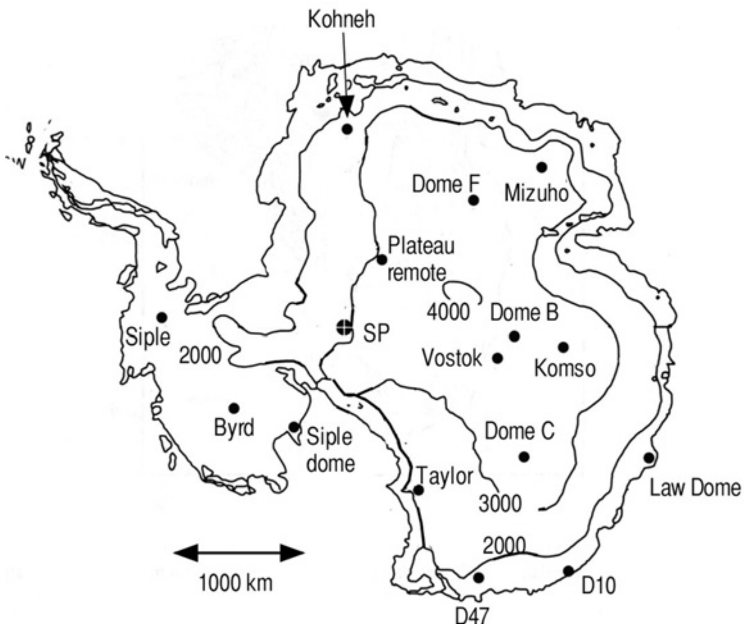

Figure 4.8. Antarctica topographical map showing locations of several major ice core sites (adapted from Oard, 2005).

Table 4.3. Characteristics of the 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

summarized in Table 4.3. Annual snowfall is much lower than at Greenland, averaging about 5 cm/yr over the main dome area (Dome F to Dome C). However, it reaches over 60 cm/yr of water (equivalent) near Law Dome on the coast. Temperatures are much colder than in Greenland (e.g., the average temperature at Vostok is −55°C).

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

4.2.2 Homogeneity of Antarctic ice cores

There is good evidence that the various ice cores taken at Antarctica yield similar results. Figure 4.11 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

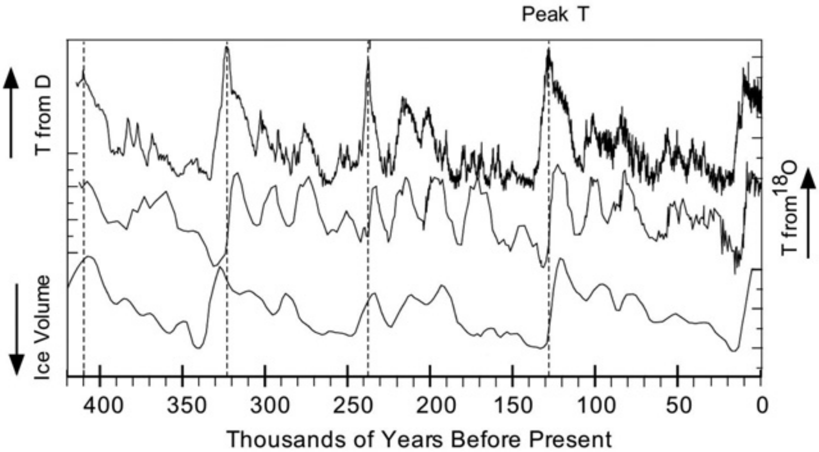

Figure 4.9. Vostok ice core data. The upper curve is the variation of temperature as interpreted from δD vs. depth of the ice core. The middle curve is the $\delta^{18}O$ profile in the atmosphere from gas bubbles. The lower curve of ice volume implied by $\delta^{18}O$ in ocean sediments is provided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

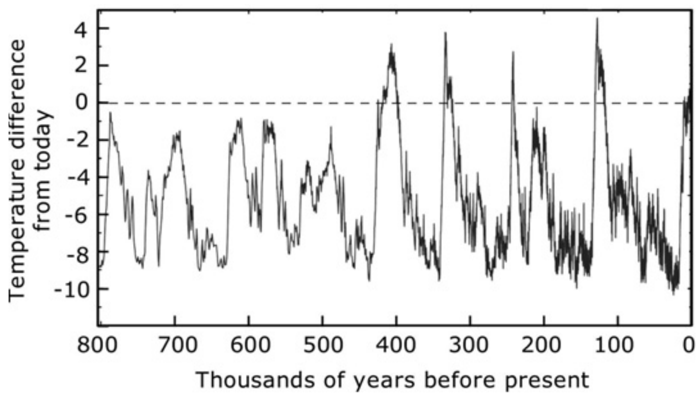

Figure 4.10. Estimated temperature difference from today at EPICA Dome C vs. age (EPICA, 2004).

Antarctica, which is about 1,500 km distant from the Vostok site. The Dome Fuji core extends back about 330,000 years 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, although it involves considerable orbital tuning. Using this chronology, tie points were made between the Fuji $\delta^{18}O$ curves and the Vostok δD curves as shown in Figure 4.12. The entire Vostok core could then be dated by interpolation. The resultant δD curves are compared with Fuji $\delta^{18}O$ curves as a function of age in Figure 4.13.

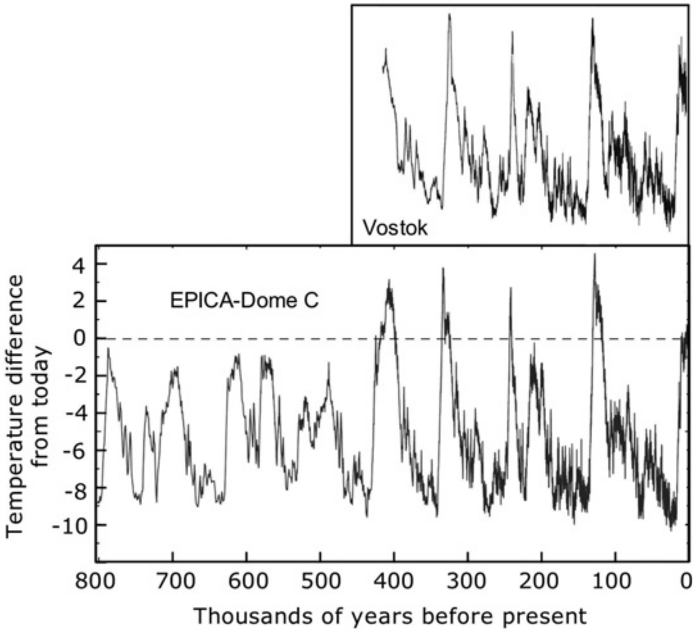

Figure 4.11. Comparison of Vostok and Dome C ice core data.

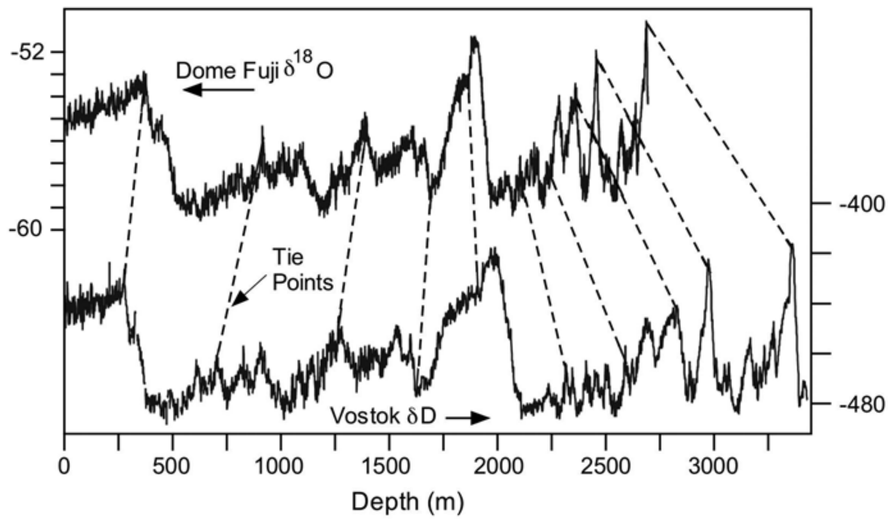

Figure 4.12. Comparison of the Vostok and Dome Fuji isotopic records of $\delta^{18}O$ as a function of depth (Watanabe *et al.*, 2003).

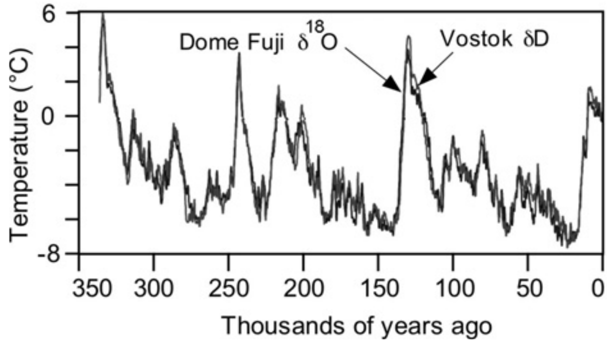

Figure 4.13. Comparison of the Vostok and Dome Fuji isotopic records of $\delta^{18}O$ as a function of time, after scaling as shown in Figure 4.12.

4.3 NORTH–SOUTH SYNCHRONY

A central issue in climate dynamics is whether major changes in the Earth's climate originate in one or both of the northern and nouthern 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 the timescales, particularly when they are based on a comparison of 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 (Δ-age) for Greenland sites was estimated to be around 800 years whereas for Antarctica it ranged from 6,100 years at recent times to 6,300 years at

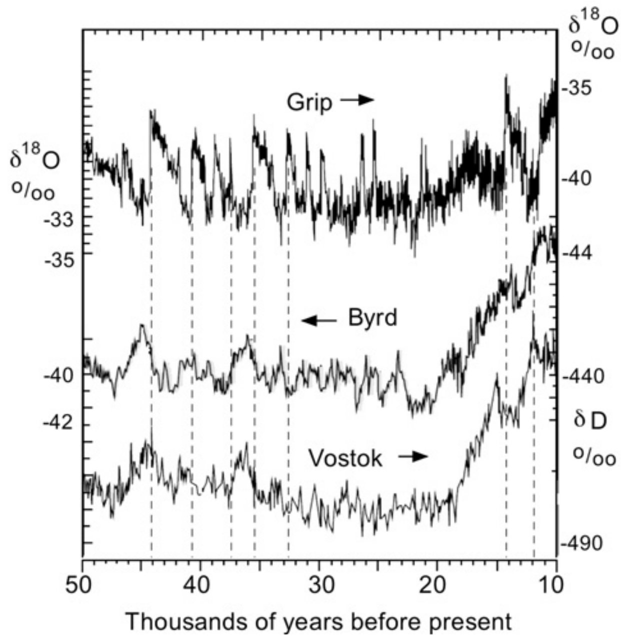

Figure 4.14. Comparison of Greenland and Antarctica isotope records. Dashed lines indicate the onset of selected major sudden heating (Dansgaard–Oeschger) events in the NH (Blunier *et al.* 1998).

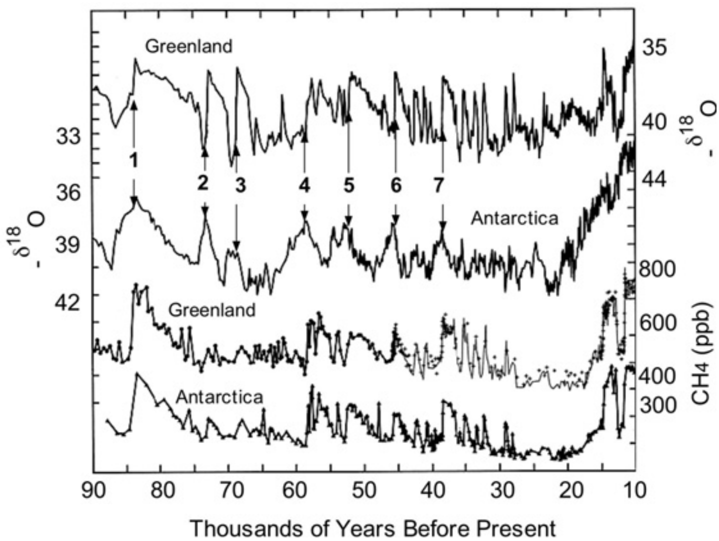

Figure 4.15. Isotopic and CH_4 data from Greenland and Antarctica on the GISP2 timescale (Blunier and Brooke, 2001).

earlier times. Their result is shown in Figure 4.14. This work was extended to a 90,000-year period in a later publication as shown in Figure 4.15. The CH_4 data in Figure 4.15 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 4.15 indicate that over the past 90,000 years the Earth has been predominantly in an ice age, with a breakout into an interglacial period starting about 15,000 years ago. However, the Ice Age at 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 at Greenland and slope changes at Antarctica. The seven vertical lines shown in Figure 4.15 indicate where major sudden temperature increases occurred at Greenland. There seems to be a causal relationship between these occurrences and temperature patterns at Antarctica. The data in Figure 4.15 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. Each sudden rise at Greenland occurs near the end of a more protracted rise in Antarctica.

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 4.14 and 4.15. As in the case of Figures 4.14 and 4.15, the occasional sharp rises in Greenland data also appear to be preceded by slower, more gradual increases at 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 via heat transport via ocean currents known as the *bipolar seesaw* (Barker and Knorr, 2007). 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 the *thermohaline circulation*, and when some non-linear 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, melt water in the Greenland area interferes with the North Atlantic Deep Water (NADW) formation, reducing the 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 the temperature variations in Greenland and Antarctica), visual comparison of features can 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 4.14 and 4.15 are comparable to the timescale over which relationships between north and south are sought, claims that there is a time phasing of the 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 4.14 and 4.15 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 ~30 yr) at Antarctica and at Greenland. New data on the nitrogen and argon isotopic composition of gases trapped in the 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.

4.4 DATA FROM HIGH-ELEVATION ICE CORES

According to the 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 Guliya icecap 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 (10,000 to 26,000 years ago). However, the Guliya core from Tibet reached back to 125,000 years. 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 the 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 10,000 years and 15,000 years ago, 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 from across the Tibetan Plateau (Thompson *et al.*, 2006).

4.5 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 4.16. 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 ppm to 200 ppm during glacial peak periods and about 280 ppm during interglacial periods.

However, there is some evidence that the CO_2 concentration rise (or fall) lags the 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),

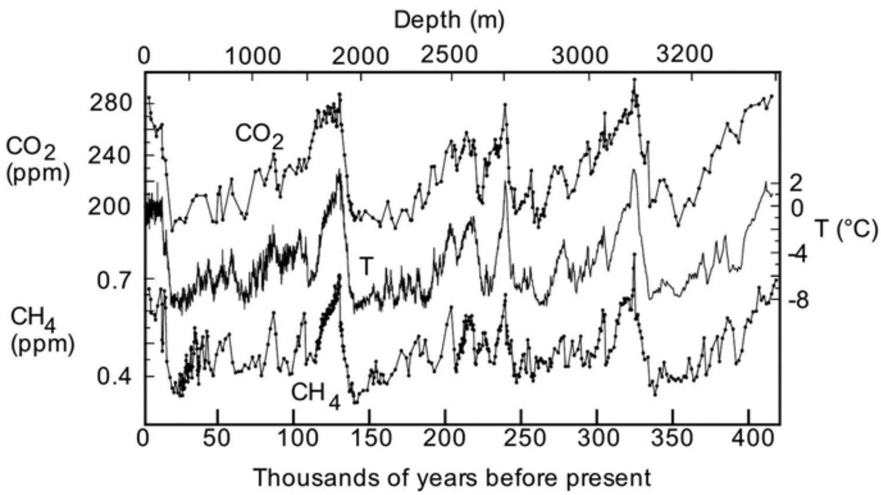

Figure 4.16. Vostok (Antarctica) record of CO_2, CH_4, and temperature (from δD) (Petit *et al.*, 1999).

800 ± 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 could provide positive feedback and thus be both a primary effect and a secondary cause.

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 of the 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 ppm–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 the glacial cycles. Carbon in the terrestrial biosphere is available on shorter timeframes, 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 the atmospheric CO_2 change is the oceans, which can hold enough carbon to absorb the atmospheric decrease and can change on 1,000-year 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 (GICCs). 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 indicated that pCO_2 is extremely sensitive to the biological pump in 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 the 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 ppm to 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 $\sim$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 marine 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—involving an increase in the 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) Reduced ventilation of CO_2—of water exported to the deep Southern Ocean, either via sea ice "capping" or a change in ocean interior mixing efficiency.
(3) 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), each of these approaches has difficulties individually 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 the 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 the sea ice coverage to maximize 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.

Skinner (2006) emphasized that one factor from these models that emerges as being fundamental is the competition between carbon export from the surface of the 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 into 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 deepwater 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 the oceans' physical carbon pump. Any model to explain the GICC must provide scenarios for these oceanic processes.

A website (*www.atmos.umd.edu/~cabo/METO658A/dlove.ppt*) provides a number of interesting new ideas regarding GICC that are beyond the scope of this book.

4.6 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 4.11). 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 the slowly changing solar input, and hence scientists have sought explanations outside the realm of 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 years ago). 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 4.17 shows the numbered Heinrich events that occurred over the past 100,000 years. Wilson *et al.*

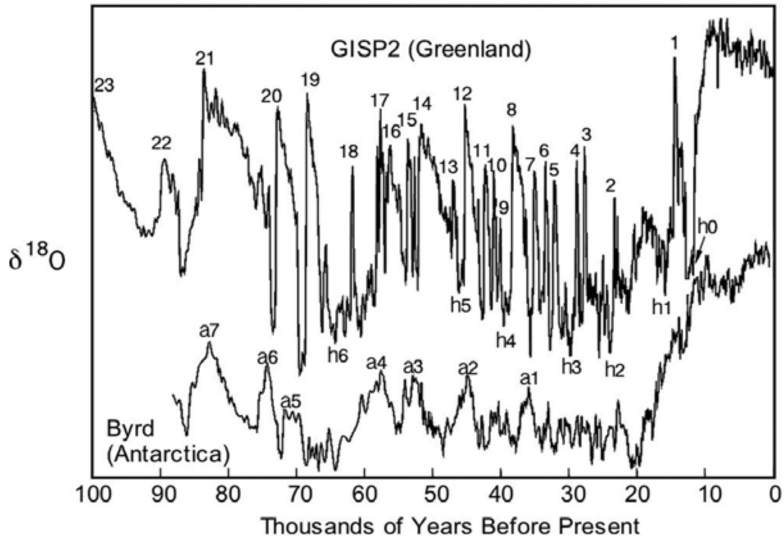

Figure 4.17. Sudden climate change events at Greenland and Antarctica: numbered peaks are D–O events; h-numbered minima are Heinrich events; and a-numbered events represent warming at Antarctica (adapted from Alley, 2007).

(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 the longer term glacial–interglacial cycles. This implication does not seem to have been emphasized by the 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 the ice sheets (see Figure 4.4). The main cooling event that marks the beginning of the Younger Dryas seems to have occurred within less 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.*, 1997; Adams, 2002).

The start of the present warm phase, 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 two thousand more years to disappear completely. The Earth entered several thousand years of conditions warmer and moister than today; the Saharan and Arabian deserts almost completely disappeared under vegetation cover, and in the 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 years ago (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, changes in atmospheric concentrations of greenhouse gases or haze particles, and changes 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, we observe smaller climate variations such as the Medieval Warm Period and the 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 EEM interglacial period and it is not clear how the EEM 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 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 timescales remains open to discussion, particularly because timescales have typically been "tuned" by comparison with astronomical theory.

According to Bruckner (n.d.):

> "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 ($CaCO_3$). The carbonate, originally dissolved in the oceans, contains oxygen, whose atoms exist in two naturally occurring stable isotopes, ^{18}O and ^{16}O. The ratio of these two isotopes is dependent on past temperatures. When the 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 subtropics) 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 more and more 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.

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

If calcium carbonate (of a marine organism) 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 sea bed 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 a 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 dating 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:

$$T = 16.9 - 4.2(\delta c - \delta w) + 0.13(\delta c - \delta w)^2$$

where T is the water temperature (°C) in which the sample precipitated; δc is the departure from current standard seawater of $\delta^{18}O$ in the carbonate sample; and δw is the departure from current standard seawater of the water in which the sample precipitated. While δc can be measured accurately, it is difficult to estimate δw 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 δc due to colder sea surface temperatures during glacial times is complicated by the increase in δw.

By analyzing the isotopic records of deep-water organisms, one can attempt to resolve how much of the increase in δc 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 (~ -1°C to 2°C) have changed very little since glacial times (the last glacial maximum being about 20,000 years ago) and increases in δc 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 sea beds 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 probably measures primarily total ice volume. 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 a simple temperature interpretation of δc 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 with an accurate age model from benthic $\delta^{18}O$ records, 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 the 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:

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

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 m to 15 m, in contrast to the depth of up to 3,000 m in ice cores. The standard used in this case is not Standard Mean Ocean Water (or SMOW), but instead is the so-called PDB, which was 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).

Muller and MacDonald (2000) (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 meters 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 meters. 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. 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 can 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 δ^{18}O of foraminiferal calcite tests provide an important record of climate change. Foraminiferal δ^{18}O is a function of the temperature and δ^{18}O of the water in which it forms, and the δ^{18}O of seawater is a function of global ice volume and water salinity. (The scaling between δ^{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 δ^{18}O records and the global nature of the ice volume signal, δ^{18}O measurements also serve as the primary means for placing marine climate records on a common timescale. Stacks, which are averages of δ^{18}O records from multiple sites, improve the signal-to-noise ratio of the climate signal and make useful alignment targets and references for comparison. Benthic δ^{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 δ^{18}O change. While a stack alone cannot [resolve] the relative contributions of ice volume and temperature to the benthic

[1] J. D. Wright provided a similar estimate at *http://geology.rutgers.edu/~jdwright/JDWWeb/2000/Wright2000.pdf*

$\delta^{18}O$ signal, a good stack does provide an accurate estimate of how much total change must be explained'' (Lisiecki and Raymo, 2005) (L&R).

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 astronomical theory, and if that is done it reduces the value of the data as a test for 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 last interglacial high temperature which other evidence now suggests was about 135,000 years ago. 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 to this point based on radiometric (K/Ar) age estimation of the polarity change in lava flows as 780,000 years. 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 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 L&R 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 timescale 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 $\gtrsim$50,000 years. John Imbrie is perhaps the world's leading expert on 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 astronomical theory is usually referred to as "orbital tuning".

Tuning was proposed initially by Hays *et al.* (1976). Their tuning procedure adjusted the timescale 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 timescale for ocean sediments (and ice cores as well) is to test theories that purport to explain the occurrence of, and transitions between, glacial and interglacial periods, particularly with 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 much of the reported timescales in many papers are primary and independent, and how deeply tuning has penetrated into adjustment of the timescales.

In order to convert the depth scale to a timescale, 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 L&R who relied on previous chronologies over the past 135,000 years by graphically comparing features with previously dated sediment studies:

- The top 22,000 years of the stack were dated by correlation of key features to a previous ^{14}C-dated benthic $\delta^{18}O$ record, assuming that all ocean sediment sites display the same features at the same times.
- From 22,000 to 120,000 years ago, 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$135,000 years ago.

They 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 the ice sheets (as inferred from the derivative of the isotope record) was expressed in terms of a forcing function: the calculated insolation curve for 65°N, with two parameters that were adjusted with age 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, L&R adjusted the two constants (B and T) in the Imbries' model to increase with time toward the present because the data suggest a long-term

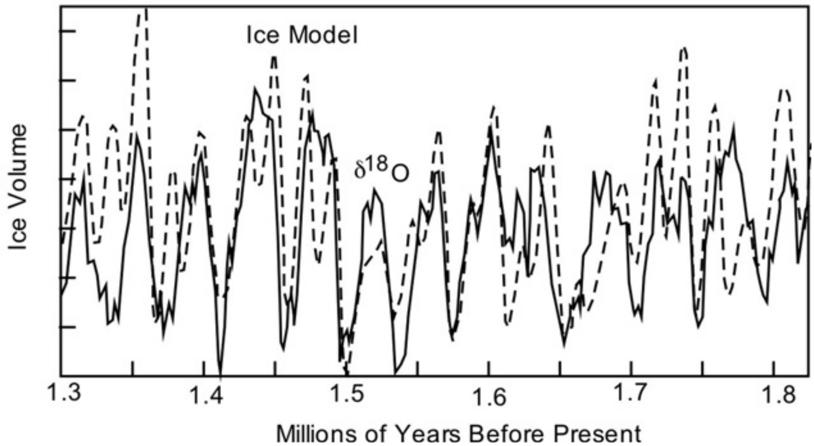

Figure 5.1. Fit of a portion of the $\delta^{18}O$ curve to the ice model of L&R.

increase in global ice over the past few million years. Whereas the Imbries found a best fit with $B = 0.6$ and $T = 17{,}000$ years for the time period over the past 150,000 years, L&R used $B = 0.3$ and $T = 5{,}000$ years for the time period from 5.3 million to 3.0 million years ago, a linear increase to 0.6 and 15,000 years from 3.0 million to 1.5 million years ago, and constant values of 0.6 and 15,000 years from 1.5 million years ago to the present. This had the effect of compressing the timescale at early times, and stretching it out at more recent times. Then, by overlaying the $\delta^{18}O$ curve on the ice model curve, they established a timescale 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 Imbries' 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 Imbries' model were adjusted to get a best fit. Furthermore, the absolute timescale is tied to the astronomical theory via the Imbries' ice model with arbitrarily chosen parameters. This approach seems to lie somewhere between mathematical curve fitting and a physical model but it is not immediately obvious where it lies between these extremes.

Evidently, it would be extremely desirable to develop a chronology that does not depend upon 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 to apply that insight to construct a timescale 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, which they termed ''depth-derived ages''. However, it was claimed that none of these was 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

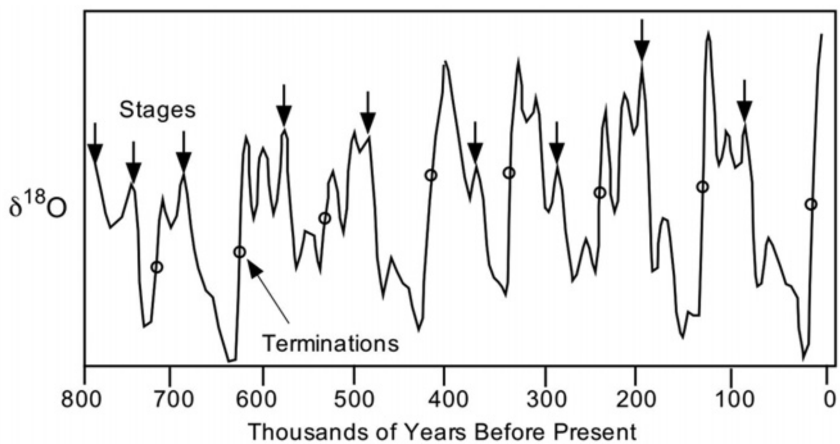

Figure 5.2. Assignment of stages and terminations by H&W. Stages are designated by arrows and terminations are defined by circles.

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) a 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 ten 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 location was constant and the timescales were chosen for each to make the ice age terminations (vertical dashed lines) occur at roughly the same times. The fact that the terminations do not line up precisely with each other suggests that the sedimentation was not perfectly constant for each record. M&M concluded that it is remarkable that the pattern of oxygen isotope variations appears to be so similar around the world. It is noteworthy that the terminations of the ice ages often appear to be abrupt.

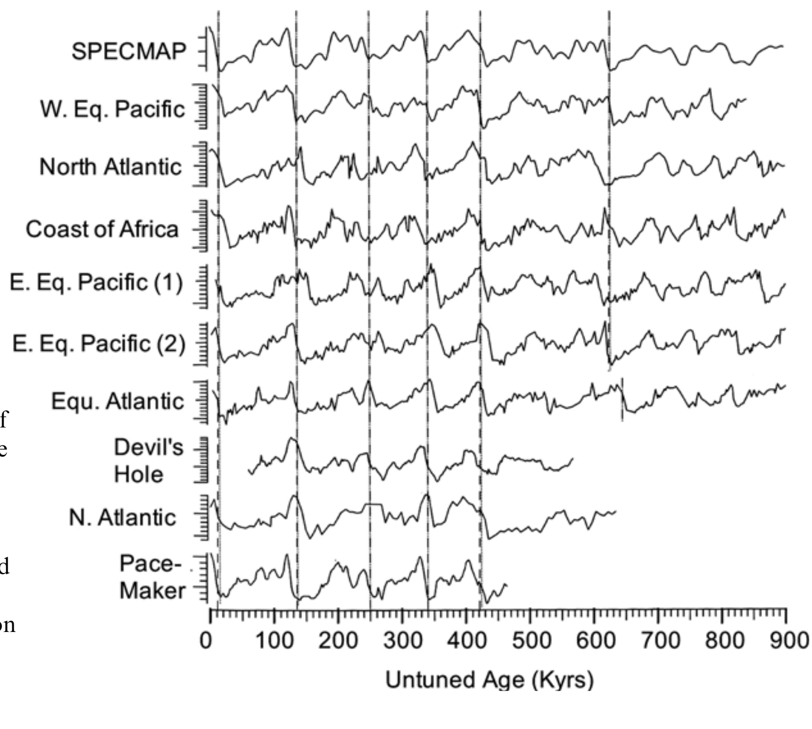

Figure 5.3. Universality of oxygen isotope patterns from forams from around the world (adapted from M&M with permission of Praxis Publishing).

5.4 SUMMARY OF OCEAN SEDIMENT ICE VOLUME DATA

An influential early attempt to extract the underlying ^{18}O signal from multiple records is called 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 indicated with an odd number, beginning with the present as Stage-1, and counting backwards. The 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.

Over a longer time period, the data from a stack of 57 records are shown in Figure 5.6.

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 oceans' oxygen isotope composition because the ice sheet contains an excess of ^{18}O, leaving 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, which 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°C to 3°C colder than today. Bintanja *et al.* (2005) developed an

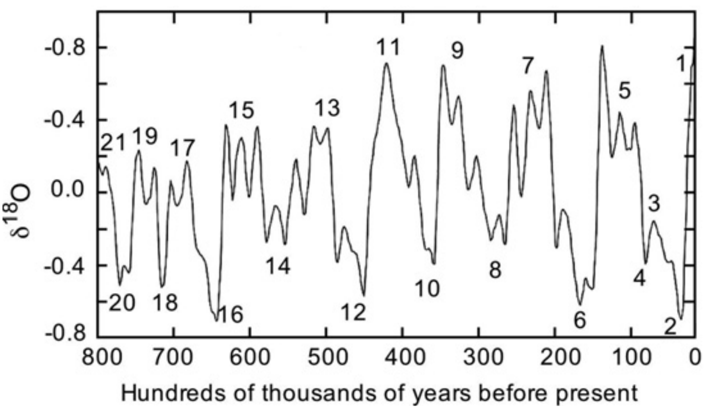

Figure 5.4. SPECMAP showing marine isotope stage numbers (adapted from M&M by permission of Praxis Publishing).

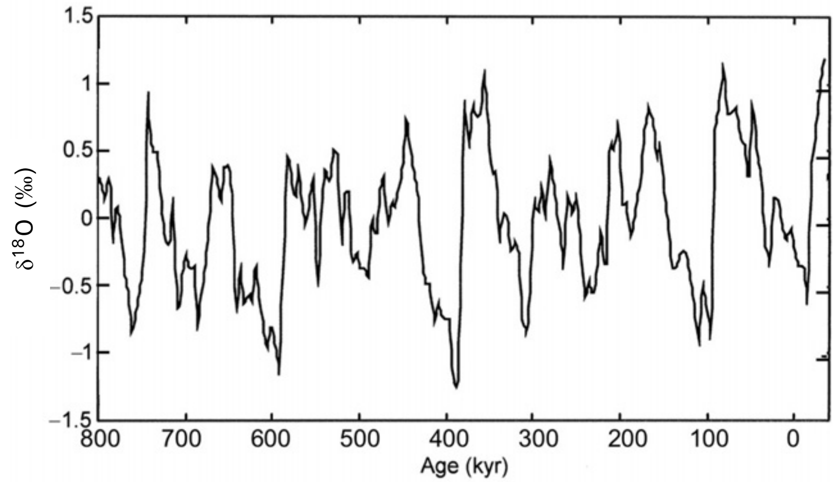

Figure 5.5. $\delta^{18}O$ for Site 806 (adapted from M&M, p. 257 with permission of Praxis Publishing).

alternative model for estimating the contributions of each of the two major effects. They argued that on glacial–interglacial timescales, the main contributors to the mean benthic oxygen isotope record—the northern hemisphere ice sheet isotope content and the local deep-sea temperature—are both strongly related to northern hemisphere mid-latitude to subpolar 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 L&R that 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 COMPARISON OF OCEAN SEDIMENT DATA WITH POLAR ICE CORE DATA

In previous sections, we presented isotope data from Greenland ice cores, Antarctic ice cores, and ocean sediments. Greenland ice cores date back as far as about 140,000 years. Antarctic ice cores date back as far as 400,000 to 800,000 years, and ocean sediment data date back beyond 2.7 million years.

The 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 the total ice volume on the Earth.

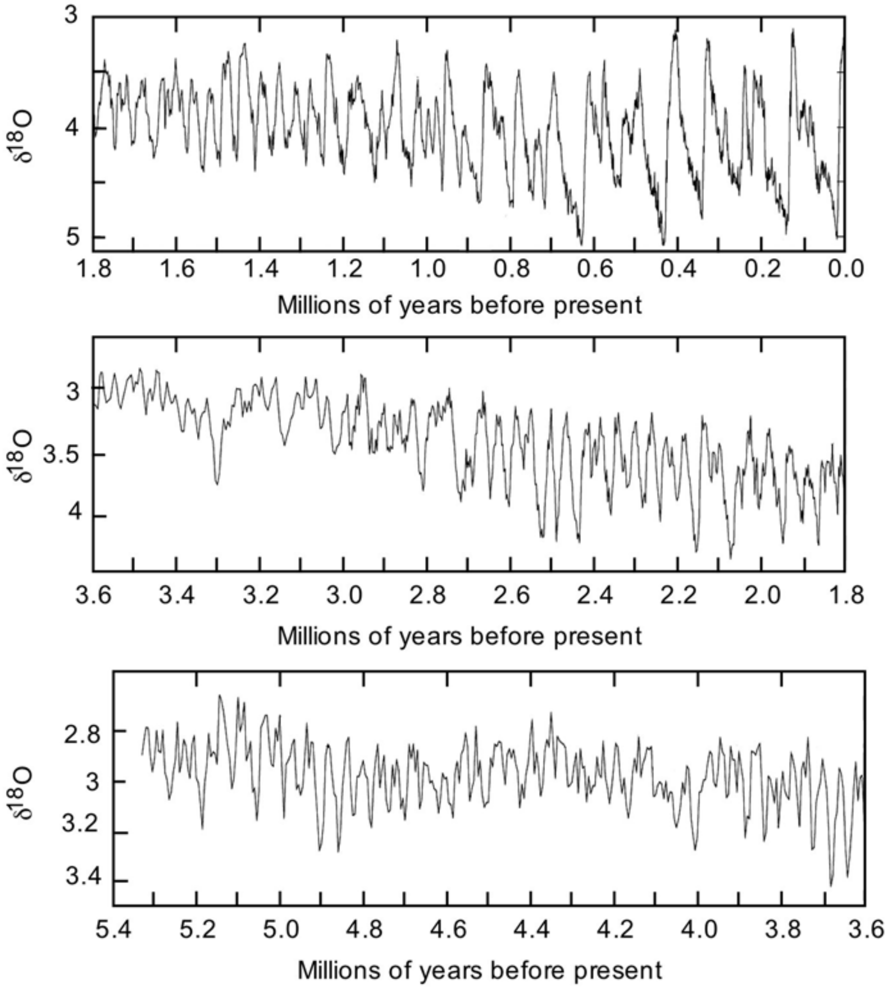

Figure 5.6. Isotope data from a stack of 57 records as derived by L&R.

The raw data from Greenland and Antarctica are predominantly time series of $\delta^{18}O$ and δD, 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 Imbries' 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). Furthermore, the ice volume is an integral over relatively rapid variations in solar intensity that lead to slower variations in the ice volume. Therefore, one might expect *a priori* that the 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

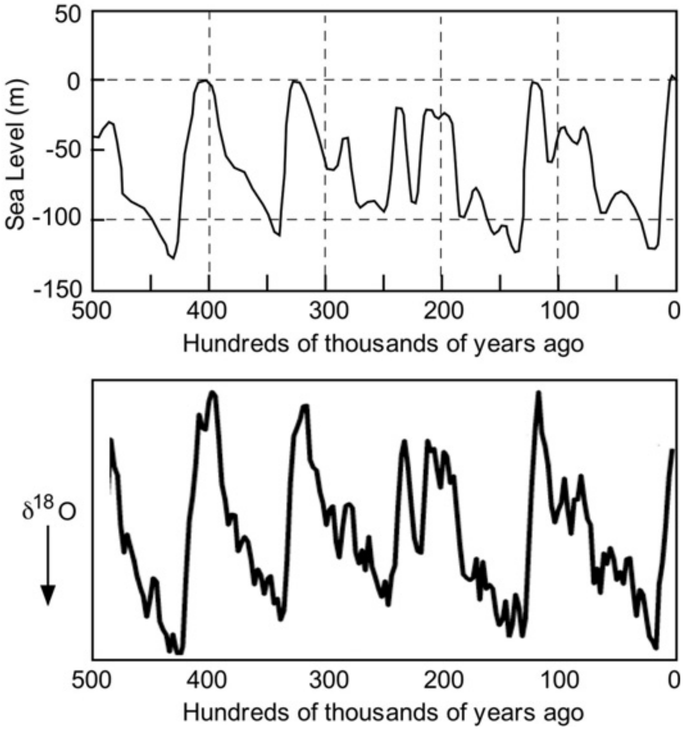

Figure 5.7. Comparison of the variation of $\delta^{18}O$ data from L&R (lower graph) with estimated sea level (inverse of ice volume) from Bintanja *et al.* (2005) over the past 500,000 years (upper graph).

smoother and show less high-frequency variation; however, some of this is due to averaging of a "stack" of data from different localities. But there is no evidence at all of significant time lags between these datasets. This indicates 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 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.

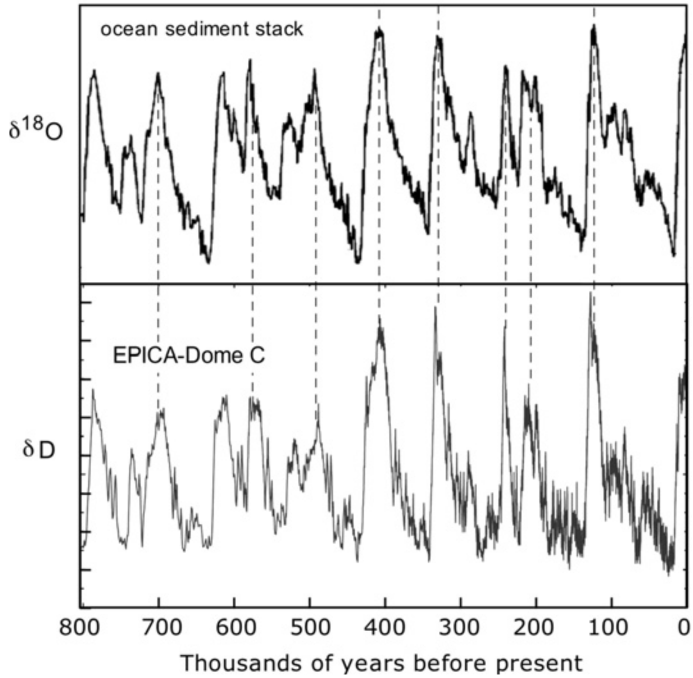

Figure 5.8. Comparison of ocean sediment data (L&R) with Antarctica EPICA Dome C data. Vertical scales represent the D isotope ratio at Antarctica and the O isotope ratio in ocean sediments.

However, L&R seemed comfortable with benthic and Antarctic time series overlaying one another.

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. Imbrie and Kipp (1971, 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. Imbrie and Kipp (1971, 1976) developed a mathematical relationship that related water temperature to 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, we might consider the full range of ocean temperatures. 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. And in fact, the results indicated that sea surface temperatures were 2°C–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 makeup 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—with various methods 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 the 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 the icebergs break up or turn over. Eventually, all the incorporated debris becomes 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 grains per gram of sediment, and size of the largest dropstone 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 ground-water discharge area in south-central Nevada; it is located approximately 115 km west-northwest 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 ground water. 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 timespan 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 ground-water recharge tributary areas to Devil's Hole. The 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 radioactive isotopes of uranium and thorium. (^{238}U decays to form ^{230}Th, which decays with a half-life of 77 kyr; 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-spectrometric (TIMS) uranium series

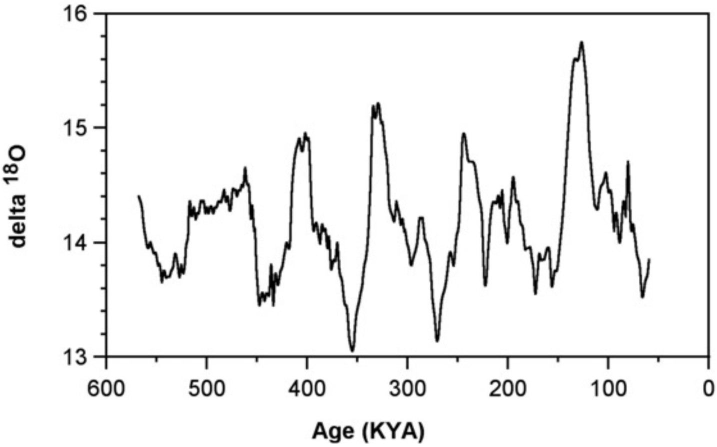

Figure 6.1. Measured oxygen isotope variability at Devil's Hole (Landwehr *et al.*, 1997).

methods (Ludwig *et al.*, 1992). The dating has been independently verified using ^{231}Pa analyses. These data are unique among 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 Comparison of Devil's Hole data with ocean sediment data

When Winograd *et al.* published the first major Devil's Hole paper in 1992, these authors pointed out that there appeared to be several discrepancies between the timing of glacial–interglacial transitions and the predictions of astronomical theory, suggesting that astronomical theory had deficiencies. Imbrie *et al.* (1993) (noted defenders of astronomical theory) immediately responded with a rebuttal. They argued that if the Devil's Hole chronology is 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).

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

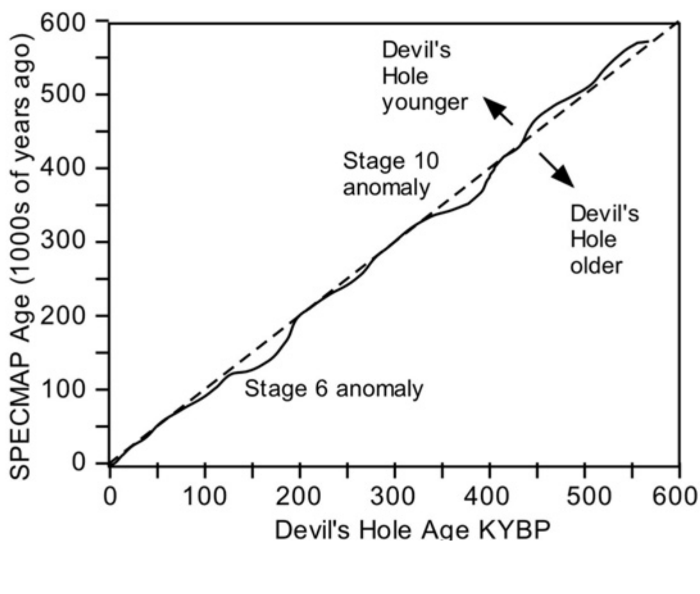

Figure 6.2. Comparison of ages from Devil's Hole with ages from SPECMAP.

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 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 two thousand 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 the ices ages as determined in their paleoclimate record that cannot be reconciled with astronomical theory. In addition to the problem of timing, W&L pointed out that the Devil's Hole record indicates three other challenges to astronomical theory: (1) the duration of interglacial climates is closer to 20 kyr than to the predicted 10 kyr duration; (2) the length of glacial cycles increases steadily as one comes forward in time which is inconsistent with the assumption of a quasi-100 kyr cycle; and (3) a well-developed glacial cycle occurs in the period 450,000 to 350,000 years ago at a time when astronomical theory indicates none should occur.

6.1.3 Devil's Hole: global or regional data?

Questions were also raised regarding whether the 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 (SSTs) 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 paleotemperatures. 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 astronomical theory and utilizes "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 Comparison of Devil's Hole data with Vostok data

This section is based on the paper by Landwehr and Winograd (2001). We will refer to this reference as "L&W".

Most ice cores, including those from Vostok, cannot be radiometrically dated, and 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, as well as some combination 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 in the critical time period of the termination of the previous ice age, as shown in Figure 6.3.

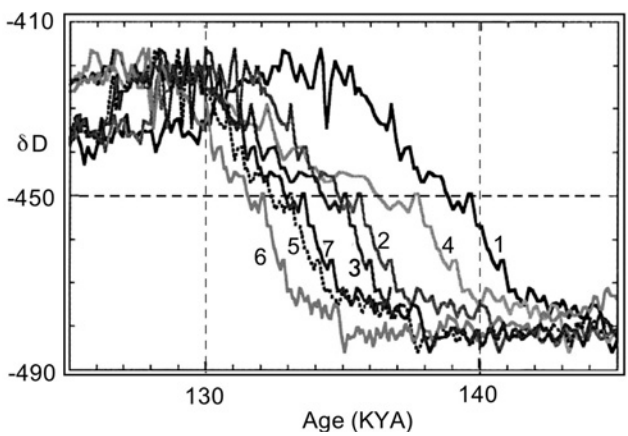

Figure 6.3. Vostok δD chronologies during the deglaciation of about 135,000 years ago as derived by seven different investigations (L&W).

While L&W provided reasons why the Devil's Hole $\delta^{18}O$ and the Vostok δD records should be proxies for the same physical phenomenon, they raised the question as to whether these two paleotemperature 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 despite 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 chronological overlap.

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 in Greenland alone, so they suggested that one should consider 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 the comparable relative magnitude are underway 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. The extrapolation of the Vostok age–depth curve to greater depths is suspect because the layering was disturbed by dynamic ice processes.

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.

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.

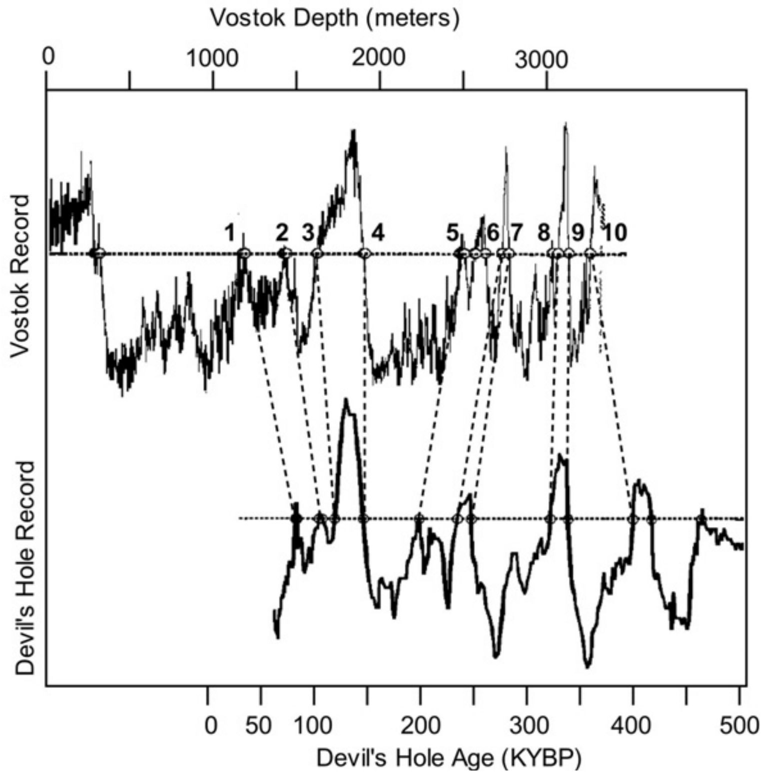

Figure 6.4. Alignment of Devil's Hole transition points with Vostok transition points.

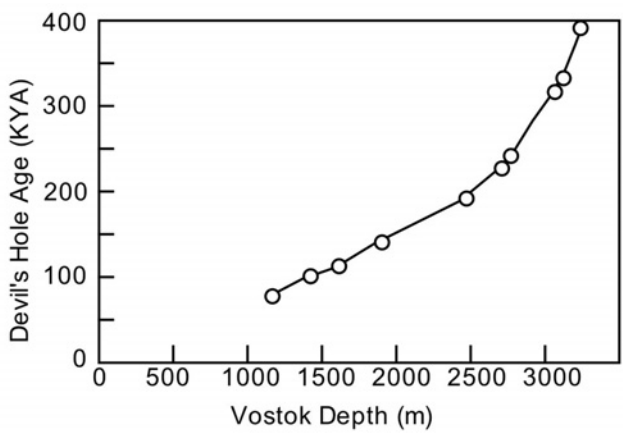

Figure 6.5. Vostok age vs. depth inferred from Devil's Hole.

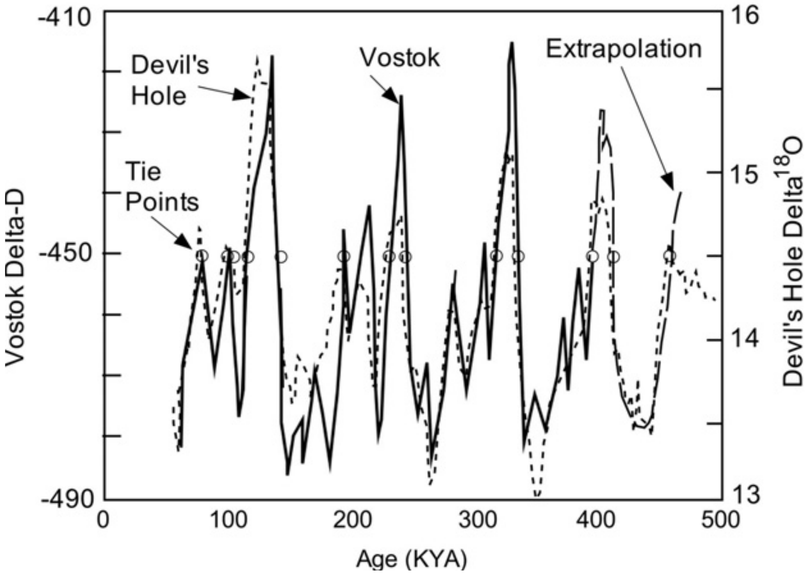

Figure 6.6. Relationship between Vostok data and Devil's Hole data based on Devil's Hole chronology.

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 years ago (Yuan *et al.*, 2004). This cave is located in China at 25°N latitude. Stalagmites were collected 100 m below the surface, 300 m and 500 m from the entrance, with diameters varying between 12 cm and 20 cm. Stalagmites were subjected to oxygen isotope analysis and ^{230}Th dating by thermal ionization. The resultant time series of δ^{18}O bore some similarity to δ^{18}O data from the GISP2 ice core over the past ~70,000 years.

Precipitation of δ^{18}O at this cave site is believed to be largely a measure of the fraction of water vapor removed from airmasses 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 inter-glacial 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 aage. They found a large sudden increase in precipitation at 129,000 years ago, a fairly constant level of high precipitation from 129,000 to 120,000 years ago, and a large sudden decrease in precipitation at 120,000 years ago.

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 140,000 years ago to 133,000 years ago, high temperatures persisting from 133,000 years ago to about 121,000 years ago, and a sharp decrease in temperature from about 121,000 years ago to 112,000 years ago. 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

Magnetic properties of thick (100 m–300 m) deposits of windborne 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 the ice cores, they are a potential source of continental paleoclimate information for non-Arctic land regions.

When sediment is deposited, the magnetic particles within the sediments 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 the 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 timescale, 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. The increased magnetic susceptibility values may result (in principle) from either a higher concentration of magnetic iron-bearing minerals in the interglacial windborne dust, or formation of such minerals from pre-existing non-magnetic or magnetic materials, as a result of chemical changes during soil formation.

A number of papers have been published reporting studies of 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 magnetic susceptibility in rocks buried in lake sediments provide a proxy record of past temperatures. However, the description of how it

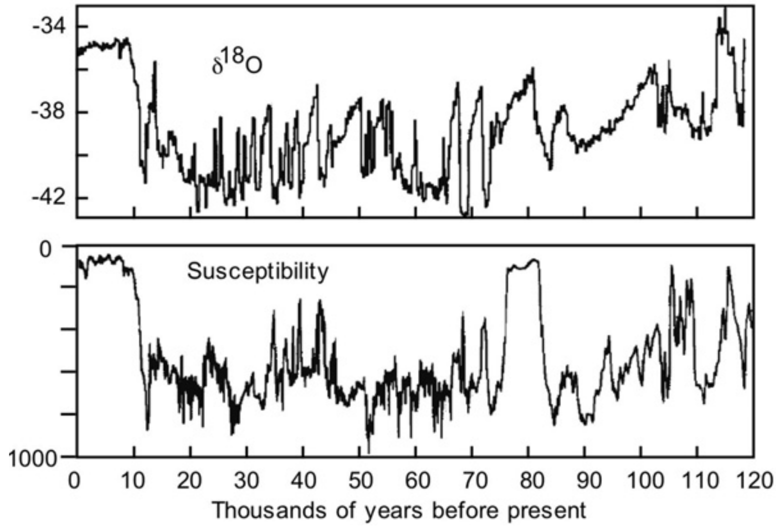

Figure 6.7. (Upper panel) $\delta^{18}O$ from GRIP in Greenland. (Lower panel) Measured susceptibility of lake sediments in France.

works is not very clear. There exist so-called *maar-diatreme phreatomagmatic explosion craters* that form when magma rises close to the surface and interacts explosively with ground water. 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 of length >50 m were taken. It was claimed that past cold climates tended to preserve residual magnetism in the rocks in the 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 the Greenland ice core measurements, suggesting that 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, and 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 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 years ago the only trees were birch, with a small amount of willow and juniper. Birch pollen probably indicates tundra (mostly dwarf birch). There was also sedge, grass, and herb pollen. Starting around 9,600 years ago, 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 varieties 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).

Paul 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 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 the 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 last 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 would only be 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. Corals can be dated by radiocarbon for the past 40,000 years and by the formation of ^{230}Th through 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 icecaps at historical times. Since the oceans are presently roughly 100 meters 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 ^{230}Th/^{234}U ages on corals from raised shorelines in many locations in the tropics revealed a prominent high stand of the sea with an age of about 124,000 years. These radiometric methods depend upon the presence of *Acropora palmata*, which is known to grow only within two meters 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, with 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.

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 the solar input to high northern latitudes minimized around 138,000 years ago, peaked around 125,000 years ago, and minimized again around 114,000 years ago. Based on solar input alone, one would expect a time lag for maximum sea level after peak solar intensity, so one might guess that astronomical theory would predict a maximum sea level somewhat more recently than 125,000 years ago. Figure 9.15 shows that according to the Imbries' model for ice volume based on integration of solar intensity, the ice volume would have had an intermediate peak at around 137,000 yeas ago, and would have minimized about 120,000 years ago. Thus astronomical theory seems to point to a high water mark at around 120,000 years ago 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 years ago and sea level began rising at around 140,000 years ago when solar intensity was low. This led M&M to conclude that there is a "causality problem" with astronomical theory. 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 6.8. With this change, the peak sea level is reached around 128,000 years ago, but sea level nevertheless began rising at around 135,000 years ago, when 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

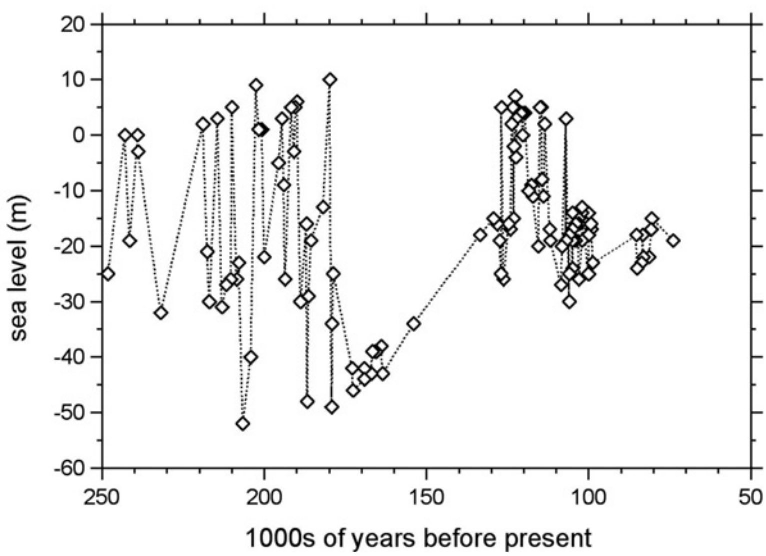

Figure 6.8. Estimates of sea level by Thompson and Goldstein (2005) with ages calculated from open-system equations.

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.''

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 last glacial maximum. In most places, the lowering was in the range 830 ± 70 meters, 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 the pollen grains extracted from the sediments of mountainside lakes and bogs.

Over the last three decades, ice core records have been recovered from ten high-elevation ice fields, nine of which are located in the lower latitudes. These ice core histories provide evidence that the growth and decay of large ice fields at lower latitudes are often asynchronous, both between the 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 at 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 past variability of sea level using dynamic models for the Red Sea and its interchange with the oceans at large.

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 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.

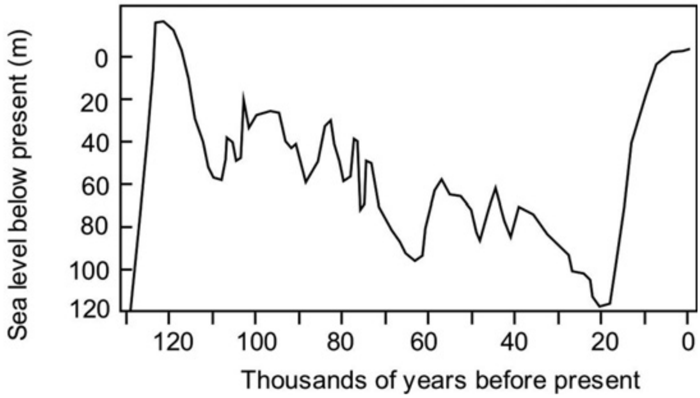

Figure 6.9. Smoothed data on sea level based on Red Sea sediments and coral terrace data (Siddall *et al.*, 2003).

This amplification was previously used to calculate sea level low stands at times of maximum glaciation during the past 500,000 years ago (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 the 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 Bab el Mandab, 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 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 6.9.

Almogi-Labin (n.d.) 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 a 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 eolian dust content in sediments.

7

Summary of climate variations

7.1 ORIGIN OF GLACIATION—PAST 34 MILLION YEARS

This topic is discussed in Section 2.3.2. About 55 million years ago, Australia began to drift northward away from Antarctica. By 34 million years ago, a circumpolar ocean current developed around Antarctica which 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 million years ago, the temperature of the Earth has been on a generally downward path, permeated by significant oscillations.

7.2 THE PAST 3 MILLION YEARS

An event that occurred around 3 million years ago was the gradual closing of the Isthmus of Panama and isolation of 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 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. Hence this thermohaline circulation was enhanced by closure of the Isthmus of Panama. As moisture was provided to higher northern latitudes, ice sheets built up in the north. 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 million years ago) the oscillations were rapid (period $\sim$40,000 years) and of moderate amplitude. In the past million years, the period

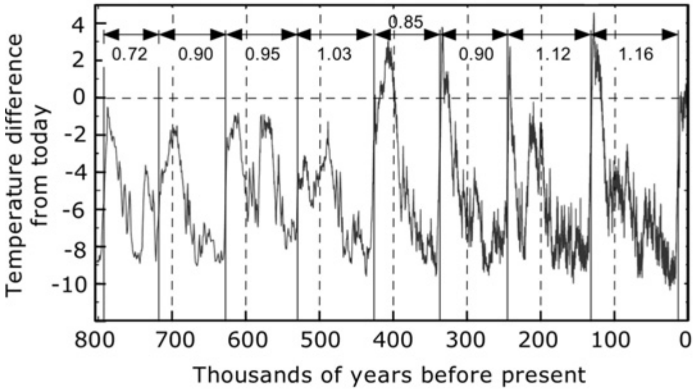

Figure 7.1. Copy of Figure 4.9 for Vostok ice core data showing the spacing between rapid terminations in millions of years.

of the oscillations gradually increased to about 100,000 years and the amplitude increased significantly.

7.3 THE PAST 800,000 YEARS

Over the past 800,000 years, the Earth has undergone about 8 major cycles of glaciation and deglaciation spaced at roughly 100,000-year intervals. These are shown in Figures 4.10, 4.11, 5.2, 5.4, and 5.5. The trend has been for long, slow accumulation of ice in northern ice sheets while the Earth cooled, followed by a 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). The amplitudes of the oscillations increased significantly over that period.

7.4 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 145,000 years ago, leading to the so-called EEM interglacial from about 135,000 to about 115,000 years ago, followed by a build-up of ice sheets in the last ice age from about 115,000 to about 20,000 years ago. This ice age was permeated by numerous very sharp, but short-lived 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 20,000 years ago when glaciation was at a maximum, went through a significant "bump" around 16,000

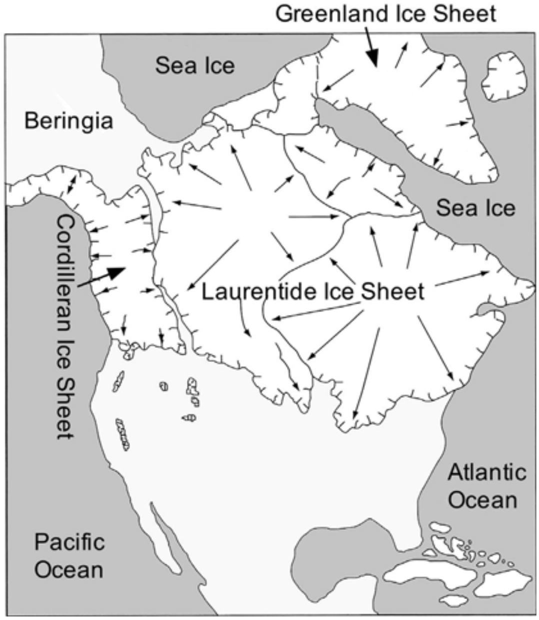

Figure 7.2. Extent and movement of great ice sheets during the last glacial maximum (Burroughs, 2005).

years ago, and then rapidly accelerated to Holocene conditions around 10,000–11,000 years ago.

One 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°N to 65°N, sufficiently high enough to be cold but sufficiently low enough to have access to airborne moisture (see Figures 2.8 and 7.2).

It is noteworthy 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."

7.5 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 continental ice sheets and mountain glaciers stood at or close to their maximum extent. The oxygen isotope ratios and dust content of polar ice still had their full glacial values. Sea level stood ~110 meters 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, 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 as a 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, 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. Seemingly the interglacial had 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 (i.e., the Younger Dryas).
- *~10,000 years ago the cold snap abruptly ended.*

Since then, interglacial conditions have remained continuously.

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 timescale is blurred by several thousand years. Hence, unlike ice cores, marine sediments are unable to detect sudden climate changes, and marine sediments 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 (e.g., see Figures 4.2, 4.3, and 4.4). Broecker (2002) also cited corroborating data from the sediments of a small Swiss lake called Gerzensee, 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 melt water 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.

7.6 NORTH–SOUTH SYNCHRONY

The relationship between climate variations in the NH and the SH can be elucidated by comparing the chronologies of 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 4.14 and 4.15. There appears to be a correlation between major climate changes at Greenland and Antarctica. Sudden temperature increases at Greenland were preceded by rather slow moderate temperature increases in Antarctica for a few thousand years. If there is a causal relationship between these events, it seems likely to involve the thermohaline flow of the oceans.

7.7 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 increasing with rising global temperature and *vice versa*. In particular, CO_2 seems to vary from about 180 ppm to 190 ppm at the height of glaciation, to about 280 ppm to 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 be simply 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 million years ago to the 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 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 ..."

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 deglaciation. We may 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 orbital parameters—quasi-periodic variations in eccentricity, obliquity, and precession of the equinoxes produce changes in sequencing of solar intensity to higher latitudes that 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 in individual parameters, eccentricity, obliquity, precession of the equinoxes, one at a time or pairwise.
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 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 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 albedo of the Earth, which, in turn, is controlled by the degree of cloudiness that goes through repetitive cycles due to ocean–atmosphere interactions.

By far, the greatest amount of effort and attention has been addressed to variability of Earth orbital parameters as the forcing function for glacial–interglacial cycles, and this model is widely accepted among scientists. Thus we devote the entire 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. The 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 $\sim$70-year period toward the end of the 17th century. This period is known as the "Maunder Minimum" and may be associated with unusually cold temperatures (Rapp, 2008). In addition, the length of the solar cycle has varied from about 9 to

13 years. These provide indications that the appearance and activity of the Sun pass through 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 TSI is an important part 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 in time for about 100 to 300 years. A few go back as far as several thousand years. None of the models provides estimates over a long enough time period that it can 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 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 ASTRONOMICAL THEORY

Astronomical theory does not depend on any innate variability of TSI, but rather, it depends on small quasi-periodic "wobbles" in the Earth's orbit about the Sun that produce changes in solar input to high latitudes. Even though the total solar input falling on the Earth may not change, the quasi-periodic changes in the distribution of solar input to the 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 the changes in the Earth's orbit over the past million years or so, and thereby to estimate the changes in solar input to high latitudes.

While astronomical theory is based on the general hypothesis that variability of solar input to high latitudes is the forcing function for glacial–interglacial cycles, the specifics of how this variability manifests itself in producing 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, clouds, precipitation, winds, changing ocean and land albedo, ocean currents, eolian 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 Greenland ice cores have been much sharper and more sudden than the 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.

Astronomical theory is the most widely used, discussed, and accepted of the theories of ice ages, and 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). Volcanoes can be classified as to size by various indices. In regard to climate change induced by volcanic eruptions, the most important factor is the radiative forcing due to 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 (AD 1980) emitted from the side of the mountain and relatively little material was injected into the stratosphere, so it had only a minor effect on global climate. The *volcano explosivity index* (VEI) is measured 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 ten in magma volume emitted. The largest volcano in the past 250 years was Tambora (VEI $\sim$ 7) in 1815.

Volcanic eruptions can inject into the stratosphere tens of teragrams of chemically and microphysically active gases and solid aerosol particles. 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 the sulfate aerosol particles have an effective radius of about the wavelength of visible light, they interact more strongly with short-wave incident solar radiation than the long-wave radiation emitted by the surface and atmosphere. Some incident sunlight that is back-scattered is 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 a location (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 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

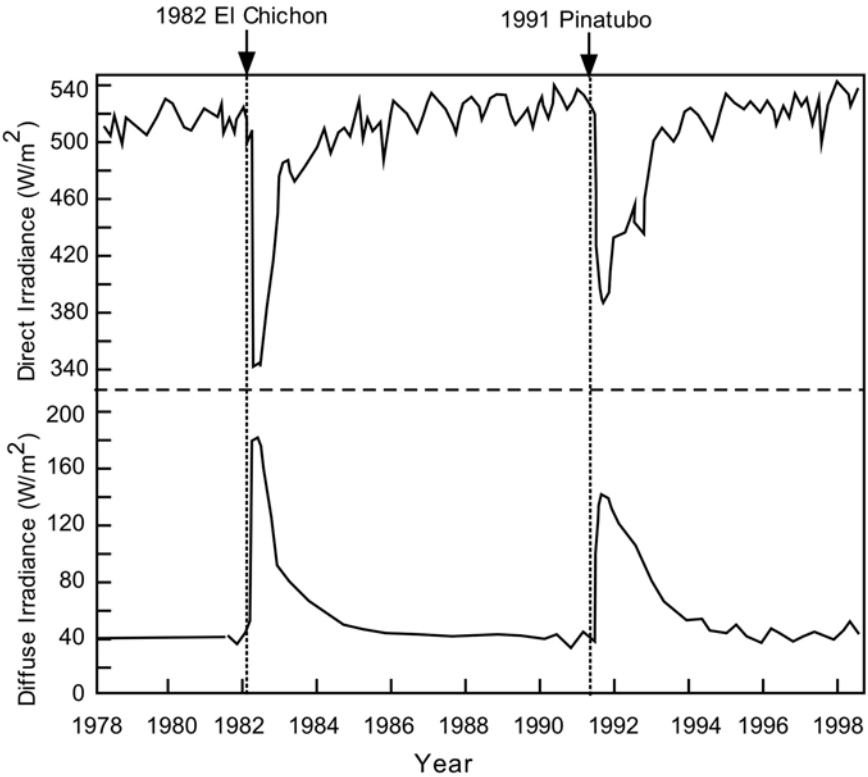

Figure 8.1. Direct and diffuse solar irradiance measured at Mauna Loa following volcanic eruptions at a solar zenith angle of 60° corresponding to the passage of sunlight through two Earth airmasses (adapted from Robock, 2000).

produces a global cooling. Although the Pinatubo eruption produced a larger stratospheric input, the center of the El Chichón cloud passed directly over Hawaii, while only the side of the Pinatubo cloud was observed at Hawaii (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 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" in 1816 in the NH.

The greatest known eruption of the past 100,000 years was the Toba eruption of about 71,000 years ago. 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—VEI ~ 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 EEM interglacial from about 135,000 to 115,000 years ago, there was a period from 115,000 to 74,000 years ago of meandering Greenland temperature that tended downward, but this ~40,000-year period lacked the wild oscillations that followed from about 74,000 to 20,000 years ago. Two very high–amplitude oscillations occurred around 74,000 and 70,000 years ago in which the Greenland temperature varied by about 20°C in about a millennium. These are also evident in Figures 4.15, 5.2, 5.4, and 5.5. The ice core records suggest that the two wild climatic oscillations from 74,000 to 70,000 years ago provided a pivotal turning point when the climate turned 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 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 1/5 as much aerosol material as Toba, and it is estimated that this led to a decrease of about 0.7°C 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°C–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 in the NH average temperature decrease. Thus summer temperature reductions 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 $74{,}000 \pm 3{,}000$ years ago. 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 non-linear climate response.

Dawson (1992) provides 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 100,000, 65,000, and 35,000 years ago. The age of the Guatemalan eruption was inferred to be about 84,000–90,000 years ago. Antarctic eruptions occurred between 30,000 and 16,000 years ago. Major North Atlantic ash deposits (possibly from Iceland) have been identified with an age around 58,000 years ago.

A study of sulfates in Greenland ice cores provided data on volcanic eruptions (VEI > 4) over the past 9,000 years (Zielinski, 1994). During this period, 69 major volcanic events were identified. Nevertheless, it remains unclear whether this volcanic activity contributed 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 in regard to the role of the oceans in climate change—not that there is no role—but rather, that the actual role might be more subtle than the consensus would have you believe.

8.6.1 Glacial–interglacial cycles: the consensus view

We begin the 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 toward the poles. Although glaciation requires cold temperatures that permit ice and snow to remain over summer seasons, it also requires massive amounts of 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 deep-water 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 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):

[1] Actually, as Figure 8.4 shows, the atmosphere transports a great deal more heat than the oceans do, 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 misleading.

[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."

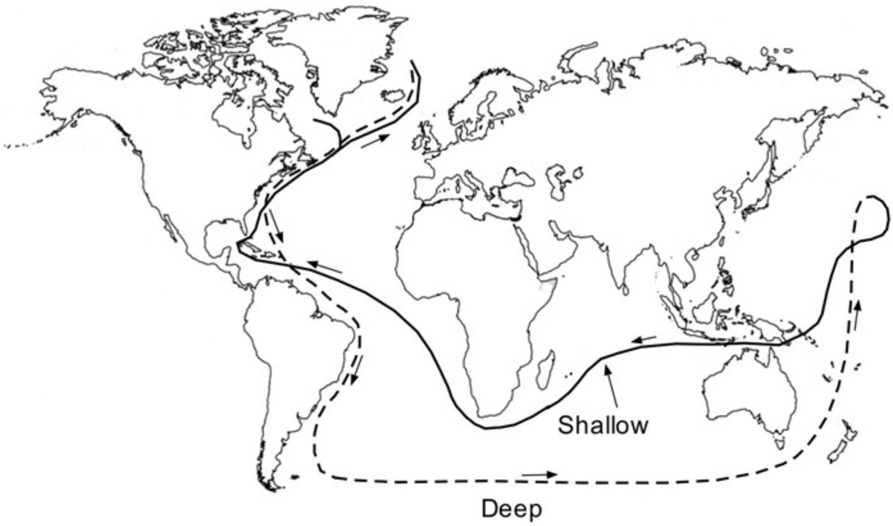

Figure 8.2. Near-surface waters flow towards deep-water formation regions—in the northern North Atlantic, the Ross Sea, and the Weddell Sea—and recirculate at depth (Rahmstorf, 2002).[4]

> "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 overly 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."

[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., December 2008).

Rahmstorf (2002) described ocean circulation (see Figure 8.2). He suggested that at different times three distinct circulation modes prevailed in the Atlantic Ocean, 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. These are illustrated schematically in Figure 8.3. In 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 depth for return to the south. In stadial mode, NADW is formed in the subpolar open North Atlantic (i.e., south of Iceland) and does not achieve the density of interstadial mode, so the return flow is not as deep. In Heinrich mode NADW formation all but ceases and waters of Antarctic 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.

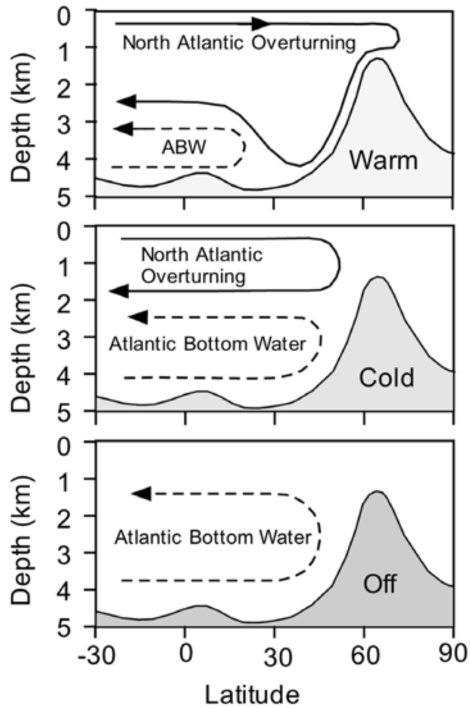

Figure 8.3. Schematic of the three modes of ocean circulation that prevailed during different times of the last glacial period. A section along the Atlantic is shown; the rise in bottom topography symbolizes the shallow sill between Greenland and Scotland. North Atlantic overturning is shown by the solid line, Antarctic bottom water by the dashed line (Rahmstorf, 2002).

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 years ago, although it quickly increased after that. Rahmstorf quoted Paillard's (1998) 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 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) 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 (EEM) 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 (Maslin *et al*., 1999; Alley, 2007). This section relies heavily on these articles, as well as 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 $\sim$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) provided a discussion of several sources of evidence that significant rapid climate changes occurred during the previous (EEM) 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 4.17 and discussed in Section 4.6.

Starting around 1985, 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 switched from its full glacial to its full interglacial condition typically in less 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 airmasses 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 ultimately comes from Gulf Stream water that sinks in the North Atlantic, and 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 sudden changes in glaciation has been discussed by many authors (e.g., Schmidt *et al.*, 2006; and Lehman and Keigwin, 1992).

Dokken and Jansen (1999) analyzed sudden climate changes over the past 60,000 years based on ice core and ocean sediment data. They assumed that Pacific sediment data reflected the global mean glacial/interglacial transitions while high-resolution sediment data from the Nordic seas represent regional variations in that area superimposed on global trends. By subtracting off Pacific trends they obtained the 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 vertical transport of ^{18}O-depleted waters from the surface to the deep. While the usual theory is that convective vertical transport is impeded during glacial periods due to the buoyancy of melt water, another mechanism is required. They suggested it was due to the higher density of brine with 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 thousand 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 at Antarctica. For example, Figure 4.14 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) also 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 visual comparison of curves, 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.

Wunsch (2003) claimed that there is little concrete evidence that abrupt climate changes recorded in 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 the continental ice sheets and that better understanding of wind fields 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 the 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 if 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 of interpretation of abrupt climate shifts that depend on several

[5] I am reminded of an event that occurred in the 1970s. At that time, there was some controversy regarding the altitude where 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 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, the expert 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!"

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.)

In regard to 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., in 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 4.15 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 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 $\delta^{18}O$."

In regard to the first point, Wunsch quoted studies which claim that most of the 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 ~1,000 years is not clear, and wetlands, though dominant, are not the only source of methane. In regard to 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) emphasized that in general, 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. In regard to the "trigger" he presented Figure 8.4 showing the contributions of 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 the heat transport by the atmosphere outweighs that by the oceans by 7:1 at 50°N latitude.

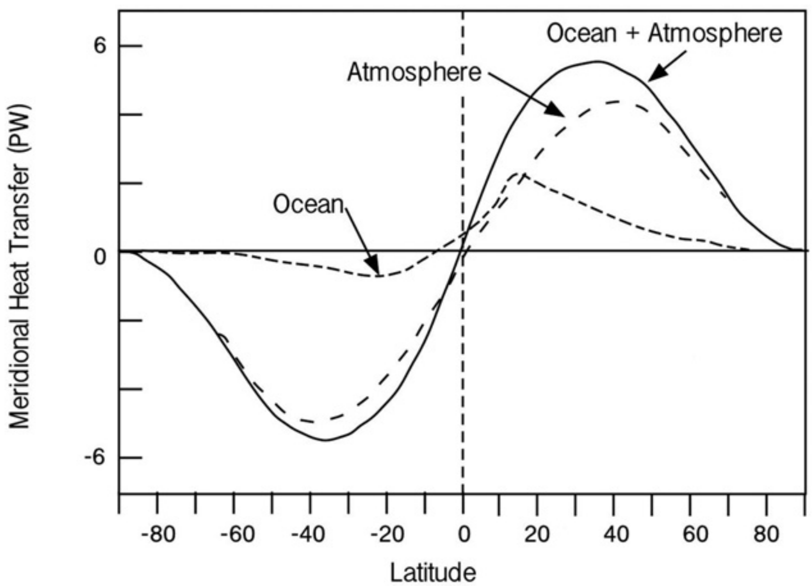

Figure 8.4. Total meridional heat flux of the combined ocean/atmosphere system estimated from Earth Radiation Budget Experiment (ERBE) satellites, direct ocean measurements, and atmospheric contribution as a residual (1 PW = 10^{15} Watts) (Wunsch, 2005, 2006).

The assumption that the prime mover of abrupt climate change is a 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 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 overturning the MOC is the major source of abrupt climate change. But Wunsch amplified this argument by questioning how such a cessation might occur. Inevitably, the theory requires an injection of freshwater, 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 $5.6 \times 10^{13}\ m^2$. A shift in the oceanic heat transport, removing 0.5 PW, would correspond to an atmospheric radiative forcing change of about $9\ W/m^2$, 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 a high heat of condensation when it precipitates. 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 a 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 meridional overturning circulation (MOC) and perhaps even failure of the Gulf Stream. In other respects it is a tribute to Wally Broecker, who championed this concept starting around 1985.

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) but 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 among paleo-climatologists, 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 the "particular importance of 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 7,000 to 9,000 years ago and from 10,000 to 16,000 years ago. In both time periods, the comparison between variable CH_4 concentration and ΔT shows some similarity but is far from convincing to this writer. Perhaps, like beauty, the comparison lies in the eye of the beholder. Figure 8.5 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 at 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 categorical for the foundation that 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.

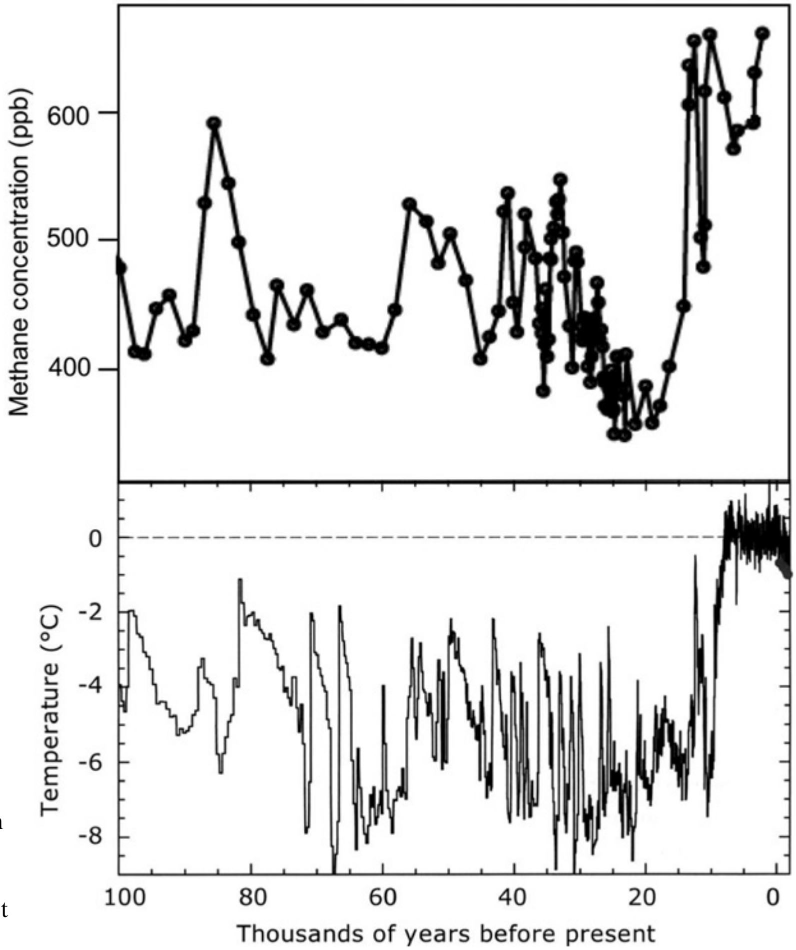

Figure 8.5. Comparison of Greenland temperature profile (from Figure 4.6) with methane profile at Vostok, Antarctica (Petit *et al.* 1999).

8.7 MODELS BASED ON CLOUDS

Cloud cover is an important factor that controls the way that 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 a net warming. Any factor tending to modify cloud cover will thus have an impact on climate so that it is important to understand the 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

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 (W/m^2)	+2.4	−7.0	+1.1	−7.5	−16.7	−27.7

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. Muller and MacDonald (2000) (M&M) provided the summary given in Table 8.1, based on estimates from the Earth Radiation Budget Experiment (ERBE).

The overall effect of cloudiness is to produce 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 alternating 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 of oceans with the atmosphere, leading to quasi-periodic changes in cloud cover. None of these models is 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 plane of planets' orbits (the "ecliptic"). This dust is probably produced by collisions between asteroids. The main bulk of the dust lies within ±5 degrees of the ecliptic but it reaches out to ±15 degrees from the ecliptic plane. The distribution of dust around the Earth is highly non-uniform. As the Earth traverses through space, its orbit parameters vary, and the tilt of the Earth's orbit plane wobbles relative to the ecliptic, and the Earth intercepts varying amounts of this interplanetary dust. The 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 that are 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. The variability of 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 that affect the Earth's climate. He provides many references. Only a brief report is given here.

The theory here is that as variations in solar activity take place, the solar wind changes. The solar wind controls the flux of galactic cosmic rays from deep space that enter our solar system and penetrate the Earth's atmosphere. The solar wind thus acts like a control grid on an old-fashioned triode vacuum tube where the 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 a 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-latitude 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 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 if higher latitude data are included, the correlation between cosmic rays and cloudiness is weakened. But a greater concern 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 11.8 and 11.9. 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 as the temperature trend is upward which supports the Svensmark 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) developed a response to Lockwood and Fröhlich (2007). In this rebuttal they pointed out that the use of running means of global temperature data over about ten years obfuscated the fact that temperatures stopped rising after 1998. In addition, discrepancies between tropospheric temperature trends and surface temperature trends lead to different conclusions on temperature variations over the past few decades. Using tropospheric temperatures without averaging, and allowing for effects of El Niños and volcanic eruptions, Svensmark and Friis-Christensen (2007) found 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 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."

Most recently, the world experienced a significant downturn in global temperature in years 2007–2008 (see Figure 11.2). At the same time, there was a serious diminution of sunspots on the Sun accompanied by a notable lack of solar magnetic activity. This time period is much too short to prove any relationship between the two phenomena, but there may be some connection. The year 2008 had 220 days without sunspots as of the end of October 2008, whereas solar minima over the previous four decades had considerably fewer no-sunspot days (70 to 160). While some solar physicists have been quick to point out that current sunspot behavior is not outside the norm of what has been experienced over several hundred years, it certainly is a departure from the previous few decades when global warming increased.[6]

Kniveton and Todd (2001) found a close correspondence between cosmic ray flux and global precipitation efficiency.

Bond *et al.* (2001) found close correlations of the extent of ice-rafted debris in the North Atlantic with fluxes of nuclides produced by galactic cosmic rays over the past 12,000 years. Figure 8.6 illustrates their results. Higher levels of ice-rafted debris are expected to reflect colder temperatures and these correlate with higher nuclide production (and therefore presumably greater cloud formation).

Unfortunately, there does not seem to be a great deal of analysis over timespans 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 with chronology 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 230,000–190,000 years ago, 135,000–110,000 years ago, 85,000–75,000 years ago, and 50,000–43,000 years ago. Comparison with Figure 4.10 shows that 230,000–190,000 years ago was associated with a moderate interglacial period, 135,000–110,000 years ago was associated with a major deglaciation, 85,000–75,000 years ago was associated with a short-term spike in temperature, and the period 50,000–43,000 years ago was associated with climatic instability. Thus, there are at least some indications that the level of cosmic ray flux may be affecting climate over the timespan 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

[6] *http://science.nasa.gov/headlines/y2008/30sep_blankyear.htm; http://science.nasa.gov/headlines/y2008/07nov_signsoflife.htm*

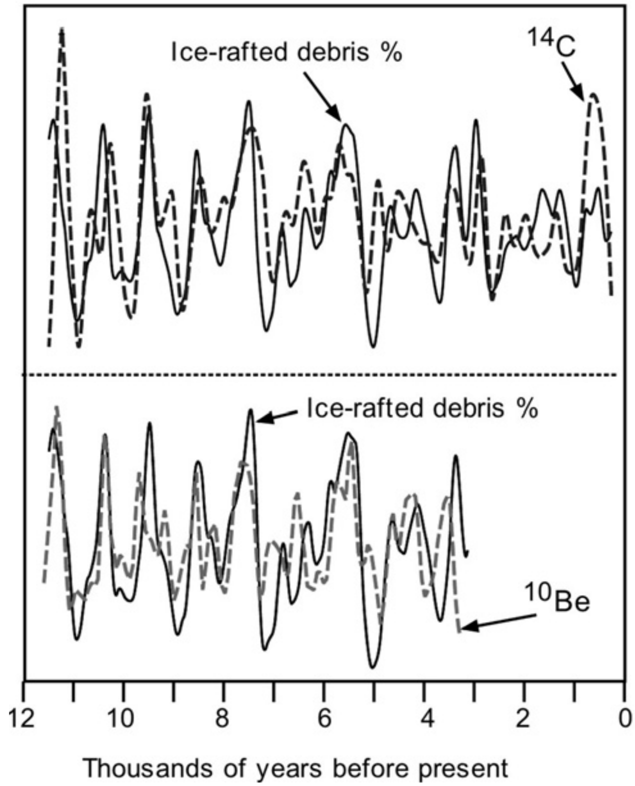

Figure 8.6. Comparison of radionuclide fluxes with relative amount of ice-rafted debris over the past 12,000 years (Bond *et al.*, 2001).

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.''

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.

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 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 it is the solar energy actually absorbed by the Earth that matters, not the small changes in solar input above the atmosphere. In their 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 the average solar input to 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 W/m^2 to 6.8 W/m^2, which would produce 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 Earth.

Consider a cold glacial period. With the Earth colder than average, cloudiness is assumed to be sub-normal because the vapor pressure of water is reduced. As a result, solar penetration to 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 slowly warm up with 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 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 that the Earth has entered a 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 again.

While formation of large ice sheets is a slowly evolving process, decay of ice sheets can be accelerated by 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 slow buildup of ice sheets and comparatively rapid decay.

The cycle proposed by Bell and Eng (2007) is somewhat affected by the rise and fall of CO_2 concentration 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 falls out naturally from the facts that the warming or cooling of the oceans lags the warming or cooling of the surface, and warming produces clouds, which in turn, produces 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 opposition to 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, in comparing the synchrony of climatic changes in the NH with the SH, Blunier *et al.* (1998, 2001) found that despite the qualitatively different temperature time series between Greenland and Antarctica, there appears to be a correlation between major discontinuities at Greenland and slope changes at Antarctica. This is discussed in Section 4.3 relevant to Figures 4.14 and 4.15. The data 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. 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 4.14 and 4.15. As in the case of Figures 4.14 and 4.15, the occasional sharp rises in Greenland data also appear to be preceded by slower, more gradual rises at 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 via heat transport by means of 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 non-linear 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, melt water 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.[7]

Recently, 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.*, 2008) this group carried out modeling that suggested that the likely cause of initiation of deglaciation after 20,000 years ago was the increase in insolation coupled with sea ice–albedo feedback as sea ice went into retreat. As the CO_2 concentration rose, this added another warming feedback. They also showed[8] that each of the last four major ice age terminations were associated with increases in solar input to the far SH. The 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.

[7] However, note that C. Wunsch (2002) insists (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."

[8] Lowell Stott, pers. commun., November 2008.

9

Variability of the Earth's orbit: Astronomical theory

9.1 INTRODUCTION

The history of the origination and evolution of astronomical theory (often called "Milankovitch theory") was 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 the 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 the insolation variations' climatic influence as the physical agents."

It is well established that over the past 3 million years, the Earth has undergone a long series of ice ages interspersed with interglacial warm periods. 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 multiple tens of thousands of years.

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 both show quasi-periodic variations with comparable timespans 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 solar energy input to higher northern latitudes is lower than average, lower solar input may "trigger" feedback processes that lead to spreading of the ice cover and the start of ice ages. Conversely, time periods with high solar energy input to higher northern latitudes may trigger feedback processes that cause melting, leading to deglaciation.

Thus, it is generally accepted that variability of the Earth's orbit about the Sun is a primary factor in determining the timing of ice age–interglacial cycles.

Muller and MacDonald (2000) (M&M) asserted that there are several persuasive reasons to think that astronomy is responsible (at least to some extent) for the observed glacial/interglacial variations. 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 kyr, 41 kyr, and 23 kyr, 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 (~800,000 years), these oscillations remain coherent (i.e., they maintain a roughly constant phase). However, as Figure 7.1 shows, the coherence is only approximate and there has been a systematic increase in spacing of the ice ages over the past 800,000 years. Even more important is the fact that the coherence was 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 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, and natural processes in geology and climate do not. Narrow peaks are characteristic of processes that have low loss of energy. That implies a lack of mechanisms that can drain 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 atmosphere and oceans. For example, if the glaciation/deglaciation patterns were caused by changes in thermohaline circulation, why wouldn't the spectrum of the data be broader? This seems to be a strong point in favor of an astronomical factor being a contributor to glaciation/deglaciation cycles.

It is not immediately obvious which measure of solar intensity is of greatest relevance in 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 the fact 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 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, there is also some evidence that suggests that the key site for solar-induced climate change might be in the SH, with variations in oceanic transport of the heat link from the NH to the SH, but with a time delay.

At higher latitudes, almost all of the solar irradiance occurs between March 21 and September 21, with a peak on June 21. In the present book, we utilize the yearly integral of solar irradiance as a measure of solar input to high latitudes. For higher latitudes, this is essentially equivalent to total summer irradiance.

In Sections 9.2 to 9.6, we derive the variability of 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 past climate? There is no immediately obvious connection between the time sequences of solar variability and isotope variability. The simplest version of astronomical theory suggests that solar variability is the forcing function that causes glaciation/deglaciation cycles. However, 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 buildup of major ice sheets is greater than 10,000 years. Therefore, if solar variability is the main factor producing glaciation/deglaciation cycles, there is likely to be a significant time lag of the ice volume curve behind the solar irradiance curve. Testing astronomical theory by comparison of historical solar variability with isotope variability is far from straightforward. While several investigators have claimed to have done this, and thereby proclaimed validation of astronomical theory, closer examination raises some doubts as to the veracity of such comparisons. This topic is discussed further in Section 9.6.

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 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 as *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. The variation of the eccentricity has a period of roughly 100,000 years but the amplitude of these variations is highly variable.

Summer solstice (June 21) occurs in the northern hemisphere when the spin axis of the Earth is pointed exactly toward the Sun, and winter solstice (December 21) occurs in the northern hemisphere when the spin axis is pointed directly away from the Sun. This is illustrated for the present case in Figure 9.1. The solstices in the southern hemisphere are reversed. These solstices may occur anywhere along the elliptical orbit of the Earth. The third parameter is the so-called *longitude of*

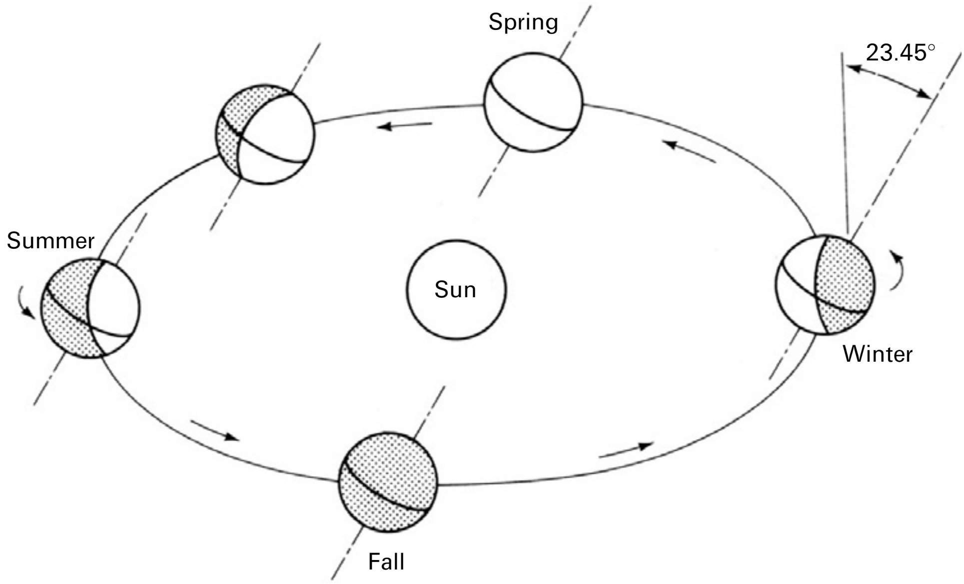

Figure 9.1. Motion of Earth about the Sun. Seasons are for the northern hemisphere. The current obliquity is 23.45°.

perihelion. The longitude of perihelion is the angle measured counterclockwise in Figure 9.1 from northern spring, to the point on the Earth's orbit where the minimum distance of the Earth from Sun occurs.

Variation of these parameters over the past 400,000 years is shown in Figures 9.2, 9.3, and 9.4.

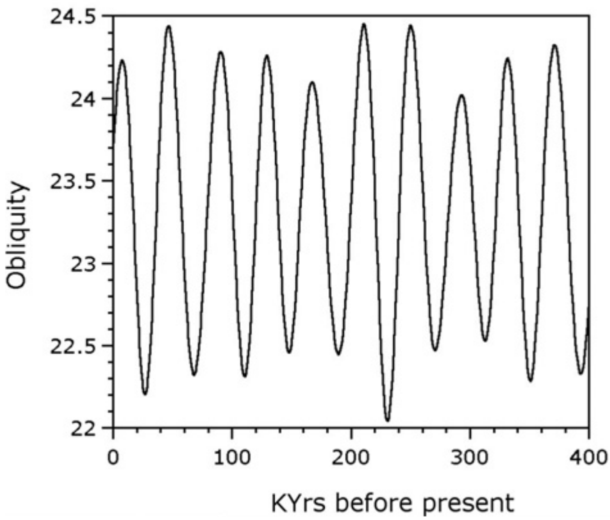

Figure 9.2. Variation of obliquity over the past 400,000 years.

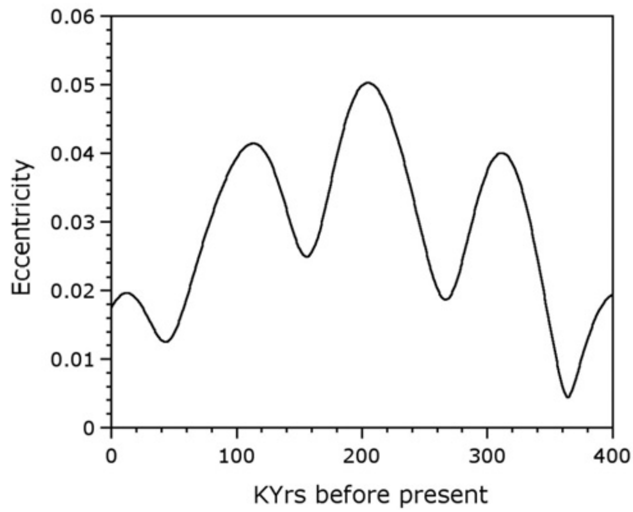

Figure 9.3. Variation of eccentricity over the past 400,000 years.

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 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. To the extent that formation of ice ages or interglacial periods is influenced by 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. If the 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 winter solstice in the north. This is illustrated in the upper panel of 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 the torques of 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

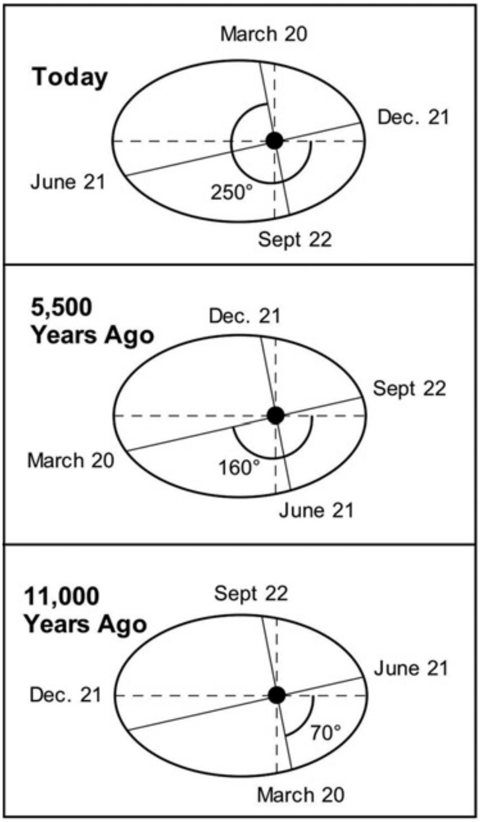

Figure 9.4. Variation of the longitude of perihelion over the past 400,000 years.

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 $\pm 0.5^\circ$ 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 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.

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. The actual solar input to the Earth will depend on the degree of cloudiness, the moisture

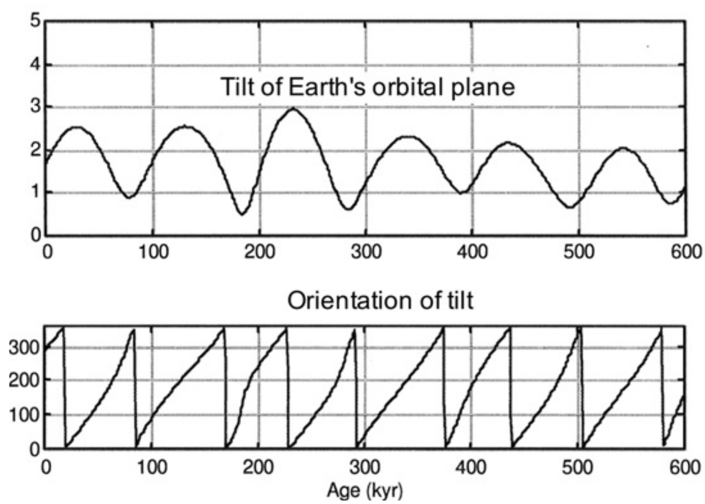

Figure 9.5. Variability of the tilt of the Earth's orbital plane.

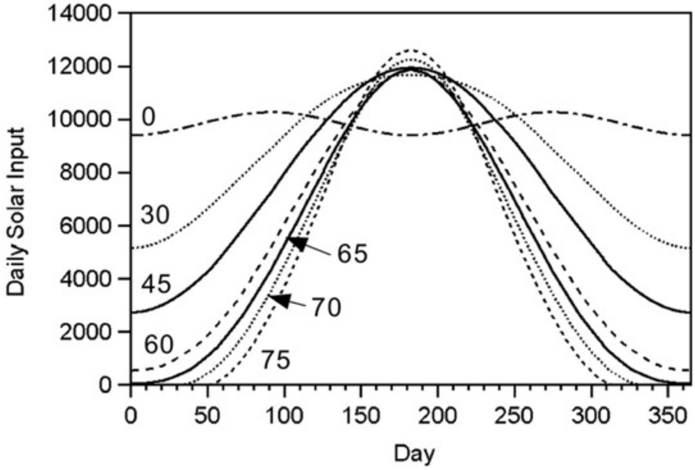

Figure 9.6. Variation of daily total solar irradiance (Wh/m^2) with day of the solar year (December 21 = day 1) for several northern latitudes.

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. We calculate the yearly total of solar intensity in units of kWh per m^2.[1] Total solar intensity was integrated hourly over each year.

Declination (d) depends on obliquity (q) and L_s, the longitude of the Sun which varies from 0° to 360° during the course of a year (being 90° at winter solstice and 270° at summer solstice in the northern hemisphere).

Declination can be calculated from the formula:

$$\sin d = \sin q * \cos(L_s - 90^\circ)$$

The direct normal solar intensity on any day of the year (defined by L_s) is given by:

$$S_N = 1{,}367\{[1 + e\cos(L_s - L_p)]\}^2/(1 - e^2) \quad (\mathrm{W/m^2})$$

where e is the eccentricity; and L_p is the value of L_s at perihelion.

The solar intensity that impinges on a horizontal surface at any hour of any day is:

$$S_H = S_N * \cos Z$$

where Z is the angle that the Sun's rays make with the vertical:

$$\cos Z = \sin d \sin L + \cos d \cos L \cos[(h - 12)(\pi/12)]$$

where L is latitude; and h is the hour (varies from 0 → 24, and is 12 at solar noon).

The calculated values of S_H can be integrated over a year, hour by hour, to obtain the yearly energy input to a hypothetical horizontal surface at any latitude if there were no atmosphere. At higher latitudes, most of this solar input occurs in summer, with a maximum at June 21. Figure 9.6 illustrates how daily solar irradiance varies with day of the year for various latitudes. At latitudes greater than 66.55° (for

[1] For details, see *Solar Energy* by Donald Rapp, Prentice-Hall, 1981.

the current obliquity) there is a period of no solar irradiance centered on December 21. For high latitudes, solar input during summer is of primary concern because that is when most of the solar input takes place.

9.4 IMPORTANCE OF EACH ORBITAL PARAMETER

Each of the orbital parameters has an effect on the variability of the distribution of solar input to the Earth.

The variation of eccentricity has 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 is the variation of solar input to 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 Earth orbit's major axis. If we integrate this over dL_s from 0 to 2π, and divide by 2π, we obtain the average value of r:

$$r = A(1 - e^2)^{1/2}$$

Since total annual solar input to Earth is proportional to the inverse square of r, it follows that total annual solar input to Earth is proportional to

$$\frac{1}{1 - e^2}$$

Thus, total annual solar input to Earth depends on eccentricity (but 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 range of variation of total annual solar input to Earth is 0.24%. Since the average value of the 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 $0.0024 \times 342 = 0.8\ \text{W/m}^2$ of forcing. This does not appear to be large enough to be the cause of ice ages.

The longitude of perihelion varies with a period of ~22,000 years. Actually, it is 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 $L_p = 250^\circ$, 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 solar energy input to higher latitudes and determines the positions of peaks and valleys of solar irradiance with time at higher latitudes. The slowly changing eccentricity acts as an amplitude envelope for the more rapidly varying longitude of perihelion. Eccentricity affects solar intensity when the Earth is closest to the Sun, and the longitude of perihelion determines the season when that distance of closest approach occurs.

In order to show the dependence of solar input to high latitudes on the combination of high eccentricity and coincidence of the longitude of perihelion 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 (in Figure 9.7) will be enhanced further if obliquity is high at that time.

Thus, we see that solar input to 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 coincidence of longitude of perihelion occurring near local midsummer (north or south) assures that high solar input to the local high latitude will occur in the summer (when high latitudes obtain 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. As these parameters evolve with time, solar inputs to higher latitudes undergo 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 changes 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 affects total yearly solar input to the Earth. However, increases in eccentricity 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.

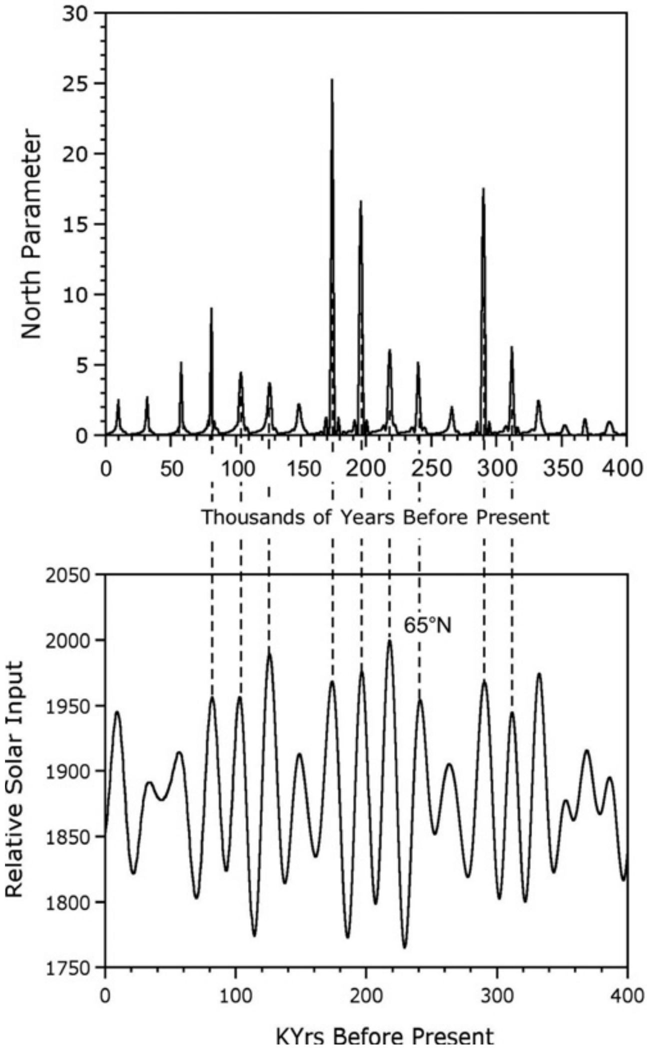

Figure 9.7. Peaks in solar input to Earth occur at peaks in parameter *P*.

A great deal of research has been carried out using spectral analysis applied to ice age isotope data and on modeled solar variability. It is unfortunate that some of these researchers have discussed the comparison of astronomical theory with isotope data as if each of the factors—eccentricity, longitude of perihelion, and obliquity—acts independently in contributing to changes in climate. The forcing function from astronomical theory is solar intensity, which is dependent on all three factors in the manner previously described. None of these factors acts alone. However, the Earth may react to variability of solar intensity in such a way that it is more responsive to some of the parameters than others. This would constitute a variant of conventional astronomical theory.

9.5 HISTORICAL SOLAR IRRADIANCE AT HIGHER LATITUDES

In almost all descriptions of the variability of solar irradiance at high latitudes, an offset zero is used to emphasize variability. However, when plotted in the normal way with zero as the base of the vertical scale, calculated yearly solar irradiance at 65°N is as shown in Figure 9.8. This figure shows that the actual magnitude of variations is small compared with the average level. Yet, according to astronomical theory, it is these small variations in solar intensity that drive glacial/interglacial cycles.

Calculated yearly solar irradiance at several high northern latitudes over the past 400,000 years is shown with a greatly expanded scale (with an offset zero) 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. A graph for the most recent 150,000 years is shown in Figure 9.12. It can be seen that the patterns for several latitudes are all very similar, although yearly irradiance decreases as the latitude increases. The magnitude of variability of solar irradiance over 800,000 years about the mean is about ±5% at 60°N and it increases to about ±7% at 75°N.

We may regard the pattern of variability of solar intensity in Figure 9.10 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 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 the 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.

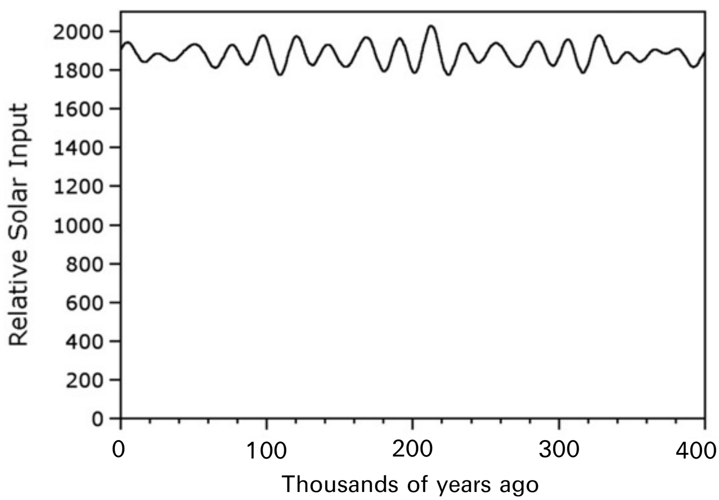

Figure 9.8. Calculated yearly solar irradiance (kWh/m^2) at 65°N.

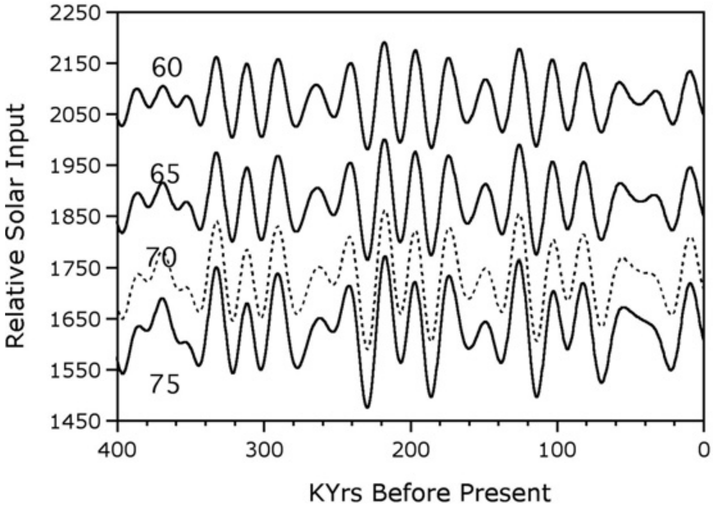

Figure 9.9. Calculated yearly solar input (kWh/m^2) at four northern latitudes over the past 400,000 years.

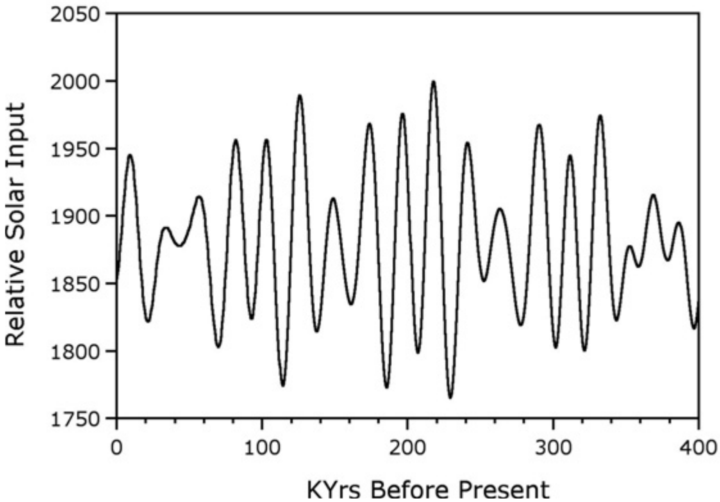

Figure 9.10. Calculated yearly solar input (kWh/m^2) to 65°N over 400,000 years.

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 the solar input to high latitudes in the two hemispheres will be anti-phased, as shown in Figures 9.13 and 9.14.

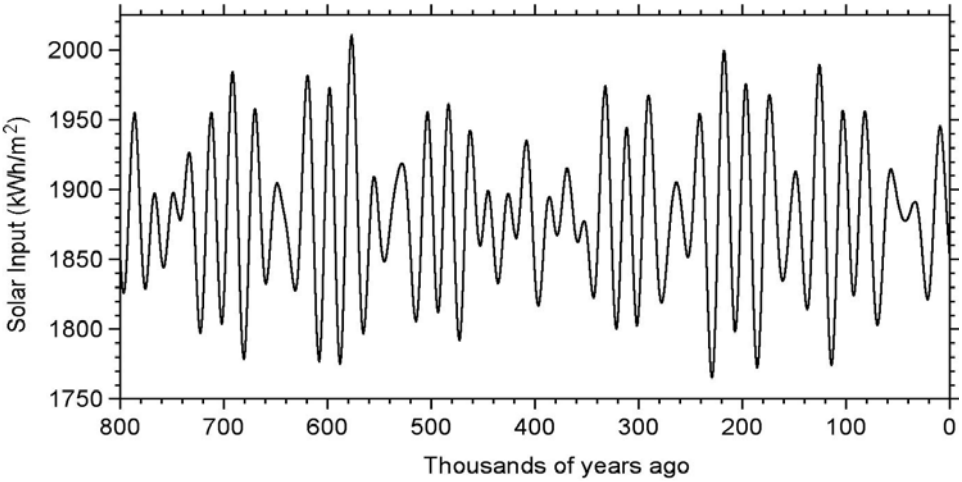

Figure 9.11. Calculated yearly solar input to 65°N over 800,000 years.

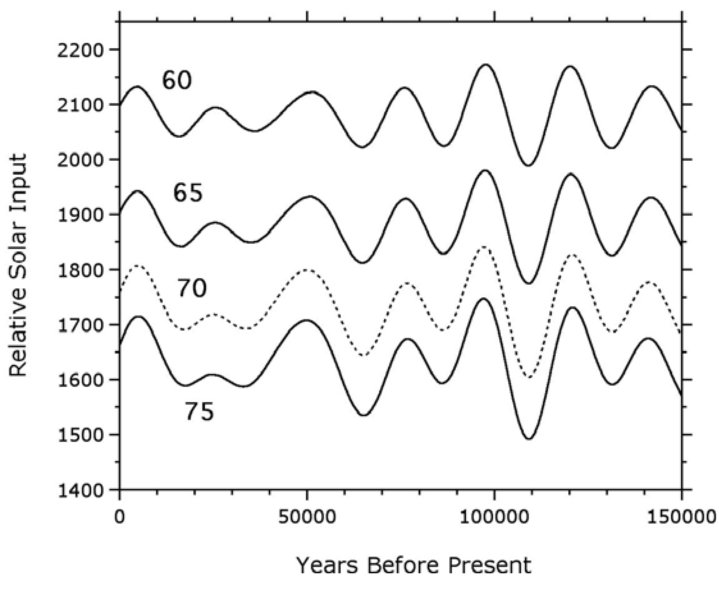

Figure 9.12. Calculated yearly solar input (kWh/m^2) to several northern latitudes over the most recent 150,000 years.

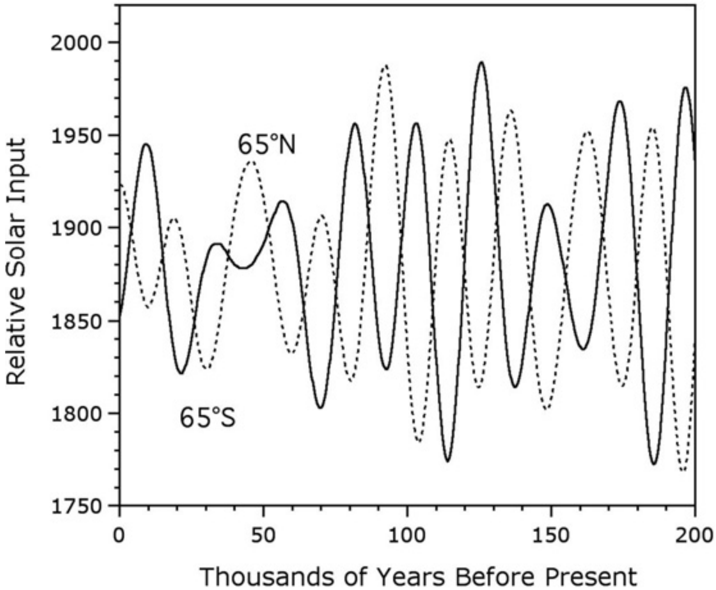

Figure 9.13. Comparison of solar input (kWh/m^2) with a horizontal surface above the atmosphere at 65°N and 65°S over 200,000 years.

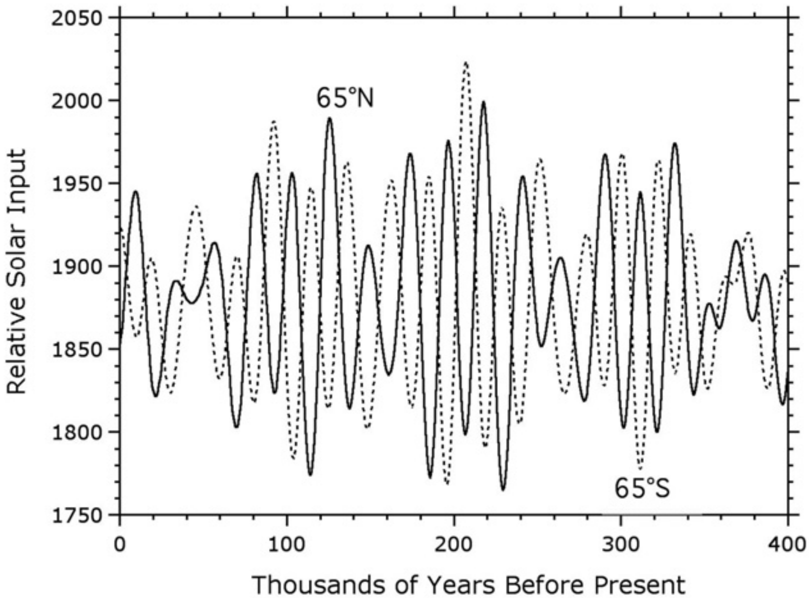

Figure 9.14. Comparison of solar input (kWh/m^2) with a horizontal surface above the atmosphere at 65°N and 65°S over 400,000 years.

9.6 CONNECTION BETWEEN SOLAR VARIABILITY AND GLACIATION/DEGLACIATION CYCLES ACCORDING TO ASTRONOMICAL THEORY

The astronomical theory of ice ages postulates that variability of distribution of solar input to 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 of solar input to Earth 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. 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. There are also concepts that imply that it is solar input to the south that affects ocean currents which produce climate change in the north. In addition, there are theories that climate change emanates from changes in the tropics. Nevertheless, assuming for now that solar input to high northern latitudes in summer is the critical factor, there remains the question of which measure of solar input is most relevant. Some have used solar input in a single midsummer's day. Others integrated over the month of July. A few have integrated over the summer. In this book, we take yearly solar input (at any latitude) as our measure of solar influence. For high latitudes, this is almost the same as the summer input for all practical purposes.

Despite the many published papers on astronomical theory, there is an appalling lack of modeling of specifically how solar variations produce extreme climate change. Perhaps that can be excused to some extent because of the extreme complexity of the issue, but that being the case how can so many scientists reach firm conclusions on the veracity of astronomical theory? In actual fact, astronomical theory is merely 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 is very satisfying—at least to this writer.

While credible mechanisms for the processes by which solar variability affects climate are not available, nevertheless one may hope to gain wisdom by comparing the solar curves (from the previous sections) with isotope data from ice cores and ocean sediments. Here, the situation 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 the two have important frequency components that agree, there is an implication that the two are coupled. That is somewhat in 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 over hundreds of thousands (or even millions) of years to determine 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 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 that has no adjustable parameters, which allows unequivocal comparison of theory with data. Unfortunately, all models developed to date have been limited by their simplicity, as well as the obvious bias of many scientists determined to "validate" astronomical theory via curve fitting. The combination of fixing the chronology of isotope data fixed by "tuning" to astronomical theory and using adjustable parameters to fit simplistic models to the "tuned" data raises questions of circular reasoning. However, one could argue 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 determination of physical parameters, or mere mathematical curve fitting.

The "bottom line" seems to be that astronomical theory may well be correct to some extent in principle (i.e., there may be a solar influence on 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 δD 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 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 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. To the extent that in the first place the chronology of the data was inferred by "tuning" to 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 starting in the late 1960s. Some models dealt with the question of whether the known variability of solar intensity was great enough to cause climate shifts leading to ice ages. Later studies attempted to model the effects of the 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 astronomical theory.

An early paper estimated the change in temperature produced by changing solar intensity, but it used current atmospheric and surface properties (it did not account for changes in albedo due to ice sheet growth or other secondary factors). The calculated temperature changes 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 the variability of solar intensity, although ice sheets were not included in this model. This paper is difficult to follow, and it includes a multitude of 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 a strong point of why he chose 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 (e.g., see Figure 9.9). 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:

$$dV/dt = \begin{cases} -C_1(S - S_0) & \text{if } S > S_0 \\ -C_2(S - S_0) & \text{if } S < S_0 \end{cases}$$

where V is ice volume; S is solar intensity; S_0 is threshold solar intensity; t is time; and C_1 and C_2 are (different) constants. These equations were integrated over 1,000-year

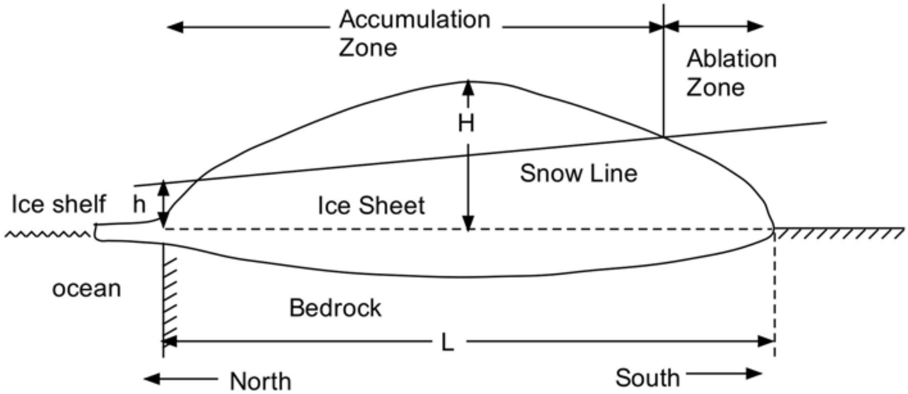

Figure 9.15. Weertman's ice sheet model.

time steps and the accumulation of ice volume vs. time was tabulated. He added the constraint that when $V \sim 0$, dV/dt cannot be negative. While Calder (1974) did admit that his assumptions "were almost frivolous", one must wonder about the word "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 on 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 to get a best fit to the data, one must choose $C_2 \ll C_1$. However, Calder did not divulge the details.

Weertman (1976) developed a model to estimate whether solar irradiance 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 the volume (or dimensions) of the ice sheet. He considered a two-dimensional ice sheet that rests on a land surface which was flat before the ice sheet formed on it. Figure 9.15 shows the ice sheet in profile.

The lower ice surface is not flat because of isostatic depression of the land surface. The northern edge of the ice sheet borders the Arctic Ocean and the southern edge is on land. The total width of the ice sheet is L. Weertman (1976) hypothesized a "snowline" such that wherever the height of the ice sheet locally exceeds the snowline, accumulation takes place, whereas wherever the snowline is higher than the ice sheet, ablation occurs. Based on his rough estimates of the properties of ice and bedrock, as well as some additional guesses, he estimated that h (the height of the snowline at the northern edge of the ice sheet) would have to be between 0 m and 540 m to enable a stable ice sheet to persist. In his model, when $h \to 0$, $L \to\sim 2{,}500$ 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 of 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 that 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 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 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.'' 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 Imbries' point of view, the task at hand was to adjust parameters in a model (i.e., tune the model) to seek maximum agreement with isotope data. In their view, there was no doubt at all *a priori* that astronomical theory was correct in principle, even though it was not clear how the variability of solar intensity led to variability of the 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 in the 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 is eccentricity, q is obliquity, and w is longitude of precession. These parameters can be calculated by methods given in 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." Or, 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 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, or 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 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 those are chosen, solar irradiance is essentially uniquely determined, and in fact the Imbries showed this in their Figure 3. Thus, there should really be only one parameter of interest in regard to the 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 the system function. Here, they pointed out that the simplest system they could imagine was 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, the ice sheet volume); x is a parameter that characterizes variations in solar input (in their case, solar intensity in summer at some high northern latitude); and T is a time constant that produces a lag between a change in solar input and a resultant change in climate. Unfortunately, the Imbries did 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 be either positive or negative. The Imbries wrote this equation without the minus sign in front of x, but that does not make sense to this writer. When solar irradiance is lower than average ($x < 0$), the 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 term y was included on the right-hand side. Under average solar conditions ($x \sim 0$) the presence of the term y 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 the model. As we mentioned previously, there is considerable evidence in isotope profiles that suggests 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):

$$\frac{dy}{dt} = \begin{cases} -\dfrac{1+B}{T}(x+y) & \text{if } (x+y) > 0 \\ -\dfrac{1-B}{T}(x+y) & \text{if } (x+y) < 0 \end{cases}$$

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 the ice volume should enter this equation on the right-hand side. Previous modelers always inserted a term $-y$ 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. Growth of ice sheets requires a source of moisture, and evidence suggests that as the ice sheet grows, such sources become more distant, and therefore at 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 that by tuning this model to the (tuned) geological record of the past 150,000 years, they arrived at "optimum model values". 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 fourfold faster than ice sheet buildup when $B = 0.6$). Their solar intensity was taken at 65°N in July (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 the (tuned) data validates astronomical theory, or merely defines the best fit to this model assuming 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 sought to model the time evolution of ice volume over the past 2 million years in order to validate astronomical theory (Paillard, 1998). He emphasized the

"100 kyr problem" and pointed out that previous investigators suggested that non-linear 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 that 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 can 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 the ice sheet needs some minimal time t_g in order to grow to the point where the 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. In other words, 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. But since it turns out that the best fit occurs for $i_1 = i_2$, the $g \rightarrow G$ transition and the $G \rightarrow i$ transition are controlled by essentially the same parameter.

These transitions are assumed to be one-way: a $g \rightarrow i$ transition is 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 a 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 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 fit to 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 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 with lower amplitude of these oscillations 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 the 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 the ice volume exceeds the value $v_{\max}$, without any condition on 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 the ice volume; R is the current climate regime ($R = I$, g, or G); v_R are the reference ice volumes for the different regimes; F is insolation forcing; and t_R and t_F are time constants. This model implies that as the ice volume builds up, the rate of addition of new ice decreases. Physically, one might expect the rate of new ice formation to increase at first as the ice volume increases due to the cold trap for moisture that is created, but eventually for large ice volumes, the amount of prevalent moisture would presumably decrease and the rate of accumulation would diminish with ice volume.

Ice volume was normalized 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 at all clear to this writer how the above differential equation was integrated with time or how transitions between regimes occurred within the model. In addition, as in the case of the simpler model, it is not clear to what extent this curve-fitting procedure has a physical basis. Any of these 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 despite the seemingly repetitive morphology of the insolation vs. time curve over 2 million years, he finds very different ice volume patterns vs. time for the first million years and the second million years. How this comes about remains mysterious to this writer.

It does not seem necessary to define the three regimes. Paillard's equation for the rate of ice volume growth is actually very similar to that used by the Imbries, 18 years prior. Unfortunately, as in all the other models, it is difficult to resurrect the model and further explore it because the units are not given.

9.6.2 Review of the Imbries' 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 the Imbries 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 of yearly solar intensity at 65°N over the past 800,000 years was 1,882 kWh/m^2 (see Figure 9.11). As this figure shows, the peaks in solar intensity lead to yearly values in the range 1,960 kWh/m^2 to 2,000 kWh/m^2 while the minima occur in the range 1,800 kWh/m^2 to 1,770 kWh/m^2. The standard deviation was 50 kWh/m^2. 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 then taken as they came out of the integration (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 9.16). 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 two parameters (B and T) is illustrated in Figures 9.17 and 9.18. Regardless of the values of these parameters, the maxima and minima in the 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 the ice volume curve. But the important thing 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.

[2] These calculations were carried out by the present author in 2008.

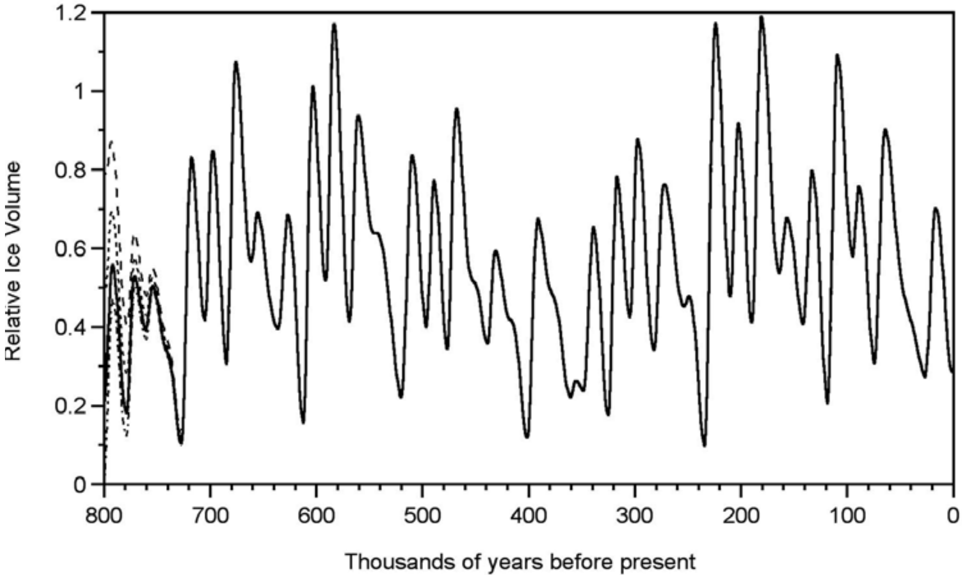

Figure 9.16. Dependence of the Imbries' integration on starting values for relative ice volume. The dashed lines are for starting values of 0.0, 0.2, and 0.8, while the solid line is for 0.5.

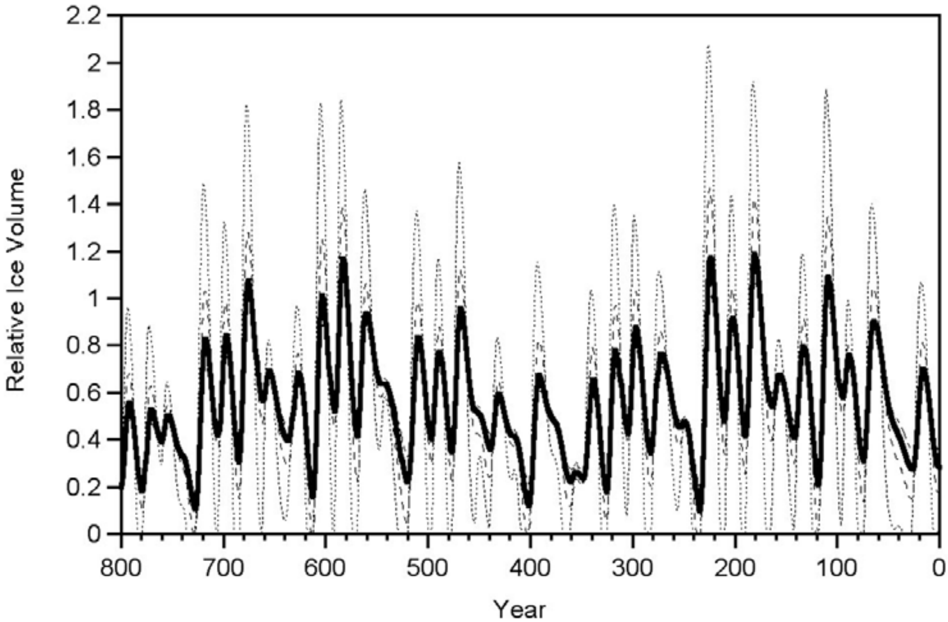

Figure 9.17. Dependence of the Imbries' integration on T. The starting value was 0.2 and $B = 0.6$.

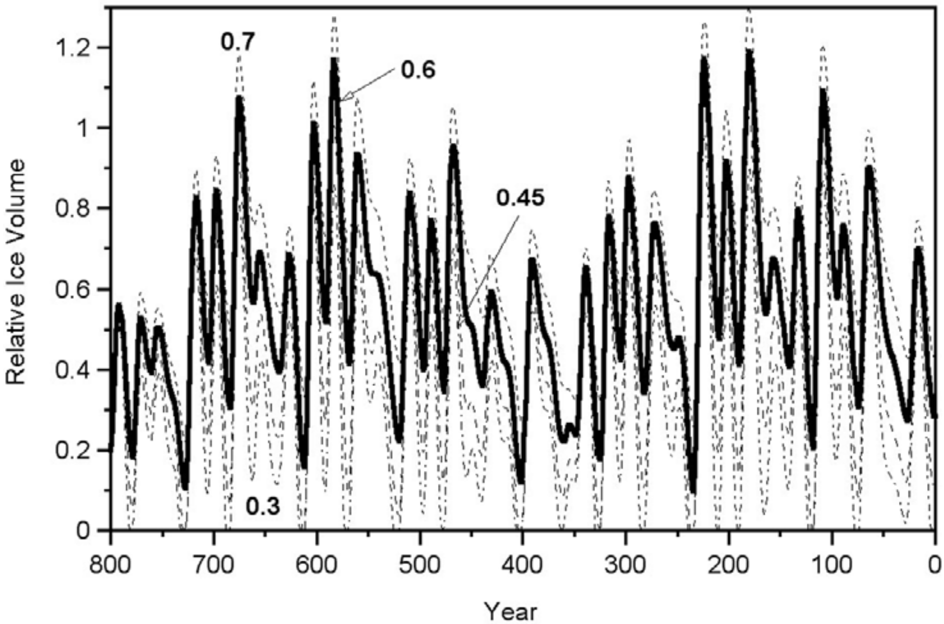

Figure 9.18. Dependence of the Imbries' integration on B. The starting value was 0.2 and $T = 17{,}000$.

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, it is really not necessary to keep one eye on SPECMAP data when applying the Imbries' model. The model, to the extent that T and B are predictable, can be construed to be an *a priori* model that can be compared with data without "fudging".

Another approach would be to use a 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 goes to $(1 - B)$ when $(x + y)$ is large-negative, and it provides a smooth continuous equation to replace the abrupt discontinuous model of the Imbries. As $K \to \infty$, the tanh function approaches the step function used by the Imbries. A reasonable value for K might be perhaps about 3.

Pisias and Shackleton (1984) embellished the Imbries' 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 form of self-confirming curve fitting to 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 it is done judiciously and independently of sediment data.

9.6.3 Memory model

Berger (1999) developed a model relating the change in ice volume as a function of solar variations that seems to be highly contrived. His function was:

$$\frac{dx}{dt} = K - xy^A m^C$$

where, 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 were about 4. While he was able to find good agreement with SPECMAP data, the tuning of the data and the artifices of the model leave this writer with the impression that this was merely imaginative curve fitting.

9.7 A MODEL BASED ON ECCENTRICITY

Bol'shakov (2008) raised a number of objections to the conventional astronomical theory of ice ages. One of these objections 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 complained about conventional 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, in fact, at latitudes greater than 66.55° there is little direct winter insolation. Almost all direct insolation occurs in summer, so his argument does not make sense.

Convinced that 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 cited Croll:

> "... 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 the positive feedback associated with albedo change due to snow and ice volume and vegetation cover change, or changes in greenhouse gas concentration. He also described enhancement of atmospheric circulation due to glaciation (the higher temperature gradient from equator to 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 may not respond to the several orbital parameters equally. 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 can operate independently on the Earth's climate system, rather than acting in concert to change solar input to higher latitudes. Thus he claimed that before about 1 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 only obliquity was affecting the Earth's climate before 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 changes resulting from eccentricity variations ``was sufficient to prevent melting of glaciers.'' In other words, he believes that prior to a million years ago, the climate was driven by obliquity changes but in the most recent million years it was driven by changes in eccentricity. When the global ice budget reached a certain point, the Earth became sensitized with greater positive feedbacks due to albedo and greenhouse gases 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 changes overall solar input to 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 against measures of ice volume, there would likely be a time lag 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 insistence that he has the answers belies the fragility of his arguments.

9.8 NORTH OR SOUTH?

If variability of solar intensity at high latitudes due to orbital changes is the key factor producing ice ages and interglacials, should we seek variability in the north, the south, or both? Figures 9.13 and 9.14 show that solar intensity in the north and south are out of phase by about 11,000 years. Therefore, any model that predicts 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 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 $135{,}200 \pm 3{,}500$ years ago. Henderson and Slowey (2000) pointed out that "this date is $\sim$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 135,000 years ago, whereas solar intensity in the south was near a maximum. However, assuming that ocean sediments measure global ice volume, time lags are involved. Nevertheless, the Imbries' model (Figure 9.16) does not show a significant reduction in ice volume until 120,000 years ago and there is no sign of a termination as early as 135,000 years ago in their model.

10

Comparison of astronomical theory with data

10.1 INTRODUCTION

In attempting to compare astronomical theory with historical climate data, a number of issues arise. One issue is the question of 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 non-linearities in the way that the climate responds to perturbations, and there may be thresholds which, when crossed, cause discontinuous "jumps" to a new state.

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 to astronomical theory, one should be careful to take into account any circular reasoning in the process of validating 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 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, one might not attempt to resolve the comparison of timing the variability in solar intensity and the isotope time series, but instead carry out a 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. Muller and MacDonald (2000) (M&M) provided a very extensive and detailed discussion of spectral analysis that is beyond the scope of this book. A brief discussion of spectral analysis results is given in Section 10.3.

10.2 COMPARISON OF DATA WITH ASTRONOMICAL THEORY

One of the stumbling blocks in the attempt to validate 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 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 or so years. 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 most recent 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 astronomical theory. In fact, it is rather common that scientists will 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) was the lead paper for many years in the quest to find support for 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 quote 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 astronomical theory is correct, and now the issue is not to validate astronomical theory, but rather to test 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, they may have declared victory for 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 non-linearity that makes a 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 1 million years ago. They pointed out that eccentricity is often assumed to be the primary driver of post-MPR climate cycles, and they called this the "eccentricity myth".

Lisiecki and Raymo (2005) were able to produce a change in the period of cycles within the Imbries' model by using different parameters for the early, mid, and late periods (see discussion in Section 5.2). However, this seems to be more in the province of curve fitting than physical reasoning.

10.2.1 Direct comparison of the variability of 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

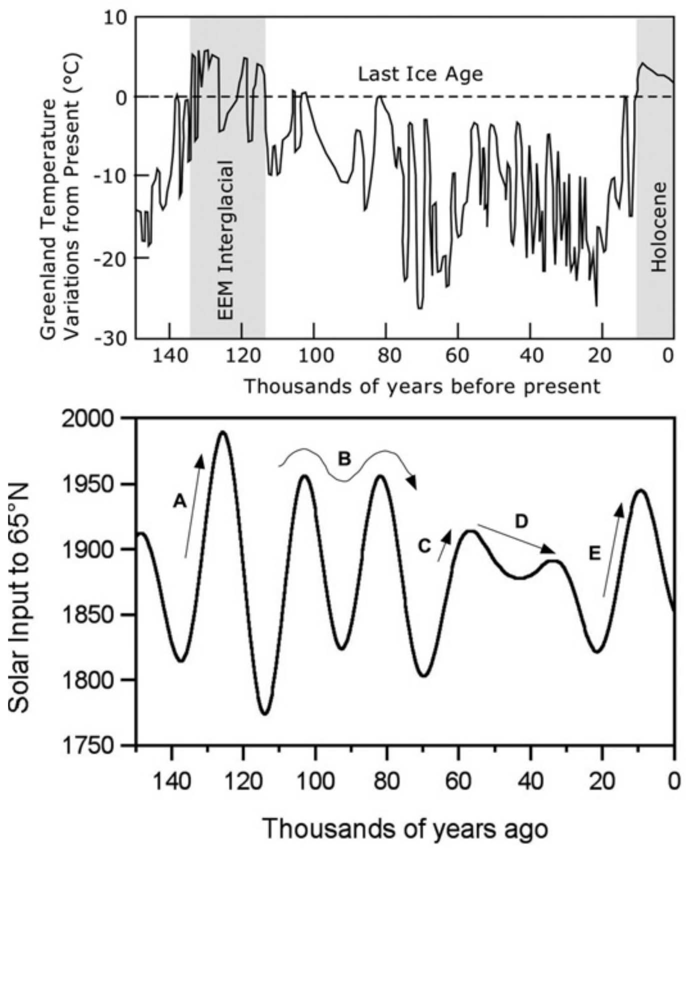

Figure 10.1. Comparison of smoothed Greenland temperature with yearly solar input (kWh/m^2) at 65°N over the past 150,000 years.

of the EEM interglacial. However, the time period from 145,000 to 138,000 years ago 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 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 operating to produce very large, rapid changes in climate, and there doesn't seem to be any way that the slow ponderous changes in solar input could directly cause these sudden changes. On the other hand, it is possible that under some conditions, solar input, or its rate of change, could "trigger" other non-linear effects that could introduce instability in the climate. The three likely candidates for such non-linear 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 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 that are superimposed on this slowly varying background do not seem to be related to

Table 10.1. Comparison of Greenland temperature trends with solar inputs for the past 150,000 years.

Time period (years ago)	*Greenland temperature trend*	*Solar input trend*	*Comment*
140,000 to ~125,000	Sharp rise	Sharp rise	Good correlation after 135,000 years ago. However, temperature rise began while insolation was decreasing
130,000 to ~115,000	Warm, not much change	Sharp drop	No correlation at all. Sharp drop in insolation was not matched by a drop in temperature
110,000 to ~20,000	Several large oscillations	Many oscillations but trending downward	Envelope of temperature data might suggest solar trends
20,000 to ~10,000	Sharp rise	Sharp rise	Good correlation
10,000 to 0	Warm, not much change	Sharp drop	No correlation at all

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 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 most recent period involving a major climate change was the termination of the last Ice Age that began roughly 20,000 years ago. Figure 9.13 shows the behavior of north and south insolation. As it turns out, southern insolation rose from a minimum around 31,000 years ago to a maximum at 20,000 years ago 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 20,000 yeas ago? 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 SH 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 the warming of the Southern Ocean began. In a second paper, Timmermann *et al.* (2008) carried out modeling that demonstrated the likely cause of initiation of deglaciation after 20,000 years ago was the increase in insolation during austral spring when the southern ice pack was at a maximum, coupled with sea ice–albedo feedback as 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 might be a necessary condition but not a sufficient one.

The last few ice ages

Figure 10.2 provides a comparison of the 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 Antarctic ice core data. Arrows depict trends between cycles. 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.

The lower half of Figure 10.2 shows that, as time progresses, solar input to higher latitudes rapidly oscillates due to precession of the seasons. The variability of eccentricity imposes an envelope on these oscillations with a period of about 100,000 years. The obliquity during periods of higher eccentricity affects the amplitude of the envelope. Table 10.2 shows that there tends to be a correlation (with some exceptions) between the amplitude of solar variations and temperature as measured at Antarctica. Temperatures do not increase or decrease in proportion to solar input. Instead, temperatures rise when solar input oscillates wildly, and temperatures drop when

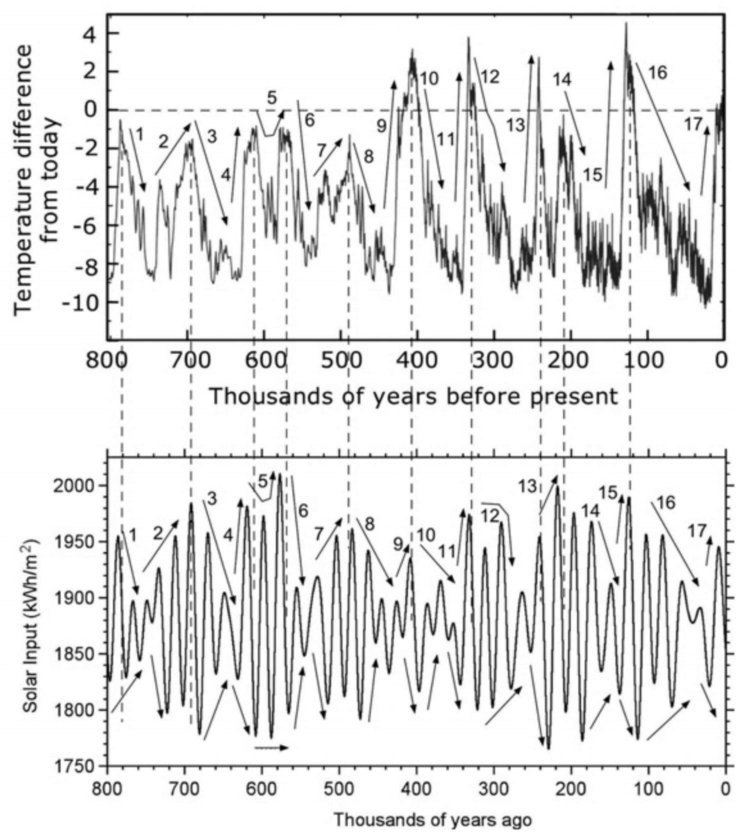

Figure 10.2. Comparison of Antarctic ice core data with calculated yearly solar input at 65°N over 800,000 years. Upper panel is Antarctic data. Lower panel is solar input to 65°N.

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.

One glaring violation of this correlation is the sharp rise in temperature that occurred about 400,000 years ago (transition 9 in Figure 10.2), when solar oscillations were minimal. Another exception occurred in the sharp rise in temperature at around 800,000 years ago when solar oscillations were moderate. The problem at 400,000 years ago 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 answer to this problem in 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

Table 10.2. Comparison of Antarctic ice core data with calculated yearly solar input at 65°N over 800,000 years based on Figure 10.2.

Transition → in Figure 10.2	*Antarctica temperature trend*	*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

don't have to push on a swing every cycle to keep it high.'' W. Berger (1999) did this with his resonance memory model. However, this model seems very artificially contrived to this writer. M&M claim that 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 10.2 (perhaps among many) is that the ''natural'' state of the Earth's climate in the past 800,000 years may be 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, the climate cools, and ice sheets build up. However, during those periods when oscillations of solar input are large, solar input gets high enough during the up-lobes of the oscillations to melt summer ice, the ice sheets diminish, and the 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" and 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 the 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 past hundreds of thousand years). Ice sheets build more slowly than they disintegrate. During periods of small oscillations, solar input does not get to 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 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 10.3. The 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 10.2 and 10.3 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 240,000 to 160,000 years ago has large solar oscillations, yet temperatures drop after peaking around 240,000 years ago. 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. There are many solar oscillations during ice ages and it is not immediately clear why some oscillations seem to produce interglacials and some do not.

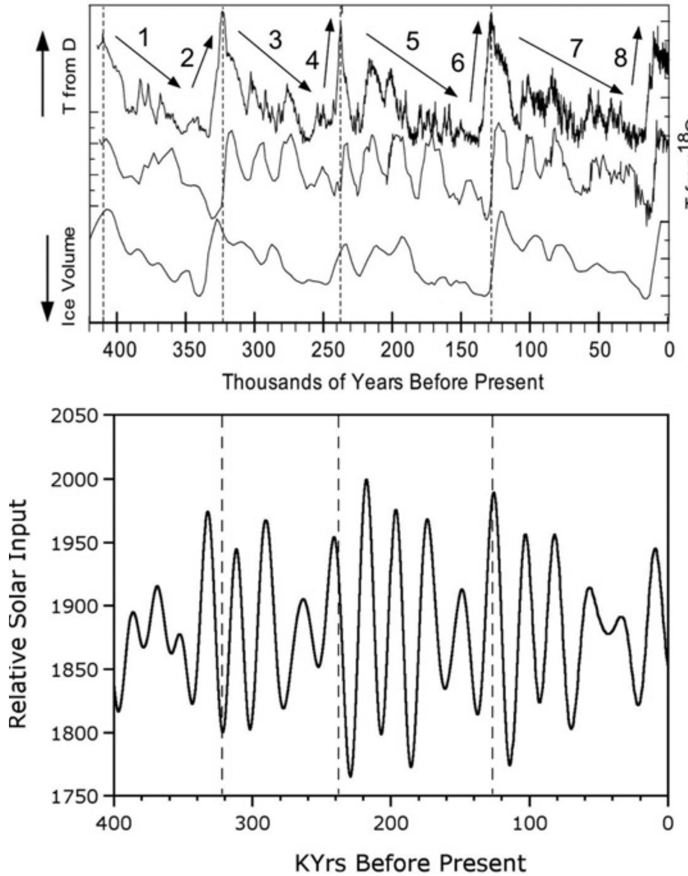

Figure 10.3. Comparison of Antarctic ice core data with calculated yearly solar input at 65°N over 400,000 years. Upper panel is Vostok data. Lower panel is solar input to 65°N.

10.2.2 Comparison of Imbries' ice volume model with ocean sediment data

The Imbries' ice volume model integrates solar irradiance with time, and its use of longer time constants for buildup rather than decay of ice sheets 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, when solar input is oscillating wildly, ice sheets will diminish. Conversely, during periods when solar input is not oscillating widely, the Earth system will revert to its (presumably) natural glaciated state.

When the Imbries' model is compared with data over 800,000 years, the result is as shown in Figure 10.4. Our independently calculated rendition of their model agrees exactly with Figure 6.10 of M&M. However, Imbries' presentation of their results (in the upper graph of Figure 10.4) differs somewhat from our version. In general, our rendition of the Imbries' model provides much larger (and more frequent) oscillations than is the case with ocean sediment data. Although there are some similarities between the model and the data, there are also significant differences.

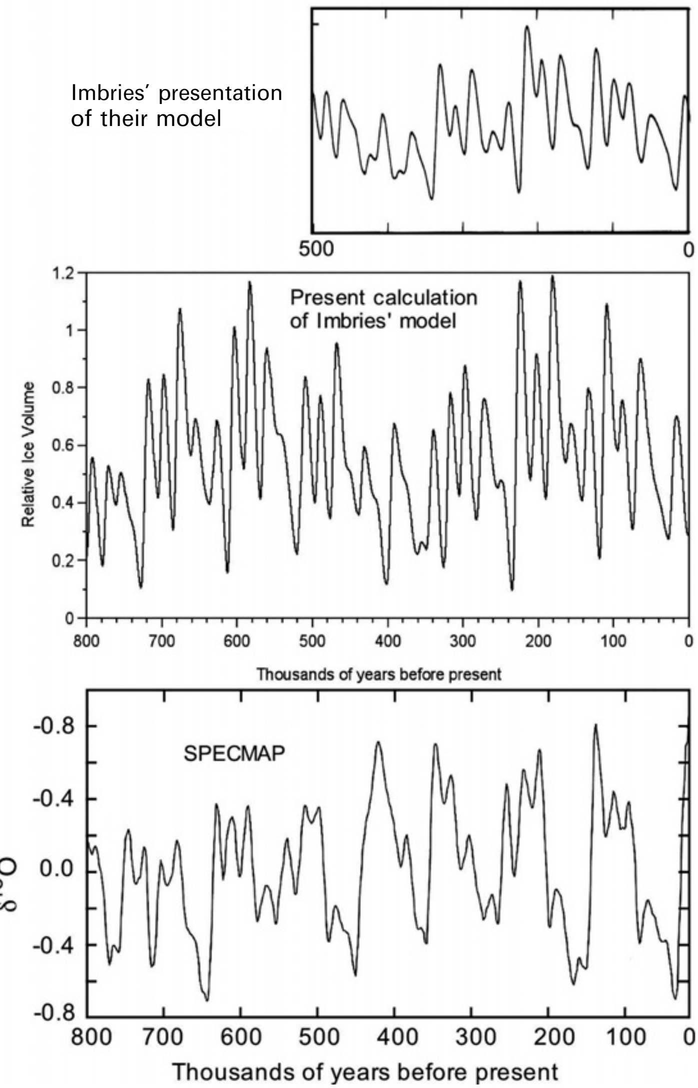

Figure 10.4. Comparison of Imbries' model with SPECMAP. The uppermost graph is the Imbries' presentation of their ice volume model. The middle graph is the present evaluation of the Imbries' model (which agrees with M&M's Figure 6.10). The lower graph is the SPECMAP.

A serious problem for 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 million to about 1 million years ago 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 Imbries' ice accumulation model by utilizing different parameters before and after 1 million years ago, but there does not seem to be any fundamental physical reason for making this choice except as an exercise in curve fitting.

The usual procedure for comparing astronomical theory with ocean sediment data is based on the assumption that ocean sediment data represent ice sheet volume, and thus it is necessary to integrate insolation (e.g., via the Imbries' ice accumulation model) to obtain a function proportional to ice sheet volume that can be compared with ocean sediment data. Figure 10.4 shows the result of such a comparison. An alternative approach was suggested by Roe (2006). In this approach, instead of integrating insolation, one differentiates ocean sediment data. The slope of ocean sediment data is interpreted as the rate of change of ice volume, and this is compared directly with the variability of insolation. Unfortunately, I was unable to reproduce his data. However, the slopes of SPECMAP from Figure 5.4 can be compared with the variability of solar intensity from Figure 9.11, and this is presented here in Figure 10.5. The comparison is not quite as impressive as that claimed by Roe (2006).

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, the time series for ice core or ocean sediment climate data) can be expressed as a sum of sine and cosine functions that oscillate with different frequencies. If the time series oscillates in a regular fashion with time, the coefficient of the sine or cosine function with a frequency that most closely matches that 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 these do not always agree with one another. Second, low frequencies might not come through clearly if the time series oscillates rapidly. Third, in comparing solar variability with time series variability, it is insufficient to merely compare principal frequencies. The phasing of the two functions is

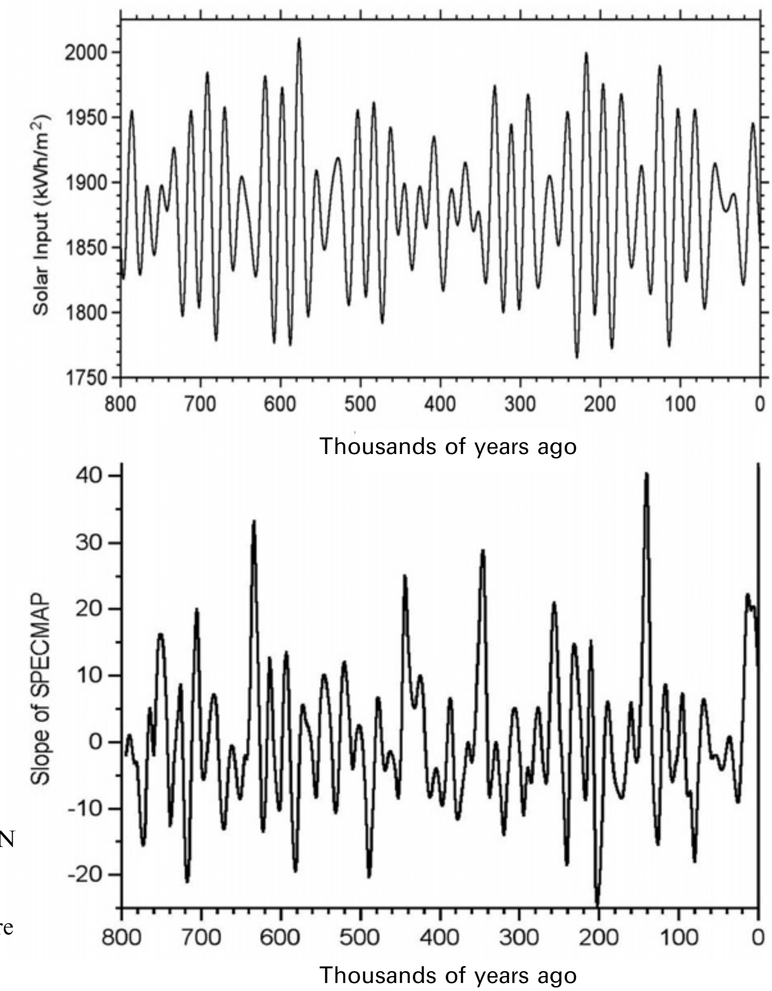

Figure 10.5. Comparison of solar input to 65°N (Figure 9.11) with the slope of SPECMAP (Figure 5.4) over the past 800,000 years.

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 may 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:

$$F(t) = \int_{-\infty}^{+\infty} H_{Tr}(f)e^{2\pi ift}\,df$$

$$e^{2\pi ift} = \cos(2\pi ft) + i\sin(2\pi ft)$$

where f is frequency; $H_{Tr}(f)$ is the weighting function for various frequencies that contribute to making up $F(t)$; and 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

$$H_{Tr}(f) = \int F(t)e^{2\pi ift}\,dt$$

and the integral is taken over all time. In actual practice, one does not deal with a continuous function, but rather with 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 with an expansion in 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.

For the case involving a set of discrete data points, we approximate the integral as

$$H(f) = \sum F_j\big(\cos(2\pi ft_j) + i\sin(2\pi ft_j)\big)$$

where the sum is taken over all the data points ($j = 1, \ldots, N$). Here, $H(f)$ is an approximation to the true $H_{Tr}(f)$.

Many sophisticated procedures have been developed for estimating $H(f)$ from the dataset (t_j, F_j) for $j = 1, \ldots, N$. 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:

$$H_C(f) = \sum F_j\cos(2\pi ft_j).$$

(3) Calculate the sum over all j:

$$H_S(f) = \sum F_j\sin(2\pi ft_j).$$

(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 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 then 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. For example, 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. 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 kyr period and a sawtooth wave with a 100 kyr period. The resultant spectra are given in Figure 10.6.

A few additional simple examples follow next.

Consider Figure 10.7. In this figure we plot the function $F(t) = \cos(2t)$ at 17 discrete points, as well as 2 modifications of this function with some noise added.

Let us pretend that we know nothing about the three functions and we desire to carry out a 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 10.8. 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 curve of strength vs. frequency but the main peak remains close to the original frequency without noise.

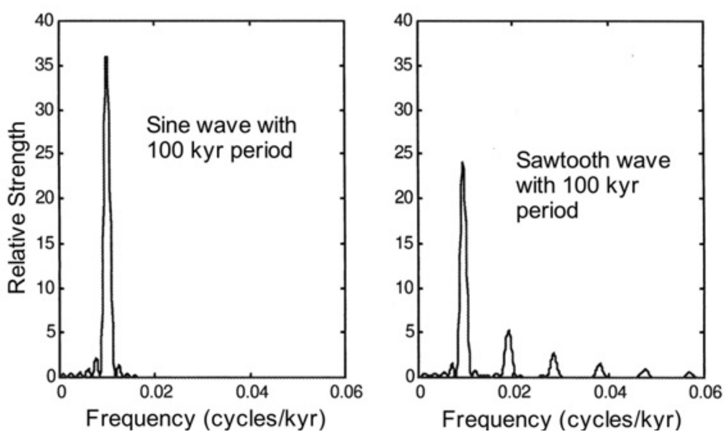

Figure 10.6. Spectra of sine wave and sawtooth wave with 100 kyr periods.

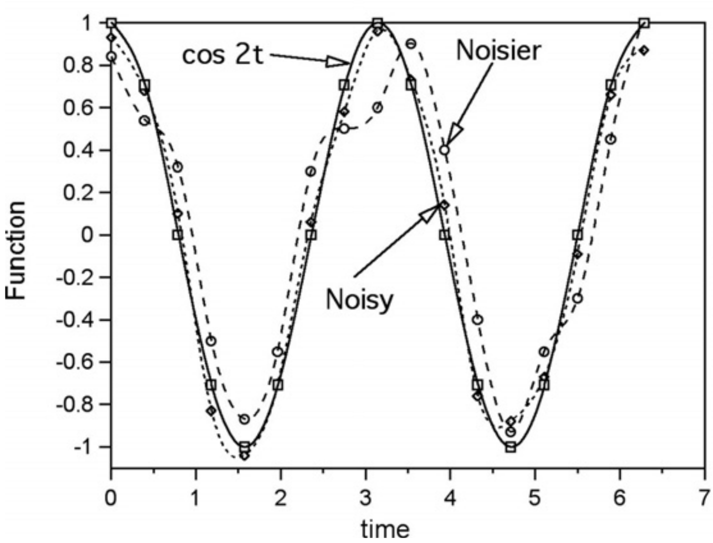

Figure 10.7. Three simple functions for spectral analysis. The solid curve is $\cos(2t)$ and the dashed curves add noise to this curve. The period of the solid curve is π.

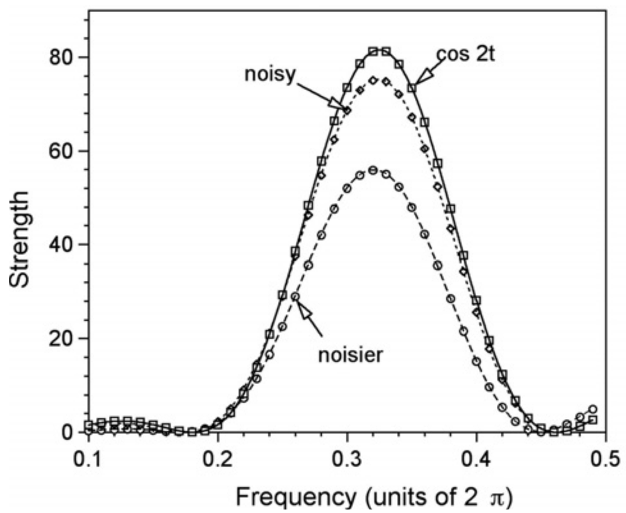

Figure 10.8. Frequency distribution corresponding to functions in Figure 10.6.

As another trivial example, Figure 10.9 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 10.10. 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.

A final simple example is shown next. Figure 10.11 shows a hypothetical function that was arbitrarily formed with a quasi-periodic structure. The frequency distribu-

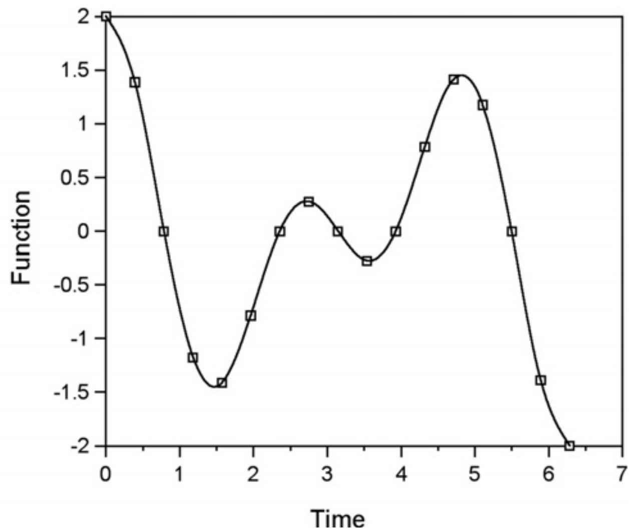

Figure 10.9. Function $F(t) = \cos(1.5t) + \cos(2.5t)$.

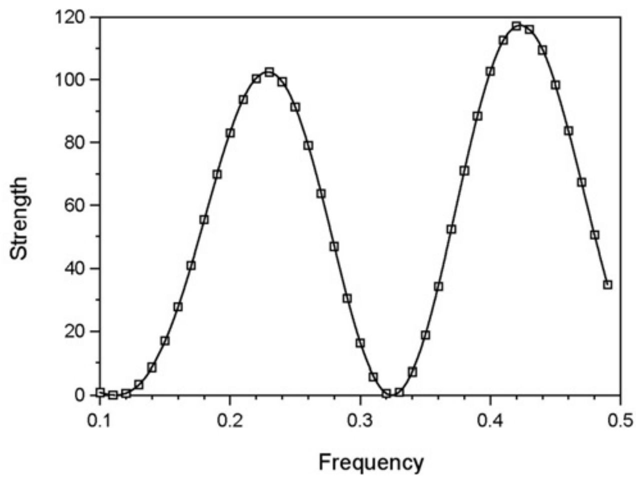

Figure 10.10. Spectral distribution of frequencies corresponding to function $F(t) = \cos(1.5t) + \cos(2.5t)$. Principal frequencies are at 0.23 and 0.42 units.

tion corresponding to this function is shown in Figure 10.12. The principal frequency is 0.5 per unit time. The period is 2 time units.

10.3.2 Spectral analysis of solar and paleoclimate data

M&M described a number of alternate approaches for estimating 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 reporting on their results.

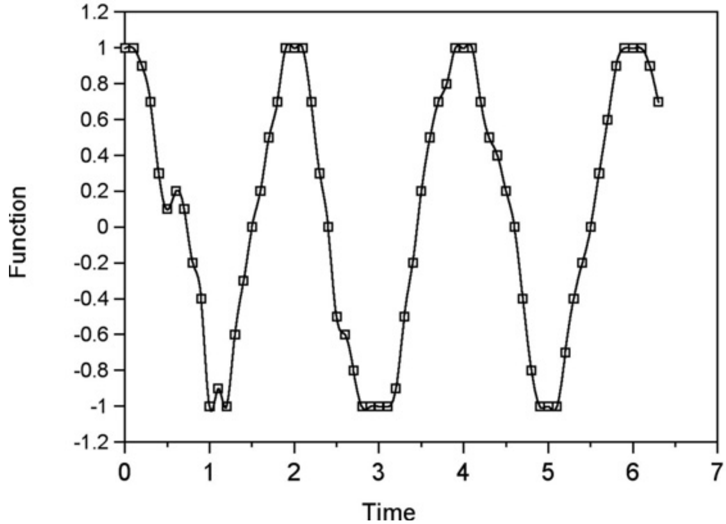

Figure 10.11. A hypothetical function with quasi-periodic behavior.

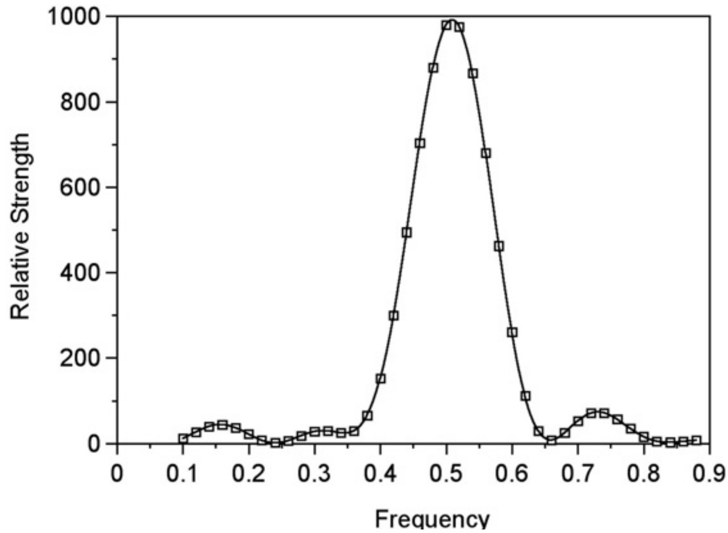

Figure 10.12. Frequency distribution corresponding to function in Figure 10.10.

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 kyr^{-1}, 0.024 kyr^{-1}, and 0.01 kyr^{-1}. Figure 9.7 shows that the dominant factor that determines the oscillations of solar intensity is the longitude of precession. The heights of

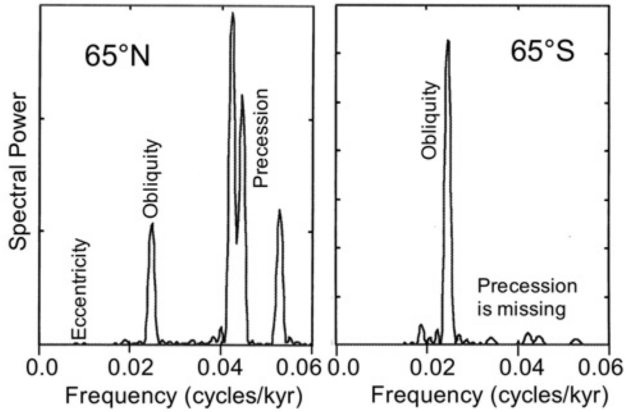

Figure 10.13. Spectra for solar intensity at 65°N and 65°S according to M&M. The 65°S spectrum does not contain a peak corresponding to precession of the longitude of perihelion, and since there is no fundamental difference between the south and the north, it seems likely that the reported spectrum for 65°S is erroneous.

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 Figure 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, ... years ago although 400,000 years ago 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 on the background of a rapidly oscillating time series.

As Figures 9.13 and 9.14 show, the 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 at 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 10.13 shows the spectra reported by M&M for 65°N and 65°S. On the left side of this figure (65°N), we clearly observe the primary peak corresponding to precession of the longitude 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 side of Figure 10.13 (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 10.14.

Spectral analysis of the Vostok deuterium time series was given by M&M and is shown here in Figure 10.15. Even a casual glance at Figure 10.14 indicates the presence of a cycle with a period of roughly 100,000 years. The influence of the

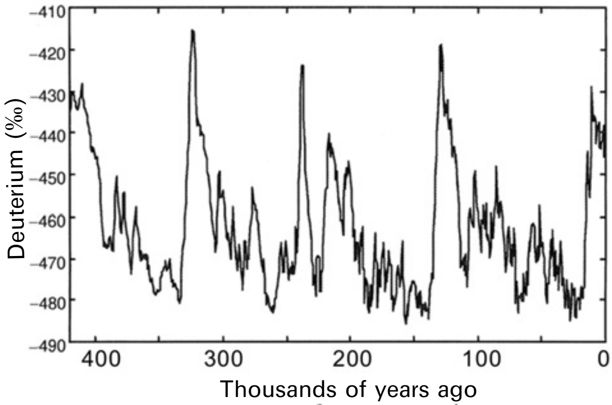

Figure 10.14. Vostok time series (M&M).

spectral peak at 41,000 years in the time series of Figure 10.14 is less obvious. There is a very small peak corresponding to ~22,000 years.

The results shown in Figure 10.15 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, as Figures 9.10, 9.11, and 9.12 show, the variability of solar input to high latitudes is dominated by precession of the longitude of perihelion. Furthermore, the spectrum of variability of Vostok temperature does not resemble the spectrum for solar input (Figure 10.13). 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

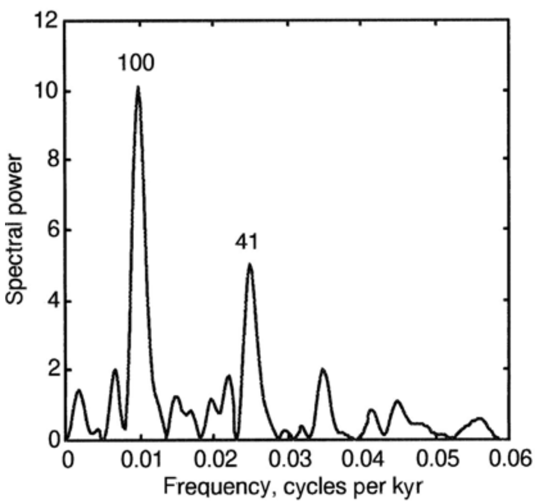

Figure 10.15. Spectrum of Vostok deuterium data according to M&M. The two principal peaks occur at periods of 100,000 years and 41,000 years.

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 4.11) (Jouzel *et al.*, 2007). Spectral analysis of these data was carried out for two time periods: 0–400,000 years ago and 400,000–800,000 years ago (see Figure 10.16). As was the case 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 400,000 years ago, 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.

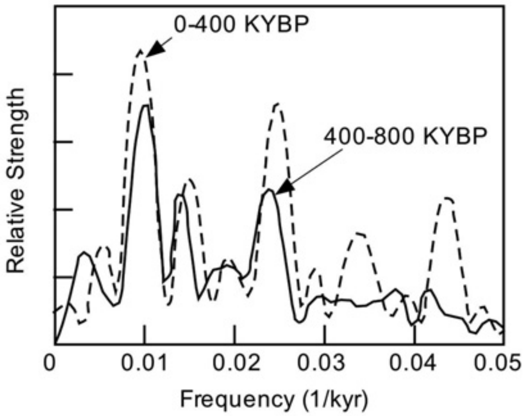

Figure 10.16. Frequency spectra of EPICA Dome C Antarctic ice core data (Jouzel *et al.*, 2003).

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 the 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-year and 100,000-year variability of obliquity and eccentricity. Hence from this point of view, when examining the frequency spectrum of ice core data, the 22,000-year period due to precession is not important; what is important is the amplitude of the 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 SPECMAP. The spectrum for SPECMAP is shown in the left half of Figure 10.17. As can be seen from this figure, all three solar frequencies are represented. SPECMAP chronology was based on tuning to solar variations as expressed in the Imbries' ice model (see Figure 9.16), so it is not surprising that solar frequencies appear. The spectrum corresponding to the Imbries' model is shown in the right half of Figure 10.17. In the Imbries' model, the lowest frequency corresponds to a period of about 400,000 years, and the peak near 100,000 years is no longer dominant. In this case a peak corresponding to precession appears. As in the case of ice core data, the

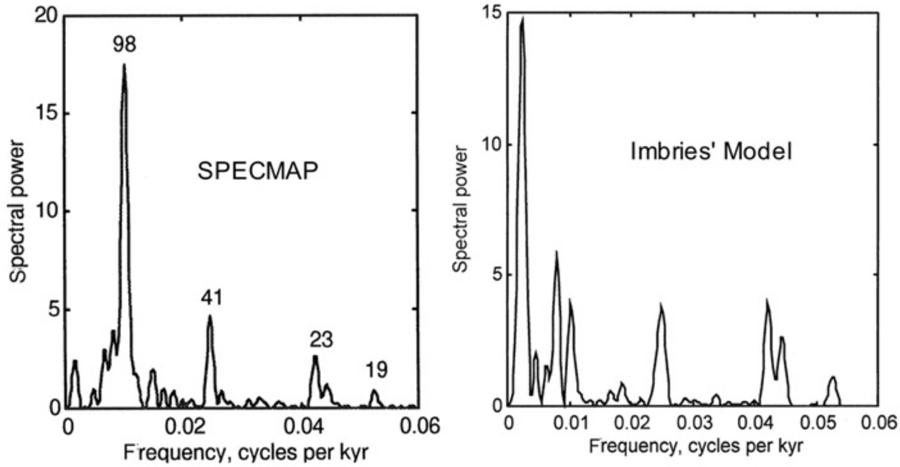

Figure 10.17. (Left) Spectrum of SPECMAP according to M&M. Numerical figures are time periods in thousands of years associated with principal frequencies. (Right) Spectrum of the Imbries' ice model (see Figure 9.16).

results are suggestive of astronomical theory in some ways but the case is far from iron-clad.

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 but it is difficult to resolve this. 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

- 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 the escape of radiation emitted by the Earth.

The net albedo of the Earth depends on a 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 is 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, as well as "hothouse Earth" conditions when all glacial ice was melted and the polar areas were tropical.

Prior to about 34 million years ago, the Earth was much warmer than it is today. About 34 million years ago, the Earth began 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. 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. Another theory postulates a declining CO_2 concentration in the atmosphere as the primary cause of Antarctic glaciation.

About 2.7 million years ago, 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 most recent 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 which, in turn, may affect heat transport to higher latitudes. Third, it is likely that cooler temperatures will reduce water vapor concentration thus reducing the greenhouse effect, and have an (unknown) effect on cloudiness, affecting the Earth's albedo. Fourth, as the 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 the dust and salt content in ice cores. Hence, once an era of heavy glaciation begins, there are forces acting in nature to propagate this trend forward in time. The questions are (1) what triggers the origin of such an ice age 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 heat due to the high heats of 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 and ocean sediments, as well as other sources, that 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 roughly describe the last four ice age cycles. Before that, the regularity of the 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" on 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 data 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 which were 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 temperatures. 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 to some extent. According to astronomical theory, this variability of solar input to higher latitudes has a significant effect on the ability of surface ice and sea ice at higher northern latitudes to withstand the onslaught of summer. It has been theorized that during time periods when solar energy input to higher northern latitudes is lower than average, the lower solar input may "trigger" feedback processes that lead to spreading of ice cover and the start of ice ages. Conversely, time periods with high solar energy input to higher northern latitudes may 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 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 spacing of the ice ages over the past 800,000 years. Even more important is the fact that the coherence was even 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 astronomical theory. There is some reason to believe that ice ages originate at high latitudes in the NH because that is where the great ice sheets grew during ice ages, and the fact 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 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. As Figure 9.6 illustrates, for higher latitudes it doesn't make much difference whether one chooses a June day, a July day, the whole summer, or the whole year. The pattern of solar intensity vs. year will have a similar appearance.

Alternatively, there is some evidence that suggests that the key site for solar-induced climate change might be in the SH, and variations in oceanic transport of heat link the NH to the SH, but with a time delay.

In attempting to compare 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 iron-clad, and involve a number of uncertainties. Nevertheless, accepting 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 the Greenland temperature increase than global temperature increase? If the main driver for climate change is NH solar intensity, how does this relate to Antarctica's climate and temperature? If one ignores these legitimate concerns and merely compares solar intensity variability with the temperature record from ice cores, the results are as shown in Figures 10.1, 10.2, and 10.3. These results are suggestive of an indirect 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 does seem to be some correlation between the amplitude of solar oscillations and ice core temperatures. In many (but not all) cases, the time periods with higher amplitude solar oscillations appear to be associated with increasing temperatures, and the 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. 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—rather, it is only 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 years ago when solar oscillations were minimal.

In a similar manner, even if we accept the proposition that isotope ratios in benthic sediments provide a measure of ice volume, how do we compare these data with variable solar intensity? In order to compare the change in ice sheet volume due to slightly 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 put forth. However, they appear to this writer to be overly simplistic and they do not take account of the complexities of the Earth's ocean and atmosphere systems. Comparison of the Imbries' model with SPECMAP ocean data is shown in Figures 10.4 and 10.5. The agreement is moderate at best and the simple ice model is highly approximate.

And while there are innumerable books, reports, and articles claiming that astronomical theory is proven, the basis for such claims seems flimsy.

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 18,000 years ago that 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. Solar input to high northern latitudes has been decreasing since about 11,000 years ago 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.

At a simplistic level, an examination of 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. And since the Holocene has now been in effect for more than 10,000 years, one may wonder when the next ice age may begin. And indeed, there have been a number 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 islands, etc.) the same forces that produced previous ice ages would likely be prevalent and, sooner

[1] If you insert "the next ice age" into Google, you obtain over 100,000 responses.

or later, a new ice age would develop. Based on Figure 10.1, it would seem likely that in this scenario the new ice age could begin almost any time within the next several thousand years.

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 (one of the world's most prominent climatologists) 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 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 an institutionalized orthodoxy has taken hold of the field and produced biased perceptions. This is important at the outset because it suggests the degree of caution and skepticism that 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, 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 suggests that this may be a major factor in the lack of progress in many areas of science.

Lindzen (2008) describes the politicization 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 overwhelming 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) has 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, as well as the fact that 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 fails 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 we 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 is relevant is 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 current 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. Worse than that, this policy has spawned hundreds of conjectural papers and press releases with heavy use of 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 Extraterrestrial 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 the 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 comparison of the credentials of those who believe it vs. the credentials of those who oppose it.

(3) The belief that 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 on this topic but have merely adopted the view of the consensus.

Lindzen (2008) and Rapp (2008) both describe what is probably the most egregious example of misrepresentation of climatological data. This is the so-called ''hockey stick'' model of Earth temperatures over the past 2,000 years. A study of climate proxies incorrectly concluded that temperatures were essentially unchanged for 2,000 years prior to the 20th century, when they suddenly shot up. This was used as propaganda by climate alarmists, who claimed that temperatures experienced in the 20th century were unprecedented. As it turns out, the claim is bogus but the entrenched paleoclimatogical cabal has diverted criticism of this scandalous misrepresentation of science. This is discussed further in Section 11.1.4.

One of the great achievements of the Internet is that any moron or any expert can voice his or her opinion. And, indeed, there are plenty of both on the Internet, with a great preponderance of the former persuasion. In searching for material on 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 come up at the top of the response list, while websites by individuals are often buried deep in the response list. As a result, the public increasingly is 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 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 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.[2] And, 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 who supports 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 effectively rebuts the CO_2 thesis is only available on an Internet 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 that has exploited the fear of natural disaster. Like the earthquake specialists who continue to warn: "the big one is coming," continued funding requires an atmosphere of fear.

Benestad (2005) discussed the tension between those who study 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."

[2] An anecdote illustrates the point. At a 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 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 over in her grave! While I was giving my talk, one attendee of the alarmist persuasion stomped out of the meeting hall audibly cursing.

However, he did not feel safe leaving it at that, and 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 kneeled 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 past CO_2 concentration in the Earth's atmosphere has tended to vary between about 190 ppm during glacial maxima to about 280 ppm during interglacial periods. Because changes in CO_2 concentration lag changes in global average temperature by perhaps 1,000 years, it seems likely that such changes are primarily effects rather than causes of ice ages. Nevertheless, such changes in CO_2 concentration might provide additional positive feedback to contribute to trends in climate change during glacial–interglacial cycles. 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). Over the same time period that the CO_2 concentration has increased, the Earth has also undergone warming. Many climatologists believe that rising CO_2 concentrations have been the primary cause of this global warming (see Figure 11.2). However, there are difficulties with this interpretation.

The first difficulty is in defining the average temperature of the Earth.[3] Most estimates of the Earth's average temperature are based on land and ocean surface measurements around the globe, with some sort of averaging scheme. However, as Rapp (2008) showed in some detail, the global network of temperature measurements stations with 100 years of data is quite sparse and is 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 over the years of the environment, the instrument or its location, 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. In addition, there are uncertainties in the calibration of long-term sea temperature records.

[3] Donald Rapp's *Assessing Climate Change* (Springer/Praxis, 2008) provides an in-depth discussion of the procedures for estimating global temperatures and the results obtained so far.

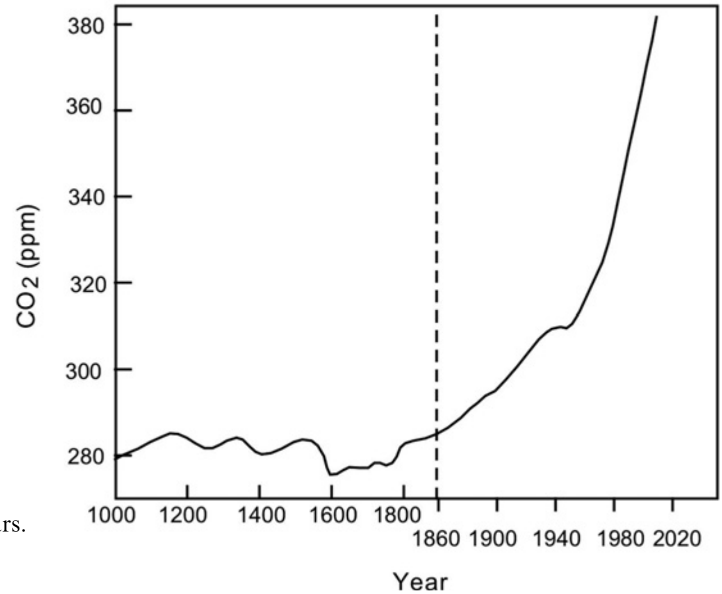

Figure 11.1. Carbon dioxide concentration over the past 1,000 years. Note the break in the timescale at 1860.

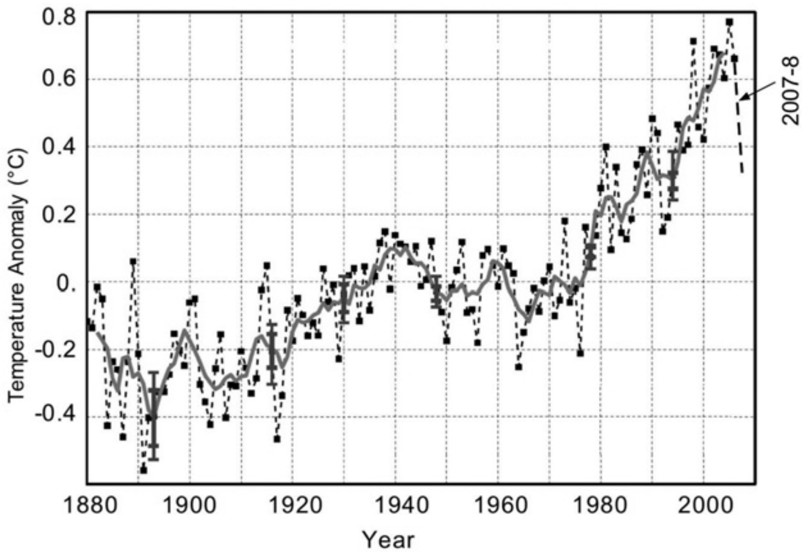

Figure 11.2. Comparison of global temperature with buildup of CO_2 in the 20th century. Global mean temperature anomalies (deviations from mean temperature) from land-based meteorological stations. Points are yearly averages and the heavy line is a five-year moving average.

Rapp (2008) quoted some leading experts in monitoring Earth temperatures who said (among 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. This approach has had significant growing pains. Rapp (2008) describes the difficulties that researchers faced in calibrating these instruments and reducing errors over the past few decades. Thus Christy *et al.* (2007), leading exponents of satellite temperature measurements, said:

> "Deep layer observations from satellites have excellent spatial coverage but suffer from inter-satellite biases, calibration deficiencies, and drifting orbits. Uncertainty in their corrections can be of the same magnitude as the long-term trends being sought. Thus observational uncertainty makes checking the variability of modeled vertical temperature more difficult . . . the production of climate time series from satellites will continue to be a work-in-progress. Usually, developers of data sets underestimate the measurement error ranges of their products. To this point, . . . the degree of veracity of the comparison data sets has not been established."

In a more recent paper, Douglass and Christy (2008) were more optimistic about space measurements, and argued that satellite measurements of temperature are superior to ground-based measurements because they provide a global view and they do not suffer from boundary layer effects or 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.

Earth temperature data based on surface measurements suggest that over the past 120 years or so, temperatures have risen the most in northern latitudes, with less temperature rise in the tropics, and still less 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 11.2).

The dip from 1940 to 1978 was seized upon by 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. The 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 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 the 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 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 or so 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 (2008) found almost perfect coincidence between oscillations in satellite-measured global temperature and an ENSO index since about 1978 (see Figure 11.3). This would seem to suggest that warming since 1978 has been heavily influenced by the Pacific Ocean, rather than by increasing CO_2.

It is noteworthy that in the last year and a half (2007–2008) the Earth's climate has undergone a significant cooling fluctuation (see dashed line at far right of Figure

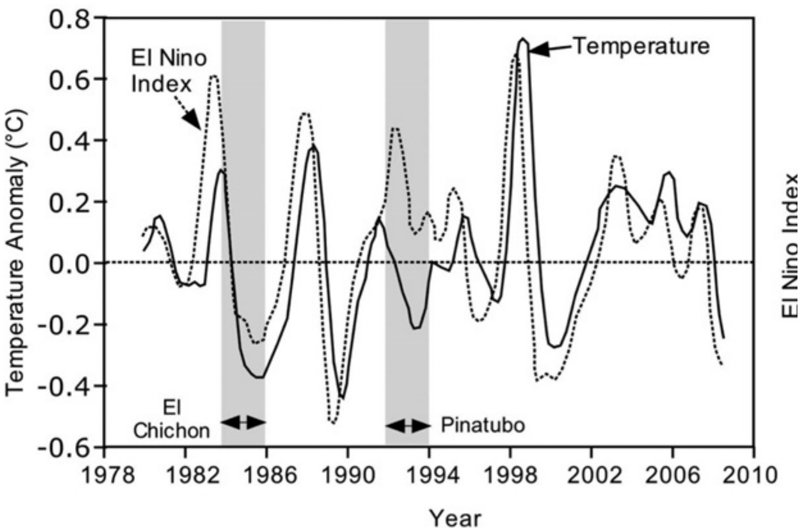

Figure 11.3. Comparison of the measured global temperature anomaly (from space) with an El Niño index (Douglass and Christy, 2008).

11.2). The naysayers greeted this observation with glee and have proclaimed (on many websites) the end of global warming. However, it seems likely that this is merely a short-term fluctuation, since one or two years do not define a trend. Naysayers have also seized upon observations that sunspot counts have been low and the Ulysses spacecraft has observed a 50-year low in solar wind activity in 2007–2008. It is not clear what this portends for the Earth's climate although, according to one theory, this will enhance cloud formation by cosmic rays and lead to further cooling (see Section 8.7.2).

It is noteworthy 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 that said: "2008 was the 36th warmest year in the U.S. since 1895." But we came out of the "Little Ice Age" in 1895, and the warmest years in the U.S. have all been after 1980. Since there were only 28 years after 1980, 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 further implies 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 why many climatologists believe that rising CO_2 has led to global warming is that global climate models predict that increased CO_2 produces 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 11.4 shows a schematic representation of the heating effect of atmospheric CO_2 as a function of CO_2 concentration.

Carbon dioxide absorbs outgoing IR radiation primarily in the absorption band between wavelengths of about 13 μm and 17 μm. The absorption of any wavelength in the atmosphere is dependent on the integral of the absorptivity times the

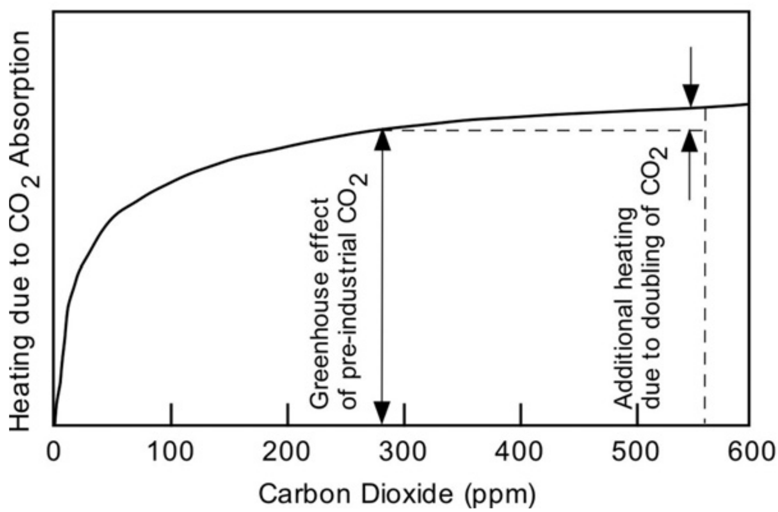

Figure 11.4. Schematic representation of heating due to CO_2 greenhouse effect as a function of CO_2 concentration.

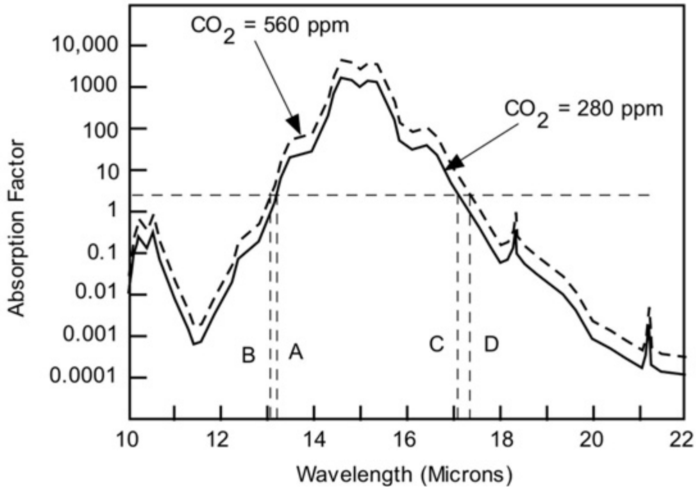

Figure 11.5. Absorption factor (absorptivity × concentration integrated over vertical path through atmosphere) for CO_2 vs. wavelength. The horizontal dashed line corresponds to an absorption factor of 3 (essentially complete absorption along a vertical path through the atmosphere).

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% of complete absorption. As Figure 11.5 shows, with the pre-industrial level of 280 ppm of CO_2, the entire absorption band from 13 μm to 17 μm is fully saturated.

Adding more CO_2 to the atmosphere does not increase the absorption significantly within the saturated region. Only at the "wings" of the absorption band is there any significant increase in absorption by the atmosphere when CO_2 concentration is increased. Thus, with CO_2 concentration of 280 ppm, absorption is saturated between vertical dashed lines *A* and *C* in Figure 11.5.

If, in the future, CO_2 concentration is doubled (from the pre-industrial value) to 560 ppm, 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 regions between *A* and *B*, and between *C* and *D*) is much smaller than the original heating effect in going from 0 ppm to 280 ppm (region between *A* and *C*). Thus we see that, as more and more CO_2 is added to the atmosphere, the heating effect decreases per unit amount of CO_2 added. This is shown in Figure 11.4. Estimating the quantitative shape of the curve in Figure 11.4 is of great importance for understanding the effect of future CO_2 emissions on future climate change. 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 ppm to about 560 ppm sometime later in the 21st

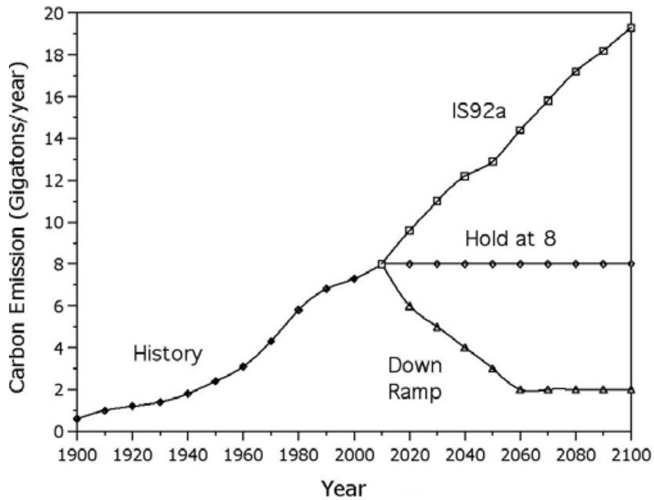

Figure 11.6. Annual emissions of carbon for three future scenarios in the 21st century.

century. The reasons for choosing the benchmark of 560 ppm for the future relate to projection of future world population growth, increasing industrialization of developing nations, and the expected increase in use of coal as the 21st century moves ahead. 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 11.6 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.[4] In the other scenario, there is a downward ramp to lower emission rates as the 21st century wears on. It should be noted that these latter two scenarios require draconian modifications to the way that industrialized societies produce and consume energy. These three scenarios lead to the buildups of CO_2 in the atmosphere as shown in Figure 11.7, assuming that half of the CO_2 emitted ends up in the atmosphere. In the business-as-usual scenario,[5] the CO_2 concentration reaches 750 ppm by the end of the

[4] 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 the business-as-usual scenario.

[5] While this 50% assumption was 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 (2001). 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*, American Assoc. of Petroleum Geologists, Special Publication, Tulsa, OK, pp. 51–82.

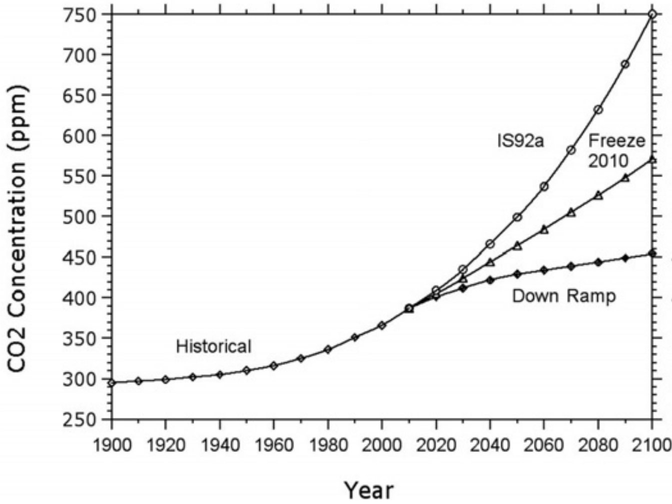

Figure 11.7. Buildup of CO_2 in the atmosphere corresponding to the three scenarios in Figure 11.6.

21st century. If the CO_2 emission rate is frozen at the 2010 level, CO_2 concentration reaches roughly a doubling of the pre-industrial level by the end of the 21st century. Even the down-ramp leads to some elevation of atmospheric CO_2 concentration. Hence, it seems likely that CO_2 concentration in the atmosphere will likely reach 560 ppm before the end of the 21st century.

Thus, faced with the likelihood that CO_2 concentration will rise to 560 ppm (or more) during the 21st century, the question turns to 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 CO_2 concentration as an equivalent amount of downward heat flow, called a "forcing". The units of a forcing 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–oceans–land-mass Earth system. We may denote the forcing due to CO_2 as ΔF_C and the change in global average temperature as ΔT_C (the "additional heating due to CO_2" in Figure 11.4). The relation between these quantities is

$$\Delta T_C = \lambda \Delta F_C$$

where λ is the so-called "climate sensitivity parameter". We use the subscript "C" to denote that this is due solely to the carbon dioxide greenhouse effect, ignoring secondary effects due to this warming. According to the GCMs, the global warming (ΔT_C) produced by the CO_2 greenhouse effect increases evaporation from the Earth's bodies of water, increasing 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 (ΔF_W) which, in turn, produces an additional temperature rise (ΔT_W). In addition, as the humidity of the atmosphere increases, the degree of cloudiness of the Earth's atmosphere increases, resulting in a change in the Earth's albedo. This will produce yet another change in temperature (ΔT_{Cl}). Depending on the nature and distribution of the clouds, this term can in principle be positive or negative but it is most probably negative. To the extent that it is negative, it will reduce the temperature rise induced by increased water vapor. Thus we see that ΔT_W depends on ΔT_C but these quantities affect ΔT_{Cl} which provides (probably negative) feedback. The total temperature change due to CO_2, water vapor, and changes in cloudiness can be expressed as

$$\Delta T_{\text{tot}} = g\lambda\Delta F_C$$

where g is a "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 ΔF_C. A wide range of values has been calculated, but a value of about 3.7 W/m^2 seems to be representative for a doubling of CO_2 from the pre-industrial level of 280 ppm. Estimates of λ in the literature range from about 0.3°C to 0.6°C per (W/m^2). For example, Schwartz estimated λ to be about 0.3, which would suggest that $\Delta T_C \sim 1.1$°C for a doubling of CO_2 from the pre-industrial level (Schwartz, 2007). However, this produced a flurry of comments (e.g., Foster *et al.* 2008) on this paper that led Schwartz to increase his estimate of λ to 0.5°C per (W/m^2) and thus he increased his estimate of ΔT_C to 1.9°C for a doubling of CO_2 from the pre-industrial level (Schwartz, 2008). However, there are many other estimates in the literature, some of which are lower. For example, Tsushima *et al.* (2005) estimated $\Delta T_C \sim 1.2$°C for a doubling of CO_2 from the pre-industrial level based on $\Delta F_C \sim 4$ (W/m^2). Broecker (2001) said that "a tripling of the atmosphere's CO_2 content would lead to only a 1.8°C global warming [not including water vapor effects]." Interestingly enough, Broecker discussed the possibility of an abrupt climate change induced by global warming but he did not seem to mention what direction the change might take (warming or cooling).

Assuming for the sake of argument that the value of λ is roughly ~0.5°C per (W/m^2), the next question is what is g?

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 negative impacts of global warming in the 21st century. Extravagant claims have been put forth, 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 knowledge and no 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 some instances.

As it turns out, the purveyors of GCMs are mainly of the alarmist persuasion and they have prepared a wide range of estimates, many of which indicate that g is roughly of the order of about 3 (or more). That would suggest that $\Delta T_{tot} \sim 6°C$. Such a temperature rise would be truly alarming and one need not be an "alarmist" to be concerned about the severe impacts of such an increase in global temperature. Tsushima *et al.* (2005) estimated $\Delta T_{tot} \sim 4°C$ and suggested that this should be reduced to fit the mid-range of IPCC estimates: 1.5°C to 4.5°C. The wide range of IPCC estimates implies a lack of precision in the methodologies involved. However, the objectivity of the scientists who develop GCMs remains open to question. Chylek *et al.* (2007) estimated that $g\lambda \sim 0.4 \pm 0.1°C$ per (W/m^2) and this would suggest that g is actually less than 1, rather than more than 3. This would lead to the prediction that $\Delta T_{tot} \sim 1.5°C$ rather than $\sim$6°C. Since we have already undergone more than half of this putative temperature rise, the negative consequences of an overall rise from pre-industrial times of 1.5°C do not seem to warrant hysterical responses. All of this presupposes that it is increased CO_2 that has been the cause of global warming.

An important analysis of the effect of CO_2 on climate was made by Lindzen (1997). Many aspects are covered in his paper; only a brief report on some parts is given here. He answered the question posed by the title of his paper with tongue in cheek by saying nothing is impossible. But the real question is 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) 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 among 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, 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 over the smaller temperature change characteristic of global warming, relative humidity would also not change. 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 doubling 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. For example, 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. And 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 a 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 estimation of globally integrated total radiative flux at tropopause levels. 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 do not do a good job of 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 likely that global warming might decrease the humidity of air descending above 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. Drying 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 take an average humidity for the whole Earth are overly simplistic.

The effect of water vapor feedback in amplifying global warming produced by increasing CO_2 concentration requires an understanding of the distribution of humidity changes resulting from warming; a global average of humidity change does not suffice. In addition, of course, even with a thorough understanding of regional dependence of humidity change, one must still cope with the problem of changes in cloudiness. Lindzen and co-workers (2001, 2007) have studied this and made four major points: (1) The 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. (4) The effect of cumulus activity must be included. A simplistic model that merely treats humidity as a global average that increases when surface temperatures rise, that ignores regional changes in humidity, and crudely treats clouds 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 have 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 as 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 to 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.* (2008a) 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, Christy demonstrated a strong correlation of global temperature with an El Niño index since 1978, and particularly for 2006–2008 (see Figure 11.3). Dessler *et al.* (2008a) also found a good correlation of global temperature with 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 the 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.* (2008b) analyzed one month's data in 2005 to infer clear-sky, top-of-atmosphere outgoing long-wave radiation (OLR) and its relationship to humidity. It is not clear to this writer that this paper sheds any light on water feedback sensitivity.

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 La Niña in 2007–2008, world temperatures dropped. 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, when the systems are so complex and poorly understood.

11.1.4 Other evidence

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 it turns out, after due consideration and analysis, 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 will 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 300 to 100,000 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 attention to the more recent past, one issue that can be construed as being relevant 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. 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 is much smaller than the current trend, that would seem to imply that current climate trends probably originate from industrialization and land use. A problem in doing this is that it is difficult to know 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 nonsense.

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 that 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, Bradley and Hughes (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 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 with the so-called "hockey stick" structure: a rather flat profile for most of the past two millennia—prior to the 20th century—with a significant rise in the 20th century.

The papers by Bradley and Hughes and Mann and Jones 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 numerous 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 timespan. The process used for data reduction is too complex to discuss in any detail here. The end result of this work was that it was found 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 horizontal "hockey stick" with the blade pointed 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 a plank in the platform of the 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 Bradley and Hughes (1998, 1999) and Mann and Jones (2003) that 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.[6] The ruling paleoclimatic cabal, ardent alarmists, used their influence to gain support for their basically untenable position from 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, they 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 McIntyre and McKitrick) of basing anomalies on the average 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[7] 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, and 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 (a very small portion of which is shown in the following paragraphs). It seems likely that the combination of mathematically averaging large amounts of democratically treated noisy proxy data will tend to cancel out variations in the past, while use of recent

[6] Climate Audit Website. Available at *http://www.climateaudit.org*

[7] Graphs for all the 1,209 proxies are available at *http://www.climateaudit.org/data/images/mann.2008/*

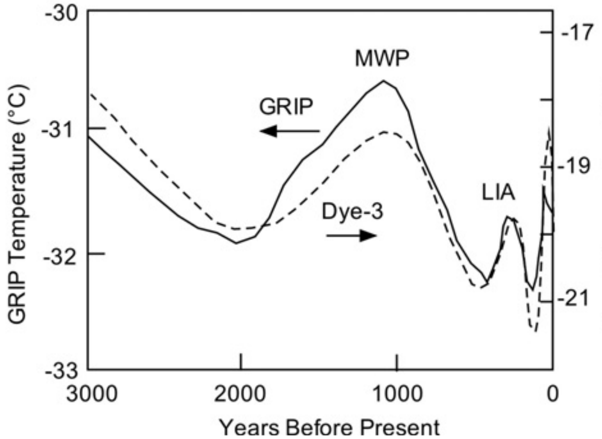

Figure 11.8. Ice core records showing the LIA and MWP.

unreliable terrestrial temperature data, biased by urban heating and other aberrations, will exaggerate the temperature rise of the past century relative to the past. And, indeed, their finding that global temperature increased by 1.0°C since 1900 is considerably greater than what has been widely reported by others. And, of course, Mann *et al.* (2008) failed to notice the fact that Figure 11.3 shows global temperatures, on balance, have not basically changed in the past 30 years. Mann *et al.* (2008) would have you believe that temperatures have risen sharply over that period. The far right of their graphs for the last 30 years show a red line zooming upward.

In actual fact, 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 MWP and the LIA in the GISP2 ice core record. Idso (2008) provided extensive evidence in favor of the existence of the MWP and the LIA.[8] Grove (1988) provided 1,000 pages of evidence for the LIA. In addition, prior to the MWP there were numerous temperature excursions comparable with or greater than current global warming.

Thorsteinsson (n.d.) 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 11.8. Dahl-Jensen *et al.* (1998) presented essentially the same data. The Woods Hole Oceanographic Institute website points out the LIA and MWP 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

[8] Evidence in favor of the existence of the MWP and the LIA is collated at the website *http://co2science.org/data/mwp/mwpp.php*

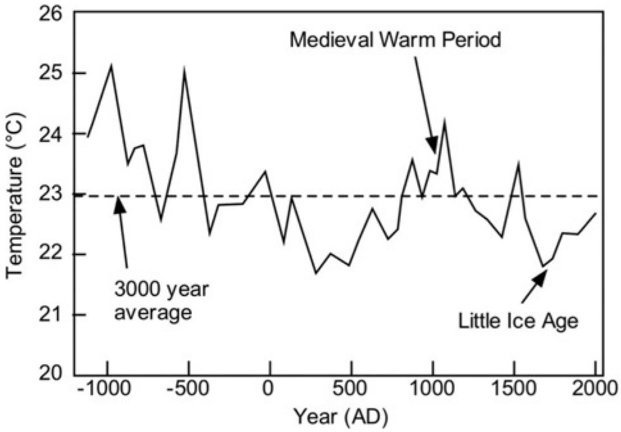

Figure 11.9. Sea surface temperatures in the Sargasso Sea (Keigwin, 1996).

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 marine organism remains in sediments at the bottom of the sea (see Figure 11.9).

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 witnessing mainly another natural fluctuation.

Evidence is also provided by mountain glacier retreat records. Kotlyakov (1996) in his extensive survey of glaciers showed that the rate of mountain glacier retreat has not changed substantially from 1900 to 1982. It has also been claimed that the rate of glacier retreat is unchanged since 1850 although the evidence for this is unclear (Robinson *et al.*, 2007).

Evidence suggests that sea level rise began well before large-scale CO_2 emissions (see Figure 11.10) (Jevrejeva *et al.*, 2008). This would suggest that the relationship between global warming and CO_2 emissions may be weak. According to this study, even though a serious rise in sea level began near the beginning of the 19th century, the pace of sea level rise has oscillated about an upward trendline during the 20th 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. There have been other studies of sea level change with varying results. Cazenave and Nerem (2004) found that sea level rise for the decade 1993–2003 was 2.8 ± 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

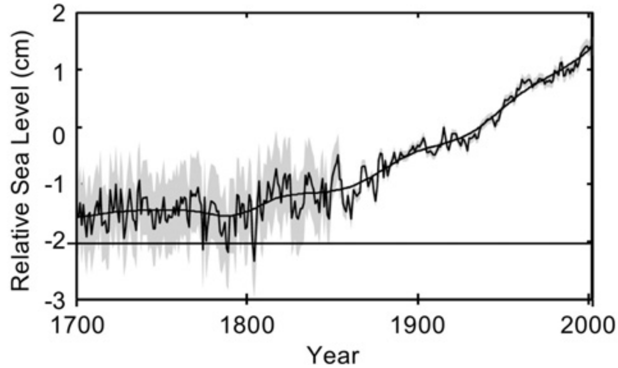

Figure 11.10. Yearly global sea level with 30-year windows. Gray shading represents standard errors (Jevrejeva *et al.*, 2008).

tide gauges. However, Holgate (2007) studied nine long and nearly continuous sea level records from around the world to determine rates of change in sea level for 1904–2003. He found that:

> "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 ± 0.35 mm/yr 1904–1953), in comparison with the latter part (1.45 ± 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 ± 0.16 mm/yr."

We have assembled a variety of data that show there is evidence that global warming began prior to the great buildup of CO_2 in the atmosphere of the past century. There is also evidence that there have been variations in climate over the past thousand years or so that are comparable with the recent global warming that we have witnessed.

Keenlyside *et al.* (2008) modeled sea surface temperatures and the MOC using past data to calibrate their model. They used the model to extrapolate into the future and forecast that over the next decade, "North Atlantic SST and European and North American surface temperatures will cool slightly, whereas tropical Pacific SST will remain almost unchanged. Our results suggest that global surface temperature may not increase over the next decade, as natural climate variations in the North Atlantic and tropical Pacific temporarily offset the projected anthropogenic warming."

11.1.5 Will global warming prevent or initiate the next ice age?

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 the causes of ice ages, it is difficult (if not impossible) to predict whether and when the next ice age will begin. It would be difficult enough to project forward the putative emergence of the next ice age if the Earth were 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 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 has been a great boon to these enthusiasts.[9] There are also blogs that deny the coming of the next ice age.[10]

Basically, there are three considerations in regard to the next ice age. One aspect is the natural turn of events, assuming that ice ages are driven by variations in the Earth's orbit. As we show below, the expectations for low eccentricity in the future suggest that, in the natural order of things, solar oscillations will have low amplitude implying that another ice age may be likely. A second aspect 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.[11] A third aspect 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 $\sim$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. As Berger and Loutre (2002) emphasized, "The small amplitude of future insolation variations is exceptional." They pointed out that a similar trend for solar oscillations occurred around 400,000 years ago (see Figure 10.2) when there was an exceptionally long interglacial period. Hence they suggested that (according to astronomical theory) we might expect a similarly long interglacial period in our future. However, Figure 10.2 shows that the period of low-amplitude solar oscillations began about 450,000 years ago and continued to about 340,000 years ago, and during that period there were both a long interglacial as well as a major ice age (that began to develop around 395,000 years ago). Thus, the period from about 450,000 yeas ago and continuing to about 390,000 years ago, 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 390,000 to 340,000 years ago provides a contrary trend.

[9] For example, *http://www.iceagenow.com/Record_Lows_2008.htm* and *http://www.citeulike.org/tag/ice-age*

[10] For example, *Warming Climate Will Not Cause an Ice Age*. Available at *http://climate-science.org/Spring.2004/index.htm*

[11] However, as we pointed out previously, C. Wunsch (2002) insists (correctly) "The upper layers of the ocean are clearly wind-driven."

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 (Broecker, 1997). 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. While the "popular press" often indicates a severe cold snap, Broecker argued that such an extreme scenario is unlikely, because models suggest that in order to force an ocean conveyor shutdown, Earth would have to undergo a 4°C to 5°C greenhouse warming. Broecker also lamented the lack of an atmospheric model that would lead (from first principles) to the observed large and abrupt changes in climate 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 ± 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) then went on to discuss aspects of the effects of global warming on thermohaline circulation assuming that rising CO_2 induces global warming, relying principally on models. He concluded that warming would have to be extreme (4–5°C) to cause such a shutdown.[12]

[12] However, as we pointed out previously, 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."

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. The poster for the film shows New York City engulfed in a mountain of ice and snow, and is for sale on a number of websites. This film grossed over $500 million. Weaver and Hillare-Marcel (2004) mentioned that this film was to some extent based 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 (North Atlantic component of global ocean overturning circulation). This would produce downstream cooling over the higher northern latitudes, leading to the onset of the next ice age. Alley[13] 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 of freshwater 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 Atlantic overturning circulation with 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 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 resulting from carbon emissions over the next 150 years amounting to anywhere from 300 Gt to 5,000 Gt of carbon. In each case, a "spike" of CO_2 concentration builds up 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

[13] *Abrupt Climate Change*. Available at *http://www.chicagocleanpower.org/alley.pdf*

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 would 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 a non-glacial state to a glacial state over the past 50 million years or so. 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 over 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.[14] 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." But in Section 11.2.1 we emphasized 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 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 that when the Sun is inactive (e.g., as evidenced by lower than normal incidence of sunspots) cosmic ray flux into the atmosphere will increase, leading to greater cloud formation, and climate cooling. The sunspot cycle has recently emerged from solar minimum and the incidence of sunspots has been unusually low in 2007–2008. Climate models do not usually take this into account.

11.2 APPROACHES FOR 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 that 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.

[14] "More on whether a big chill is nigh". Available at *http://dotearth.blogs.nytimes.com/2008/11/13/more-on-whether-a-big-chill-is-nigh/*

Humanity has become addicted to dependence on fossil fuels and, with the growing world population and the industrialization of many developing countries, the demand for fossil fuels will continue to increase in the 21st century in a 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 100 years or so, and many of them believe that continuation of a 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 the 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 that "The United States should reduce its greenhouse gas emissions by between 60 and 80 percent by AD 2050."[15] President-elect Obama proposed an 80% reduction in emissions.[16] 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 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 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) 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

[15] *http://energycommerce.house.gov/Climate_Change/White_Paper.100307.pdf*
[16] *Los Angeles Times*, November 19, 2008.

in journals that found results not necessarily supportive of the 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 in regard to the cause of ice ages which, though not necessarily political, nevertheless represents adherence to orthodoxy. It is widely believed that 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 astronomical theory that are suggestive of ice age cycles, but astronomical theory is lacking in many respects.

As we 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 seem to come from Missouri.[17] 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 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 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, not scientific conclusions. 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 in the blogs is the 830-page detailed rebuttal of the IPCC position written by Idso (2008). The most important thing to

[17] For example, *http://www.trivia-library.com/b/origins-of-sayings-im-from-missouri-youve-got-to-show-me.htm*

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 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; more likely, it was mainly an effect. Superimposed on this long-term secular 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 subsection) there does not appear to be a great deal to be gained from taking 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 at Greenland and climate change at 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 chronologies have less precision and resolution. In this connection, the *West Antarctica Ice Sheet Divide (WAIS Divide)* will collect 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 or so and will be the southern hemisphere equivalent of the Greenland GISP2, GRIP, and NorthGRIP 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 or so. 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. However, drilling is not expected to be complete until well into 2011. Thus it is of great importance that the WAIS project be pursued and completed as planned.

Recently, Stott *et al.* (2007) and Timmermann *et al.* (2008) found experimental and theoretical evidence that the termination of ice ages 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 in regard to 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) that 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.

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 these is 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." Satellites to measure humidity over dry regions over a period of years during which CO_2 is increasing would provide relevant data.

Lindzen (1997) suggested "a proper observational determination of the sensitivity to global forcing." In this approach, one would attempt measurement of the monthly average of top-of-atmosphere (TOA) flux integrated over the whole Earth for several years, along with the measurement of surface temperature over the same period. One would correlate the TOA flux with temperature. A caveat raised by Lindzen is that the 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 glacial–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. After launch in 2009, the OCO mission was supposed to collect precise global measurements of carbon dioxide (CO_2) in the Earth's atmosphere that 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 would 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. However, the OCO launch failed and it plunged into the sea. Presumably, a replacement will be built.

Cosmic ray theory

The possibility that the variability of cosmic ray penetration into the Earth's atmosphere is an important contributor to climate change requires further study. Considering that cosmic ray penetration has been high during 2007–2008 and there has been a strong cooling trend, this requires further investigation.

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