

Introduction and Overview

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Global climate has varied since the most primitive atmosphere developed on earth billions of years ago. This variation in climate has occurred on all timescales and has been continuous. The sedimentary rock record reflects numerous sea-level changes, atmospheric compositional changes, and temperature changes, all of which attest to climatic variation. Such evidence, as well as direct historical observations, clearly shows that temperature swings occur in both directions. Past climates have varied from those that create continental glaciers to those that yield global greenhouse conditions. Many people do not comprehend that this means their living climate also varies—it gets warmer or cooler—but typically does not remain the same for extended periods of time. Human history shows us that in general, warmer conditions have been beneficial, and colder conditions have been less kind to society (Lamb, 1995). We currently are living in a not-yet-completed interglacial stage, and it is very likely that warmer conditions lie ahead for humanity, with or without any human interference. Interglacial stages appear to last for about 11,000 years, but with large individual variability. We have been in this interglacial for about 10,000 years.

Geologic processes are not in equilibrium. Geologic processes are one set of drivers for climate and therefore climate cannot be in equilibrium. This makes assessing any cumulative human impact on climate difficult. What is the range of natural global climatic variability? What percentage of this may be due to human-induced activities? We may perceive the activities of humans to have the greatest impact on global climate simply because we are the advanced life form on earth. Perhaps it is a human trait to assume that the consequences of mankind on global climate must be significantly more important than the impact of “natural processes.” Geology is the one scientific discipline that routinely works backward through significant periods of time to evaluate earth’s natural processes. Our discipline brings both data and interpretation to the debate of the past history of climate, greenhouse gases, and global temperature behavior. Geology also brings to the debate a collection of climate drivers including tectonism (large and small scale), volcanism,

topography, glaciation, denudation, evolution of biota, the hydrologic cycle, carbon sequestration, and interactions between geologic and astronomic events.

The chapters of this book are arranged to take the reader through examples of geologic climate drivers ("Climate Drivers"), documentation of a number of methodologies for establishing ancient temperature and atmospheric gas concentrations ("Methods of Estimating Ancient Temperature"), followed by climate history ("Natural Variability and Studies of Past Temperature Change"), and then examination of some of the geological, engineering, and political effects of climate change ("Policy Drivers"). Many of the chapters are written for the educated lay public rather than technically trained scientists, in an effort to better communicate the geologic science of climate to those who make policy. The authors have summarized the papers of this volume in this introductory chapter. Detailed references for our summaries are in the specific chapters.

One of the most difficult concepts to communicate to the lay public is the scale of temperature changes through time compared with climate change drivers. We have tried to address this with an ordering of climate drivers and timescales (Figure 1), which suggests there is a direct relationship

(continued on p. 4)

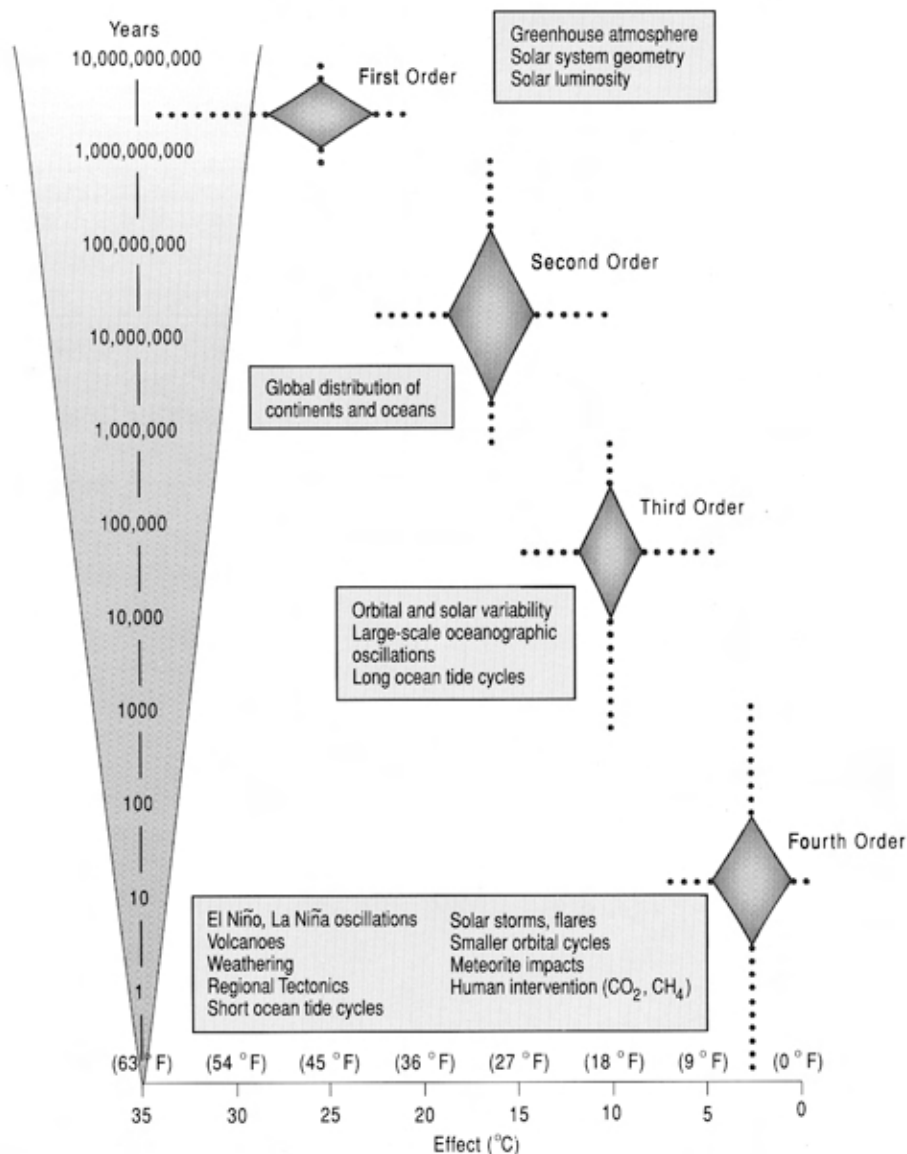
Figure 1 (opposite page) Climate drivers can be categorized by the dual attributes of range of temperature change forced by the driver and the length of time that the driver cycles through. In this graph, the vertical axis is logarithmic (units are powers of 10), and the horizontal axis is arithmetic. This interpretation permits comparison of climate drivers with their potential effects, and separation of drivers of different magnitude. Note that human intervention, which may or may not exist, is in the same category as some other small natural drivers. Diamond shapes are interpreted and literature-documented ranges of values; dots indicate possible ranges of values.

First-order climate controls: Earth has a life-supporting climate because of its distance from the sun, solar luminosity, and the evolution of a greenhouse atmosphere of water vapor, methane, CO_2 , and other gases that trap solar energy and make it usable. This atmosphere evolved over the last 4.5 billion years and continues to evolve. For instance, Berner (1994) suggested that the carbon-dioxide content has decreased over the past 600 million years from 18 times the current concentration (see also Moore et al., 1997, p. 27). The greenhouse effect itself makes the earth 20° – 40°C warmer than it would otherwise be (Pekarek, this volume, Chapter 1; Moore et al., 1997, p. 10, 12).

Second-order climate controls: Distribution of oceans and continents on the surface of the earth controls ocean currents, which distribute heat. This fundamental concept (Gerhard and Harrison, this volume, Chapter 2) explains the 15° – 20° climate variations over hundreds of million of years (Lang et al., 1999; Frakes, 1979, p. 203). Such variations are exemplified by the two major earth cycles between glacial "icehouse" and warm "greenhouse" states. The late Precambrian "icehouse" evolved into the Devonian "greenhouse," then the Carboniferous "icehouse," then the Cretaceous "greenhouse," which evolved to the present "icehouse" state. Redistribution of heat around the earth is determined by the presence of equatorial currents that keep and thrust warm water masses away from the poles. Blockage of such currents, which permits the formation of gyres that move warm waters to the poles, creates the setting that allows continental-scale glaciation.

Third-order climate controls: Solar insolation variability has emerged as a major climate driver, as are the orbital variations that change the distance between the earth and the sun (Hoyt and Schatten, 1997; Frakes, 1979, p. 9; Pekarek, this volume, Chapter 1; Fischer, 1982; Berger et al., 1984). In addition, large-scale changes in ocean circulation through changes in current structure can be significant climate drivers (Broecker, 1997, 1999). Large-scale ocean tidal cycles may drive climate, including the large-scale maximum and minimum associated with the Medieval Climate Optimum and the Little Ice Age, on an 1800-year cycle with a 5000-year modulation (Keeling and Whorf, 2000). These drivers may cause temperature changes of 5° – 15°C over hundreds to hundreds of thousands of years.

Relative Significance of Processes that Affect Climate



Fourth-order climate controls: There are many drivers that control small temperature changes (up to 5°C) over short periods of time (up to hundreds of years). Many are natural phenomena, including smaller-scale oceanographic oscillations (La Niña and El Niño), volcanic activity (such as the eruptions of Pinatubo and Krakatoa) (Moore et al., 1997, p. 47), solar storms and flares (Hoyt and Schatten, 1997, p. 168, 198, 199), small orbital changes (Frakes, 1979; NASA Web site), meteorite impacts, and human intervention (such as human-derived carbon dioxide [CO_2] and methane [CH_4] alterations to atmospheric composition). Tectonic and topographic uplift have small temperature effects and are regional rather than global, but may be of long duration (Ruddiman, 1997, p. 178, 502). Eighteen-, 90-, and 180-year cycles driven by ocean tides have been recognized by Keeling and Whorf (1997), and they drive climate by changing heat transfer rates between oceans and atmosphere.

The authors recognize that the error bars for these interpretations are broad, but the phenomena appear to fall into significant categories of effects and time.

between the range of absolute temperature change and the amount of time over which the drivers operate. This is a general statement, and simply an attempt to place in perspective the various climate drivers, the effect of the drivers on global climate, and the amount of time over which selected natural processes take place. A devolved opinion of the writers is that the less pronounced the effect, the less we understand its origin.

Several general statements are appropriate about natural systems. Climate can vary rapidly and over a range that can have a profound influence on human society. There are predictable geologic effects of climate change that occur in second through fourth order changes (**Figure 1**), such as sea-level changes, rates of glacial movement, ecosystem migration, methane hydrate formation, and agricultural productivity. Finally, we are able to predict that the next ice age cannot take place unless additional global warming occurs. Such warming must be sufficiently large so that the ice of the Arctic Ocean is thawed, thus providing a moisture source for the immense snow and ice accumulations necessary to build continental-scale glaciers (Ewing and Donn, 1956).

CLIMATE DRIVERS

The sun is the primary source of energy for the climate of the earth. Earth's distance from the sun, a function of the geometry of the solar system, is the major factor controlling the base temperature of the earth. During earth's earliest history, solar irradiance was low, but internal radioactive decay likely produced enough heat to melt the earth's crust. Slowly, solar irradiance has grown, perhaps by as much as 25%. Eventually, in perhaps a billion years, the growing solar irradiance will have burned away the earth's atmosphere and made the planet uninhabitable (Hoyt and Schatten, 1997; Pekarek, this volume, Chapter 1). According to current theory, based on solid geophysical measurements of density distribution in the earth, differentiation of the hot earth segregated a core, a mantle, a crust, and an atmosphere of light gases. These gases, which constitute the atmosphere that exists today, have varied somewhat in composition through geologic time, and have caused greenhouse conditions to develop. We know of no scientists who will argue that the greenhouse envelope of the earth's atmosphere, evolved over 4.5 billion years' time, is not the primary temperature control that permits life, as we know it, to exist. Without that envelope, it is likely that the earth's temperature would be 15°–30°C below its present level (Moore et al., 1996, p. 12; Pekarek, this volume, Chapter 1). About 80% to 95% of the total greenhouse gas budget is water vapor (including clouds) and the remainder consists of CO₂, methane, and other gases.

We consider these two effects, solar-system geometry and fundamental greenhouse conditions, to be first-order climate controls (**Figure 1**).

Second-order climate control is by the distribution of continents and oceans upon the planet (Gerhard and Harrison, Chapter 2) (**Figure 1**). The earth has undergone several cycles of icehouse and greenhouse climates, from at least the Vendian (late Precambrian) through the present. Glacial activity is reasonably interpreted at various locations as early as about 3 billion years ago (Crowell, 1999). Temperature variability between the colder and warmer climates is likely between 10° and 15°C (for instance, see Frakes, 1979, p. 170, figures 6–7). Gerhard and Harrison theorize that when continental landmasses are positioned so that equatorial oceanic circulation patterns exist, general global climate conditions are warmer. Conversely, when landmasses are positioned so as to impede or prevent equatorial circulation, "icehouse" conditions prevail. When warm waters are moved to polar regions, high rates of evaporation create continental glaciers and facilitate widespread global cooling. Conversely, strong and persistent equatorial currents preclude heat transfer to high latitudes, and warm conditions prevail. These relationships help to illustrate that thermal

energy or heat is transferred around the earth much more effectively by oceanic circulation patterns than by atmospheric circulation.

Temperature variation under this scenario ranges up to 15°C, with major global impacts. Second-order control of global temperature is natural, driven by earth dynamics, and occurs over tens to hundreds of millions of years. For instance, the Cretaceous “greenhouse” condition changed to the modern “icehouse” condition over a period of 60 million years. There appears to be a relationship between the intensity of temperature variation and the length of time over which it occurs.

Third-order temperature drivers (**Figure 1**) include variability of solar energy caused by actual luminosity changes and by orbital “wobbles” of the planet earth (Pekarek, Chapter 1). Temperature changes caused by these wobbles are named “Milankovitch cycles” (the orbital wobbles were first popularized as climate drivers by Milankovitch; see Pekarek, Chapter 1, for references). Also among third-order drivers are temperature changes that occur by major reorganization of ocean currents (Broecker, this volume, Chapter 4).

Variations in solar energy reaching the earth’s surface modify the climate. Several factors control the influx of solar energy, including variations in (1) the earth’s albedo, (2) earth’s orbit and rotation, and (3) solar energy output. Potential temperature changes driven by these variations can be as much as 10°C and the changes may take thousands of years (Pekarek, Chapter 1). Minor climate changes and those that mark the changes from glacial to interglacial may be the signature of these events (i.e., Frakes, 1979, figures 8–9).

In the short time since 1978, direct measurement of total solar irradiance (TSI) by satellites has shown cyclical variations in solar energy of 0.1% in conjunction with the 11-year sunspot cycle. Indirect evidence from the sun and other sunlike stars indicates that TSI has had significantly greater variation as the sun goes through its energy output cycles.

Correlations between climate and TSI variations are statistically solid. Small variations in TSI initiate indirect mechanisms on earth that yield climate changes greater than that predicted for the TSI change alone. At least three solar variables are known to affect earth’s climate: (1) TSI, which directly affects temperatures; (2) solar ultraviolet radiation, which affects ozone production and upper atmospheric winds; and (3) the solar wind, which affects rainfall and cloud cover, at least partially through control of earth’s electrical field. Each affects the earth’s climate in different ways, producing indirect effects that amplify small changes in TSI. Individually, they do not cause the entire observed climatic changes. Collectively, they create changes. Because solar forcing of earth’s climate is still an emerging science, some effects may not be fully understood. Many of these changes take place in a more or less regular cycle, as if the sun itself has periodic changes. Earth orbital changes are periodic. The most commonly observed solar cycle is the 11-year sunspot cycle. Statistically optimized simulations suggest that direct solar forcing can account for 71% of the observed temperature change at the earth’s surface between 1880 and 1993, corresponding to a solar total irradiance change of 0.5%. The full effects of solar irradiance changes, including Milankovitch effects, must be interpreted from imprecise historical data, because direct measurements have been systematically available only since 1978.

The world ocean is vast, and owing to the specific heat of water, it contains vast amounts of thermal energy. Much of that energy is transferred around the earth through ocean currents. Some is transmitted to and from the atmosphere and controls local weather. Ocean currents are driven by wind, the Coriolis effect, and thermohaline circulation (which depends on density differences of waters entering the ocean). Fresh waters are lighter than saline waters, and warm waters are lighter than cold waters. The density of a water mass will determine whether it rises or sinks in the water column.

Broecker (this volume, Chapter 4) suggests that warm events after glacial events provide low-salinity, thus low-density, meltwaters into the ocean, which tend to float rather than sink in areas where sinking (downwelling) normally takes place. This action interferes with total normal oceanic circulation; for instance, the Gulf Stream may be diverted eastward by meltwaters from the North American arctic, depriving England and northern Europe of heat now moderating their climate. If massive events such as floods of fresh water backed up in proglacial lakes were to spill into the ocean, then very rapid climate changes could take place by changing the ocean circulation patterns. Broecker argues that at least two such events took place near the beginning of the present interglacial stage, with dramatic (up to 4°–5°C) rapid temperature swings in the Sargasso Sea.

Broecker postulates that this process would become effective around the time that atmospheric carbon-dioxide concentrations reach about 750 parts per million (ppm), or about twice ambient. He believes that such concentrations might be reached by 2100. If this is a valid cause and effect, then at some time in the future, assuming that the current interglacial stage continues to full melting of the Arctic Ocean, Broecker expects such dramatic climate changes to occur, regardless of whether human influence is shown to affect climate. If Broecker is correct, then the process to the next “flickering switch” climate change is toward the end of this century. If he is not correct in his assumption of human impact on climate, then the change could occur any time in the next thousand or more years. Fitzpatrick (1995) has discussed such changes without regard to thermohaline circulation. There are few other explanations for the dramatic temperature swings seen in the ice-core records.

A large number of smaller-scale geological climate drivers exist. Among these are volcanic eruptions, meteorite impacts, solar storms and flares, shorter solar cycles, small orbital changes, tectonism (mountain building and erosion), weathering of rocks, small ocean-circulation changes (i.e., La Niña and El Niño oscillations, North Atlantic Oscillation, etc.) and, although not geological, human interventions through increased greenhouse gas emissions. We consider these effects, which may alter climate up to perhaps 3° or 4°C, to be fourth-order climate drivers (**Figure 1**). Some new concepts involving sudden release of massive amounts of methane through methane hydrate disassociation along continental edges have been advanced (Katz et al., 1999). Ruddiman (1997) has compiled an extensive collection of papers detailing tectonism. Well-known effects of the 1883 Krakatoa eruption that affected climate for two years or more and the recent Pinatubo eruption in the Philippines include the particulates blown into the upper atmosphere that caused cooling to take place.

The recent scientific literature is crowded with examples of short-term or moderate- to low-intensity, fourth-order climate-change demonstrations. The public media have documented El Niño and La Niña events. We will not further elaborate on details of fourth-order climate drivers except to present one discussion of the role of human activities’ potential for climate effects (Mackenzie et al., Chapter 3).

Mackenzie et al. in Chapter 3 have modeled the cycles of carbon, nitrogen, phosphorus, and sulfur with the purpose of extracting human contribution to those cycles over the last 300 years. Their conclusions are that fossil-fuel emissions, land-use changes, agricultural fertilization of croplands, and organic sewage discharges to aquatic systems, all coupled with a slight temperature rise, have disturbed the carbon cycle. Land-use changes affect the uptake or release of carbon. Deforestation of Russia and the tropics may result in weakening of the terrestrial carbon sink in the future. Reduction of the thermohaline current transport of CO₂ into the deep world ocean could be a result of increased global temperature, and the increased temperature could then be further increased because of the reduction in sequestration of CO₂ in the deep ocean. In addition, such a change in the intensity of the thermohaline circulation could increase the ability of coastal marine waters to store atmospheric CO₂.

Mackenzie et al. have modeled the effects of the proposed Kyoto protocol on future carbon-dioxide (CO_2) concentrations. Despite a reduction in emissions of CO_2 in their model, concentrations of CO_2 would continue to build because of the continuous emissions of fossil-fuel and land-use CO_2 to the atmosphere, albeit at reduced rates for the former, complex interactions, and a sluggish response of the system to the reduction in emissions. This would be in part due to continued rise of CO_2 in the atmosphere owing to land-use changes and to the fact that CO_2 has an approximate 10-year residence time in the atmosphere. Mackenzie et al. suggest that the Kyoto approach might be useful in reducing the rate of increase of future atmospheric CO_2 concentrations, but only if the physical and biogeochemical mechanisms of redistribution of CO_2 among the atmosphere, land, and ocean do not significantly change from the present.

Other effects that may occur include reduced precipitation of carbonate minerals in biotic frameworks and increased transport of organic carbon, nitrogen, and phosphorus into coastal sediments. They suggest that human factors could impact mineral and organic carbon sedimentation, as already seen in lakes in industrialized countries.

METHODS OF ESTIMATING ANCIENT TEMPERATURE

The geologic record contains a large number of clues about former climate, with which we must compare any changes that we estimate might occur, either naturally or human induced. The methods are not infallible, but the vast majority of the proxies used to interpret past temperatures agree well enough to build a consensus about the more recent geologic past, and general acceptance of large-scale changes in the more distant past. The accuracy of interpretations of past climates declines as we go farther back into the past. Pleistocene climates are well documented, but those of 600 million years ago are less well documented, and those of billions of years ago are poorly documented. It is the nature of the geologic record that records become progressively destroyed by erosion and tectonic cycling as time passes. Parrish (1998) gives an excellent summary of paleothermometry methods.

One possible means to ensure that temperature proxies for past periods of time are robust and not subject to uncertainties related to erosion, tectonism, or sedimentation processes is to develop techniques based on materials that represent well-constrained and continuous time intervals. Reconstruction of paleoclimatic conditions based on the study of stable isotopes in ice core materials is one such proxy, and it has evolved into a well-recognized and powerful methodology. The review paper by Thompson (Chapter 5) illustrates how stable isotopic data are acquired and interpreted, and demonstrates how this technique has emerged as a climatic indicator. Ice-core materials from mid- to low-latitude glaciers represent a time span of approximately 25,000 years and provide valuable insight to regional variation in climate patterns.

Isotopic data are presented for several ice cores collected from three low-latitude but high-altitude locations of the Tibetan Plateau and from the Andes Mountains of South America. The results show that the Tibetan Plateau area experienced warm climates (like that of today) about 3000 years ago. In the Andes, such conditions existed about 5000 years ago.

Thompson suggests that tropical warming, as demonstrated by significant losses of ice mass from low-latitude glaciers, is enhanced by (1) evaporation of oceanic water and (b) the release of latent heat (due to condensation) at higher elevations. He also proposes that water vapor, the most important greenhouse gas on earth, is pumped into the atmosphere at low latitudes. Any increases in CO_2 levels may contribute to an increasing global inventory of water vapor and may strongly influence global changes.

The technique developed by Nagihara and Wang (Chapter 6) relies on data from boreholes drilled into the seafloor as a means to determine variation in bottom-water temperature (BWT) over the last few hundred years. The study is based on 18 temperature measurements collected from an ODP (Ocean Drilling Program) site in the Straits of Florida; the water depth at this location is 669 m. Temperature measurements were made at subseafloor depths between 26 and 348 m, and those from the seafloor down to about 100 m show a different temperature trend from those taken at greater depths. The authors use an inversion technique to detect temporal variation of BWT at the ODP site.

The variation of BWT is compared with Key West surface air temperatures collected between 1850 and the late 1990s and found to be in good agreement. The air-temperature data show higher values between about 1860 and 1885, a rapid cooling during the late 1880s, and a progressive increase for the first half of the twentieth century. The BWT reconstructed history at this location shows the same relationship. Nagihara and Wang use published data for locations off the coasts of Massachusetts and New Jersey to further demonstrate the methodology. The second example involves temperature data collected since 1925 at a water depth of 800 m. These measurements show systematic warming from the late 1920s through the 1970s, and the reconstructed BWT curve shows a similar history.

This technique requires that (1) borehole temperatures are free of drilling disturbances, (2) a sufficient number of measurements are made over small vertical depth intervals, and (3) effects of sedimentation, erosion, and pore fluid movement can be accurately determined. When such conditions can be satisfied, BWT-reconstructed history curves may become very powerful tools for assessing global climate change.

Coralline sponges or sclerosponges live in tropical marine waters but cannot compete with reef-building corals and primarily exist at depths to which light does not greatly penetrate (i.e., below the photic zone). These organisms precipitate calcium-carbonate (CaCO_3) growth rings from seawater to form their exoskeleton structure. Hughes and Thayer (Chapter 7) present evidence that Mg:Ca and Cl:Ca elemental ratios of the precipitated CaCO_3 material have potential application for evaluating past seawater temperatures and salinity conditions. In addition, these workers review the literature concerning precipitated CaCO_3 in fossil ostracodes, mussels, bivalves, etc., and paleotemperature conditions.

A sclerosponge began growing on a submerged marker plate that was attached to a submarine cave wall in July 1989, and it was collected for study nine years later. Chemical analysis of the sectioned specimen was made using energy dispersive spectroscopy (EDS), and elemental ratios were determined at discrete locations across individual growth bands. Temperature and salinity data are known from the specific location where the sponge was growing, and a correlation was developed between them and the measured elemental ratios. The preliminary result was the creation of a curve that provided submonthly temporal resolution and temperature variations on the order of tenths of a degree Centigrade.

This technique has potential as a means to evaluate marine paleotemperature and paleosalinity conditions. Because individual sclerosponges can live for centuries, it may be possible to reconstruct high-resolution seawater temperature profiles for the past 2000 years. Such a tool would be quite powerful in helping to understand and quantify past global climatic conditions.

In addition to techniques that may reveal paleoclimate information from marine settings, some lines of evidence are based exclusively on terrestrial organisms (Ashworth, Chapter 8). Insects, specifically fossil beetles, provide such evidence. The estimated 1 million to 7 million species of beetles account for approximately 20% of all species on earth. They are found in almost

all habitats, ranging from high mountain settings to rain forests. Beetles occupied the interior part of Antarctica until the Neogene, when the growth of the polar ice sheets resulted in their extinction. The fossil record indicates that beetle diversity has not increased due to rapidly changing climate changes. Hundreds of species now in existence have been reported from Pleistocene and Holocene studies. This indicates that different species of beetles do not readily develop over extended periods of time and suggests a pattern of stasis or constancy.

A fossil beetle assemblage collected from northern Greenland demonstrates an unusual level of stasis through approximately 2 million years, even though the climate at that time was significantly warmer than that of today. The number of species remained relatively constant through several episodes of glaciation.

Beetles are highly mobile insects, and their most apparent response to variation in climate is migration from one location to another. This is well illustrated by the replacement (21,500 B.P.) of a forest fauna along the North American Laurentide ice sheet by a glacial fauna when temperatures were approximately 10°–12°C below current ones. When the ice sheet receded (approximately 12,500 B.P.), a forest fauna returned. Overall, beetles have survived global climatic changes due to their mobility, but reduction in areas suitable for habitat make future extinctions more likely.

The use of fossil biosensors to estimate paleoatmospheric levels of CO₂ is an area of active research, and Chapter 9 by Kurschner et al. is especially interesting due to early results as well as potential applications. The technique is based on the fact that all higher land plants rely on stomata to regulate the exchange of gas between the atmosphere and leaf tissue. Herbarium materials collected during the last 200 years and growth experiments conducted under preindustrial conditions all demonstrate an inverse relationship between stomata development and atmospheric levels of CO₂. Elevated levels of CO₂ produce fewer stomata than do decreased levels.

SI (Stomatal Index) values for birch trees dated (by radiocarbon) at 10,070 years are in the 12 to 14 range and correspond to CO₂ levels of approximately 240 to 280 parts per million, volume (ppmv). Birch trees that are 9370 years old have SI values of 6 to 8 and indicate CO₂ concentrations of 330–360 ppmv. Thus, these findings indicate an 80–90 ppmv variation in naturally occurring CO₂ levels over a 700-year period. Additionally, SI data suggest a dramatic change of 65 ppmv CO₂ levels in less than a century.

Several lines of evidence indicate that early to middle Miocene time was one of the warmest periods of the entire Cenozoic. Kurschner et al. studied exceptionally well preserved fossil angiosperm materials of middle Eocene age and found that SI values were elevated. By extrapolation of SI data, the authors offer an estimate of 450–500 ppmv for the CO₂ level of the middle Eocene atmosphere. Based on these results and those obtained over the last few years, it appears that plant biosensor technology has good potential as a proxy for assessing paleoatmospheric CO₂ concentration levels.

NATURAL VARIABILITY AND RECORDS OF CHANGE

Interpretation of geological evidence for climate change results in development of curves that illustrate climate change through time and effects of climate change through time. This section offers four papers that document climate changes over the last few million years (Blumle et al., Chapter 10), effects of climate change on shorelines and thus population in northern Europe (Harff et al., Chapter 12), sea-level changes that are a global response to climate variability (Shinn, Chapter 13), and, finally, some biogeochemical effects of climate variability (Yates and Robbins, Chapter 14).

In a previously published article, Bluemle et al. (1999; also this volume, Chapter 10) have recreated the Pleistocene climate variability in sufficient detail to draw conclusions about the impacts of fourth-order climate changes. Pleistocene glaciations are reflected in second- and third-order drivers (**Figure 1**), but have superimposed on them all of the variability of fourth-order drivers.

Bluemle et al. present several lessons. First, over the last 60 million years, in central Europe, temperature has dropped by more than 20°C (their **figure 1**). In relatively recent times, the Medieval Climate Optimum, or Medieval Warm Event (MWE) (A.D. ~1200–1350), was the time of building of castles, growing of vineyards in northern Europe, and the settlement of agricultural colonies of Vikings in Greenland. This warm period in human history was followed by the Little Ice Age (LIA), from the end of the MWE to about 1850, when temperatures plunged to isolate the Greenland colonies by sea ice and cause their demise by starvation. As Lamb (1995) pointed out, society prospered during the MWE, but suffered greatly from starvation, plague, and pestilence during the ensuing cold years.

The second lesson from the paper by Bluemle et al. involves the range of variation of temperature. The variability of temperature has been constant, especially for those processes considered in the third-order range. Temperature changes such as those discussed above have been regular, although not clearly cyclical, parts of the current interglacial stage. That temperature varies continuously and at all scales is apparent from any cursory or detailed examination of climate data (see also Davis and Bohling, Chapter 11).

Third, none of these temperature changes is human induced, suggesting that the fourth-order changes that might be induced by human activities may be transitory and of relatively low importance. However, there is a major point about climate to be made in context of the Pleistocene record. The graphs clearly show a range of variability, but it is important to note that cold periods are at least as frequent and perhaps longer lasting than warm periods. Bluemle et al. have documented many anthropological records that clearly show the effects of climate change on society through recorded history, as does Lamb (1995).

General circulation models (GCMs) are the basis for much discussion of the role of CO₂ in the atmosphere and as a climate driver. These models tend to examine relatively short time spans for their historical perspectives, and predict atmospheric and climate changes from that perspective. The advent of data from ice cores on Greenland has provided a time series of data that might be usable to extend the GCMs' historical perspective and to validate algorithms. Before using the data, a statistical validation of the data set can identify anomalies in the data or problems in data quality and continuity. Davis and Bohling (Chapter 11) have used 20-year averages to examine oxygen ¹⁸O data from the Greenland Ice Sheet Project II (GISP2) "core." The results of their analysis demonstrate that the last 10,000 years exhibit a general cooling trend and that the current rate of increase in temperatures and warming trend are not unusual compared to the last 10,000 years. Further, past periods of consistently changing temperature have not persisted much longer than the current interval, so temperature trends may well reverse in the near future. The data exhibit distinct cyclic patterns, including a 560-year sequence of relatively abrupt change followed by a gradual reversal (it is possible that the present trend is the initial phase of such a pattern). Determination of the direction of global temperature change is a function of the time span used to make the determination (Davis and Bohling, their **figure 2**). On the 10,000-year interglacial scale, the earth is cooling from the high temperatures of the early interglacial. However, on a 16,000-year record, which initiates in the late Pleistocene glacial episode, the overall effect is global warming. Similarly, the last 2000 years show that the earth is cooling, over the last 600 years it is slightly warming, and over the last decade it is warming. The point of this comparison is to illustrate that picking the time constraint for a model determines the model's outcome, without regard to the complexity of the model.

These are important points. That the current rate of temperature increase is not unusual, despite the human-induced addition of CO_2 , implies that it is not possible to detect a human imprint on earth temperatures. But the fact that the temperature has been declining slowly since the end of the Little Dryas, 10,000 years ago, implies that the agricultural base of human society may be threatened by continued cooling. Human population has dramatically increased since the beginning of the industrial revolution, corresponding to major advances in agricultural output and the advent of modern medicine. Technology has permitted population growth. If the climate becomes colder, will the consequent decline in agricultural productivity reduce global population, or will new technology derive more nutrition from existing crops? Davis and Bohling have made it clear that the historical record of climate is a serious backdrop to future agricultural policy.

Geological interpretations are four-dimensional, that is, they consider time as well as space. Many lay people wrongly assume that sea-level effects are unidirectional, whereas they are actually relative (that is, land elevation changes as well as actual sea level). Harff et al. in Chapter 12 demonstrate that the rise and fall of sea level in the Baltic Sea region is a function of climate-driven eustatic sea-level changes coupled with tectonism and glacio-isostatic rebound. For coasts in the north (Baltic shield), glacio-isostatic rebound is clearly dominant, with rates of uplift up to +9 mm/year. In the south, there is a small amount of subsidence added to a climate-driven eustatic sea-level rise that totals a relative sea-level rise of 2.5 mm/year. In comparison, Shinn (Chapter 13) demonstrates that the rate of sea-level rise in Florida is on the order of 10–20 cm per 100 years (1–2 mm per year).

This means the area south of the Baltic Sea, a densely populated area on a low-lying coastal plain, is faced with climatically controlled retreating shorelines. Harff et al. lay the groundwork for development of strategies for the protection of subsiding coastal areas. The pattern and high rate of sea-level change in the Baltic qualify the Baltic Sea to serve as a “model ocean” for studies that reveal the effects of natural geological processes, including climate change, on human populations along coastlines.

Parenthetically, measurement of sea level is very difficult because of the roughness of the water surface, continually varying tides, slow tectonic movement of the land surface, land subsidence by water withdrawal, and wind effects. Continual improvement in techniques for measurement of actual sea level are critical to predicting the effects of climate change on coastal regions.

One issue that receives popular attention and is of very personal interest to those who live on low-relief coral atolls and islands in the Pacific is the rate and magnitude of sea-level changes to be expected under various climate scenarios. The best way to evaluate such changes is to look at the record of the recent past, the Pleistocene. Shinn (Chapter 13) has summarized evidence to demonstrate that the last interglacial sea-level rise maximum was about 6 m above the present sea level, between about 135,000 and 115,000 years ago (Stage 5e, Shinn's, **figure 1**). This gives a reasonable maximum that can be expected for the current interglacial, that is, based on the assumption that much polar glacial ice will have melted by the end of the interglacial, a 6-m sea-level rise can be predicted. Shinn uses elevated coral reefs and wave-cut notches to correlate the highstand. Much more difficult, according to Shinn, is correlation of lowstands and identification of the total range of sea-level change between glacial (lowstand) and interglacial (highstand) events.

Using new diving technologies and accessing resource exploration seismic and drilling data as well as research drilling data, Shinn has documented lowstand beaches and coral reefs whose elevations are approximately 80 m below present sea level. However, his **figure 1** indicates that the last lowstand was approximately 130 m below standard. Thus a minimum range for sea-level change through a full glacial cycle is 86 m in tropical areas where glacial rebound is not significant.

Of interest is that the sea-level record (Shinn's **figure 1**) approximates the "sawtooth" effect seen in the temperature records, that is, sharp warming episodes that gradually cool. The causes of this sawtooth effect are still being debated, but for glacial and interglacial episodes it may be the result of polar ocean freezing and cutting off moisture to feed continental glaciers, with rapid warming and sea-level rise as a consequence, or thermohaline circulation changes as postulated by Broecker, Shinn, and others (Broecker, Chapter 4; Shinn, Chapter 13).

POLICY IMPLICATIONS

Whether human-induced CO_2 is a significant factor in climate change or not, many businesses are preparing for political intervention in industrial processes to reduce CO_2 emissions. Scientists must recognize that scientific conclusions or data may not be a driver for political action; rather, social and economic issues affecting the immediate well-being of voting citizens supersede more academic approaches. In many cases, scientists have found it difficult to communicate sophisticated and complex conclusions to the lay public and government. Frequently, immediate needs of government supersede what scientists may argue is prudent action, and public perception of scientific issues may deviate from the science. Because of all those factors, it is sometimes prudent to look at technical solutions to issues, regardless of their scientific merit. If political action takes place to reduce anthropogenic emission of CO_2 , it is likely best to lead in introducing sound methods that are the most effective and the least expensive. Therefore, we present several papers that address technology of carbon sequestration and hopefully will help the political process appreciate the costs and effects of considered actions.

Sequestration is the common term used to describe methods for placing CO_2 where it cannot affect atmospheric concentrations. This book contains papers that describe two possible methods. The first, an original piece of scientific research into a generally difficult problem of the origin of lime mud in the ocean (Yates and Robbins, Chapter 14), documents that microbial activity in the ocean may be responsible for generation of lime mud. The chemistry of organic catalysis takes up CO_2 and thus provides a possible method to sequester CO_2 through sedimentation in the shallow ocean. The details of the original research are somewhat technical and may be difficult for the lay scientist to follow, but their summary provides the reader with an overview of the potential for a new geological sequestration process. Biologic catalysis can remove CO_2 from water while producing lime mud, either in sheaths around the microbe or on (or near) the surfaces of cells without sheaths. Both processes result in direct precipitation owing to the microchemical conditions surrounding the microbe. This process sheds light on the controversial question of production of large amounts of lime mud that cannot be accounted for by controlled biologic precipitation or by skeletal abrasion and disintegration.

The second paper (Bachu, Chapter 15) addresses use of subsurface (underground) sedimentary rocks as a long-term (or "permanent") host for anthropogenic CO_2 as one of several possible means to dispose of unwanted CO_2 . The physical state of CO_2 changes phase, depending on temperature and pressure conditions. This permits the gas to be a liquid or hydrate solid in the deep ocean, but the technologies to handle large volumes of CO_2 in this manner are not yet developed, nor are the long-term effects of ocean disposal well understood. On the other hand, the petroleum industry is skilled at subsurface geological exploration and development, and can access potential geological disposal sites with economical technology used in the production of oil and gas. Defining the best potential conditions for geologic disposal of CO_2 means extensive geological analysis of buried rocks and careful interpretation of the geological history of confining structures. Bachu argues that CO_2 can be

sequestered in geologic traps as a gas, a liquid, or in a supercritical state, similar to the natural trapping of hydrocarbons (oil and gas), if the proper conditions exist. Geologic trapping, hydrodynamic trapping, solubility trapping, mineral trapping, and cavity trapping are all geologic possibilities. Trapping in geologic media, whatever the method, may be the easiest and cheapest method to permanently dispose of anthropogenic CO₂. Bachu treats the subject in detail, identifying the criteria that should be used to find and effectively use geologic media for sequestration. Interestingly, some of the CO₂ can be used to produce more petroleum because of the miscibility of CO₂ with oils and coalbed methane, perhaps forming a closed loop of energy production that sequesters as much CO₂ as is emitted. A current research project of the Kansas Geological Survey and the U.S. Department of Energy is addressing this opportunity.

Using statistical methods, Kotov (Chapter 16) has examined the Greenland ice-core record for patterns that can be projected into the future. Using the geological past to understand the present is part of every geologist's training, as is the reverse. Statistical analysis of past climate variability from oxygen isotope and other ice-core data suggests that there are patterns within the apparently chaotic data. Testing these patterns suggests that there is some regularity to climate patterns, and it is this statistically identifiable regularity that forms the basis for future projection of natural variability.

Study of the past permits Kotov to predict the future. The present climate is not significantly different from much of the past, and projected future temperature variations fall comfortably within the range of the variance of the past. Kotov theorizes that at least 200 years of continued natural warming will be likely, followed by a period of natural cooling.

Corroboration of this prediction appears in a very recent related paper (Keeling and Whorf, 2000) about 1800-year tidal cycles that may be responsible for the twelfth-century climate maximum and fifteenth-century climate minimum (Medieval Climate Optimum and Little Ice Age, respectively). Based on their analysis of large-scale tidal cycles, these workers predict that continued natural warming is likely to "continue in spurts for several hundreds of years," before the next cooling episode starts. It is important to note that Keeling and Whorf expect that, "Even without further warming (from greenhouse gases), . . . this natural warming at its greatest intensity would be expected to exceed any that has occurred since the first millennium of the Christian era . . . independent of any anthropogenic influences."

It is usually significant when two completely different methodologies arrive at a similar conclusion independently of each other, and thus we offer these observations to assist readers in making up their own minds on this matter.

The paper by Idso (Chapter 17) is one of two reprinted in this volume by permission of the original publishers. It represents an unusual set of observations, measurements, and interpretations carried out while the author was studying meteorological processes over a two-decade period, wherein he and his colleagues quantified the climatic consequences of several naturally occurring atmospheric phenomena: variations in atmospheric dust content, cyclical patterns of solar radiation receipt, the greenhouse effect of water vapor over the desert Southwest of the United States, etc. This paper, originally published in *Climate Research* in 1998, represents one of the major studies to question the relationship between increasing CO₂ levels in the atmosphere and the concurrent increase in mean annual global surface air temperature, primarily on a meteorological basis.

Based on measurements resulting from eight types of "natural experiments," Idso deduced that raising the air's CO₂ concentration from 300 to 600 ppm should result in an increase in mean surface air temperature of no more than 0.4°C. This estimate is only about one-tenth to one-third of the temperature increase typically projected by numerical simulation results obtained from general circulation models used by climate modelers. After examining various data sets and finding little

evidence that elevated CO_2 levels have affected the earth's surface temperature over the last hundred years, Idso offers the possibility that "the global warming of the past century may have been nothing more than a random climatic fluctuation."

Idso also provides a summary of relative temperature changes over the last millennium. He points out that there were two episodes, each of several hundred years' duration, during which temperatures may have been somewhat higher (the Little Climatic Optimum, or, Medieval Warm Event) and lower (the Little Ice Age) than they are today, and that CO_2 levels, deduced from ice cores, showed no changes over those periods.

Of particular interest in this paper are Idso's descriptions of mechanisms that might enhance the overall cooling properties of the earth if global temperatures were to increase slightly. These negative feedbacks include the likelihood that a 10% increase in earth's low cloud cover would completely cancel the warming predicted to result from a doubling of the air's CO_2 content, plus the fact that a warmer and CO_2 -enriched world would produce clouds with an increased liquid water content and increased levels of cloud condensation nuclei (which allow clouds to last longer and cool the earth longer). And in what may be considered a bit of natural irony, some of these meteorological phenomena can be triggered by elevated levels of CO_2 alone, without an accompanying temperature increase. Finally, Idso indicates his skepticism about the ability of general circulation models of the atmosphere to correctly predict how opposing climatic forces will respond to increased levels of atmospheric CO_2 , and he expresses serious reservations about the use of such models to develop national and international energy policies related to potential climate change.

The final paper in this volume is a philosophic view of the issue of climate change and of the effects of humankind on the earth in general. Jenkins (Chapter 18) addresses the myths of stability of natural systems and the reality of human technological prowess to adapt and prosper in naturally dynamic and unpredictable systems. While developing his thesis of natural variability and yet understanding the public perception of an unchanging world, Jenkins demonstrates the fallibility of assuming stasis. Particularly poignant are his arguments that although warming may be a bother, significant cooling, geologically predictable, could be disastrous for feeding the vastly increasing numbers of people on this planet. Warming may well increase the problems of sea-level rise and provision of fresh water. The natural rates of change may well be accelerated by human influence but likely will not move in different directions. Humans may easily adapt to changes in their environment by using technology and the inherent flexibility of intelligent beings. Once people accept that the world is not dynamically stable, on any timescale, then comprehensive adaptations can begin.

In conclusion, geologists know the earth is a single dynamic system, billions of years old, that is not in equilibrium. A flat, featureless, and uninteresting earth would be the result of equilibrium. Because change is constant, inevitable, and interesting, humankind must embrace change rather than fear it. Adaptation to the changes that continually occur on our planet requires flexibility, planning, and acceptance of the earth-system constraints. Political processes cannot change earth dynamics. Changes that do take place must be placed in context of their real effects. And finally, a major and recurring theme of this volume bears repeating once more. Climate drivers are variable in both time and intensity (**Figure 1**) and—regardless of the largely political belief that human consequences on global climate are pronounced—human influences are of comparatively low intensity and take place over short time spans. The nonequilibrium systems that control natural phenomena on earth very likely dwarf man's ability to affect climatic conditions on a global scale.

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