IMPACTS OF CLIMATE CHANGE ON THE GREAT LAKES BASIN:

PERSPECTIVES FROM THE PAST AND PROSPECTS FOR THE FUTURE

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1. INTRODUCTION

Global climate has been relatively warm since our planet emerged from the end-Pleistocene Ice Age (called the Wisconsin glaciation in North America), but Holocene (the post-glacial epoch) climate has been far from monotonous and has instead been remarkably variable (e.g., Meese et al., 1994; Alley et al., 1996; Overpeck, 1996; Steig, 2002; Meyers, 2002). Nearly all of the changes in Holocene climate have been caused by natural phenomena; only recently have human activities started to play a role in climate change. The consequences of these activities are likely to increase in the coming centuries. Following the premise that the past provides clues to the future, the combination of natural and anthropogenic climate changes will impact the Great Lakes Basin. This white paper presents some examples of past climate changes, considers the nature of future climate changes, and suggests areas of research that will help us to prepare for the future.

The general strategy of this presentation is to employ our understanding of the processes affecting modern climate and weather to interpret past changes in climate so that we can anticipate what the future might bring. However, the caveat from our financial advisors that “past performance is no prediction of future profits” is apt - the past is not likely to be exactly duplicated in the future. Nonetheless, the processes that govern climate should remain the same through time, and examples of how the processes have interacted in the past to create changes in climate can therefore be instructive for the future. In this sense, this document complements the proceedings of two important recent workshops that similarly consider past and future climate change in the Great Lakes Basin (Sellinger and Quinn, 1999; Sousounis and Bisanz, 2000).

1.1. Factors Involved in Causing Climate Change

Climate is the multi-year summation of daily weather and comprises wind, temperature, and moisture. Winds move air masses from place to place and affect rates of evaporation of water. Temperature and moisture interact in complicated ways. Warm air can accommodate more water, so evaporation rates increase. Warm bodies of water increase the temperature of overlying air masses and thereby increase their capacity to carry water vapor. When water vapor condenses, it releases its latent heat of condensation, which warms its host air. Winds consequently move sensible heat, moisture, and latent heat from one part of the globe to others.

Temperatures at and near the surface of the Earth are fundamentally controlled by the balance of incoming solar energy and outgoing radiation of energy to space. The radiation balance is affected by four main factors: variations in the relation of the Earth to the Sun (the Milankovitch cycles) that influence how energy is received by the Earth, variations in intensity of solar radiation, variations in how much solar radiation is reflected back to space and not absorbed by the Earth (the albedo), and variations in atmospheric composition that delay re-radiation of energy to space. It is the interplay of these four variables that causes changes in climate.

The Earth's relation to the Sun varies in three cyclical patterns, and these variations combine to act as the metronome of global climate changes. The first pattern is fluctuation in the Earth's orbit around the sun from being elliptical to nearly circular and then back to elliptical over a period of 100 ky (ky = one thousand years). This cycle is called eccentricity and causes the amount of heat received by the Earth to fluctuate by a very small amount (±0.2%). The second Milankovitch Cycle is called obliquity, and it describes the change in the tilt of the Earth's axis relative to the plane of the Sun. The axial tilt cycles between 24.5° to 22.1° and back to 24.5° over a period of 41 ky. The third Milankovitch Cycle is called precession, and it has two components. In axial precession, the poles describe a circle in space over a period of 19 ky. In elliptical precession, gradual shift occurs in the summer and winter solstice and the spring and fall equinox to different positions on the Earth's orbit around the Sun. This component of the precession cycle takes 23 ky. The combination of the two precessional components have a mean period of 21 ky. The obliquity and precessional cycles do not modify how much heat is received from the Sun, but they are important to how the heat is distributed on the Earth. They cause warmer winters and cooler summers in one hemisphere and the opposite in the other hemisphere and thereby affect seasonal climate.

The three Milankovitch cycles interact to amplify and modulate each other, and the interactions vary over geological time. Glacial-interglacial cycles were dominated by the 41 ky obliquity cycle until about 800 ka (ka = one thousand years ago) and by the 100 ky eccentricity cycle since that time. The precessional cycle has created repetitive 21-ky climate changes in temperate latitudes as the seasonal differences between summer and winter have waxed and waned. The most recent period of precessionally amplified seasonality corresponds to the mid-Holocene Hypsithermal (9 to 5 ka).

Small variations occur in the radiative intensity of the Sun. Some of these are cyclical, but others seem to be random. The best-known variation is the 11-y sunspot cycle, which creates a change of about 0.1% in solar intensity. Apparently random variations in the strength of solar emission occur; a good example is the Maunder Minimum (1645 to 1710 AD), which coincides with the coldest part of the Little Ice Age.

Surface heating of the Earth is strongly affected by the albedo. Surfaces like the ocean, large lakes, deserts, glaciers, and snow fields have high reflectivities, whereas rough, rocky areas and vegetated areas have low albedos. The albedo of continents that have cold winters and warm summers, like North America, Europe, and Asia, changes with the seasons. It also changes over longer periods of time, such as glacial-interglacial cycles. In addition, humans modify the albedo of land areas by removing natural vegetation and replacing it with tilled farm fields, roof-tops, paved roads, and parking lots, which all absorb more heat than vegetated surfaces.

The atmosphere acts as a thermal blanket for the Earth. In the “Greenhouse Effect”, sunlight (short-wavelength radiation) passes easily through the atmosphere to illuminate and heat the surface of the Earth, but the passage of heat to space is decreased by absorption by some of the gases that make up our planet’s atmosphere. The result is that the surface of the Earth is about 30°C warmer than the surface of the Moon, which receives the same intensity of solar radiation and has an average temperature of -15°C.

The atmospheric gases that are responsible for the Greenhouse Effect are water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), nitrous oxide (N_2O), methane (CH_4), and some other minor gases that also contain three or more atoms in their molecules. Approximately 70% of the Greenhouse Effect is due to water vapor alone because this gas is the most abundant “Greenhouse Gas” in the lower atmosphere. Carbon dioxide is the second most important Greenhouse Gas. Since the beginning of the Industrial Revolution, the concentration of carbon dioxide has increased from 280 parts per million to its present value of 360 parts per million, and estimates predict that it may reach 500 to 700 parts per million within another century. Because of the heat-absorbing capacity of this gas, it is reasonable to predict that an increase in carbon dioxide concentration of this size will warm the surface of our planet, perhaps by as much as an annual global average of 3°C, which is about the same as the temperature change between the last Ice Age and modern times.

1.2. Evidence of Prehistoric Climate Changes Provided by Sediment Records

Compositions of lake sediments reflect the environments that exist within the lake and in its surrounding catchment. Past changes that have occurred in these environments commonly appear as distinctive differences in the contents of sediments that have been deposited over the record provided by the successively deeper and older sediment layers (cf., Fritz, 1996). Climate changes are a major environmental variable. Lakes in temperate latitudes are usually especially sensitive to climate changes because their seasonal stratification and primary production respond strongly to annual cycles.

A particularly valuable feature of lake sedimentary records is that they provide a history of continental climate change. Whereas land areas are subject to erosive forces that alter and erase evidence of earlier times, lake bottoms are usually locations of accumulation and storage of this evidence. Furthermore, different components of the sediments (Table 1) can be affected in distinctive ways by the changes that occur over time. Relative amounts of annual precipitation, origins of air masses that convey water to lake watersheds, annually averaged regional temperatures, and magnitudes of seasonal temperature ranges are some of the continental paleoclimatic factors that can be unraveled from lake sediment records.

Sediment records from North American lakes have provided a continent-wide perspective of local and regional responses to post-glacial climate variations. A brief interlude of post-Younger-Dryas cold climate (the Preboreal Oscillation, 9.6 ^{14}C ka) is evident in lake sediments from the Great Lakes region (Anderson et al., 1997; Yu and Eicher, 1998). The mid-Holocene Hypsithermal ((~9 to 5 ^{14}C ka) is recorded as a period of warm and dry climate in much of the central continent (Krishnamurthy et al., 1995; Schwalb et al, 1995; Dean et al., 1996; Haskell et al., 1996; Hassan et al., 1997), but as a time of warm and wet climate in the eastern Great Lakes area (Dwyer et al., 1996; Silliman et al., 1996). A period of warm and dry climate from 4.8 to 2 ^{14}C ka is reported in lake sediment records from the southern Ontario (Yu et al., 1997). These local and regional responses are parts of the global pattern of Holocene climate instability evident in ice cores (e.g., Meese et al., 1994; Alley et al., 1997).

2. POST-GLACIAL CLIMATE CHANGES IN THE GREAT LAKES BASIN

Climate change in the Great Lakes Basin over the past 20 ky (Table 2) has been strongly linked first to the Wisconsin glaciation and its recession and then to global phenomena that have been modified by regional agents. Delivery of water has fluctuated as climate gradually warmed, the rate of glacial melting changed, and drainage channels opened and closed. The shapes and volumes of the lake basins have changed as the delivery of water fluctuated and as glacio-isostatic rebound slowly elevated land areas. The rebound continues (Fig. 1), although at slower rates than initially.

The collective volume of the modern Great Lakes (24,620 km^3) exceeds that of Lake Baikal (23,000 km^3) - the world's single largest lake - and represents over 20% of the fresh water on the planet. The total surface area of the lake system is impressively large (245,240 km^2), yet the total of the land areas that drain into the lakes (521,700 km^2) is only a little over twice that of their surface areas. As a consequence, many parts of the lakes are not directly influenced by land runoff, and the lakes are especially sensitive to variations in the amounts of direct precipitation that they receive and to fluctuations in evaporation from their surfaces. Differences between volumes of the individual lakes create a range of hydraulic residence times (Table 3). Moreover, the large surface areas and thermal masses of the lakes make them agents in creating their own local climate regimes.

2.1. End of the Wisconsin Glaciation and Post-Glacial Evolution of the Great Lakes Basin

Sedimentary records in the Great Lakes date from retreat of the Laurentide ice sheet from the lake basins about 12 ka (Larson and Schaetzl, 2001). Although continuous at most locations, records are sometimes punctuated by hiatuses that reflect slumping, underwater erosion, and changes in lake level resulting from postglacial isostatic rebound and downcutting of drainage channels (cf. Rea et al., 1980, 1981; Larson and Schaetzl, 2001). Lake levels became stabilized at essentially modern depths about 4 ka.

Information about climates prior to 4 ka is difficult to obtain from the sediment accumulations in the Great Lakes themselves because their sediment records reflect both isostatic changes in their basins and the effects of climate change. Fortunately, many smaller lakes exist in the Great Lakes Basin. These lakes have been affected by the same changes in climate that the large lakes have experienced, yet their smaller catchments have not been as sensitive to the effects of isostatic uplift as the large lakes. Consequently, the sediment records of the small lakes provide important histories of post-glacial climate change in the Great Lakes Basin.

2.2. Records of Holocene Climate Changes in the Great Lakes Basin

Climate has undeniably changed in the Great Lakes Basin since the end of the Wisconsin glaciation. Following retreat of the glaciers, land ecosystems in the Great Lakes region began a progression from tundra to boreal forests to mixed temperate forests dominated by deciduous trees in the south and coniferous ones in the north (Webb et al., 1997). Most of the evolution of land plants was in response to warming, yet variations in moisture were also important. Furthermore, the changes in climate have not been a simple unidirectional trend; both temperature and moisture have fluctuated (e.g., Table 2). Lake water balances have been affected by both variables.

2.2.1. Austin Lake hydrogen isotopic record: evidence of warm, dry climate during the Hypsithermal

The hydrogen isotopic contents (δD, which represents the ratio of ^2H, or deuterium, to ^1H) of sedimentary organic matter from Austin Lake, Michigan, record changes in the Holocene climate of the Great Lakes Basin. The lake is a typical kettle lake, formed about 12 ka by melting of ice blocks stranded during retreat of the Laurentide ice sheet. Because the main recharge of lake water is from direct precipitation and the principal manner of outflow is as groundwater, the composition of the lake waters is virtually the same as meteoric waters. Moreover, in the absence of any important fluvial or groundwater inflows, the main source of organic matter to the lake sediments is plant production within the lake.

Because the hydrogen contents of aquatic organic matter originate from lake waters, the δD values of lake-derived organic matter can be used as recorders of the hydrologic balance of a lake and also of the sources of meteoric water to a lake. Two principles are involved. The first is that water molecules that contain the lighter isotope of hydrogen evaporate more readily than molecules that contain the heavier isotope, which leaves the remaining water richer in ^{2}H. The second principle is that water molecules containing the heavier isotope precipitate more readily from the vapor phase than the those with the lighter isotope, which makes the remaining water vapor richer in ^{1}H. The two principles combine to produce water vapor that is depleted in ^{2}H relative to average ocean water and that consequently has negative δD values. Furthermore, as air masses move farther from where they picked up their water vapor, their δD values become more negative because of preferential precipitation of water molecules containing ^{2}H.

Krishnamurthy et al. (1995) measured the δD values of the sediment organic matter that accumulated over the past 12 ky in Austin Lake. The δD values separate into four time intervals, which Krishnamurthy et al. (1995) interpret to reflect changes in Midwestern climate. Especially prominent among these intervals is a period between 9 ka to 2 ka during which δD values increase to *ca*. -75‰ from values that average -110‰ earlier and later. This period generally corresponds to a time of aridity that was widespread throughout the Great Plains and Rocky Mountain regions of North America (Dean et al., 1996). Krishnamurthy et al. (1995) postulate that the less negative δD values result from the evaporative distillation of the hydrogen isotopic contents of the lake waters that would occur in a warm, dry climate.

However, an additional factor that could be involved in the variations evident in the Austin Lake δD record is a change during the Hypsithermal in the relative importance of the three main air masses that bring meteoric water to the Great Lakes Basin (Fig. 2). For example, if the proportion of precipitation from the moist, warm Gulf of Mexico air mass (mean δD = -35‰) increased, then the organic matter δD values would become less negative as is reported by Krishnamurthy et al. (1995). This intriguing possibility remains unresolved.

2.2.2. Lowered Lake Erie water-levels during the Hypsithermal

Lake Erie is more likely to record the effects of climate change because of its short hydraulic residence time (Table 3) and because its basin has not experienced as much glacio-isostatic modifications as the other Great Lakes (Fig. 1). Lewis (1999) notes that the modern hydrologic balance of Lake Erie is barely positive if inflow from Lake Huron (via Lake St. Clair) is neglected. This inflow was established between 5.5 to 5 ka (Larson and Schaetzl, 2001, and sources therein). Lewis (1999) postulates that water supply to the Lake Erie Basin was probably less than present during the early Holocene because of the combination of greater insolation, different atmospheric circulation patterns, and absence of discharge from the upper Great Lakes. The consequence was lowered lake levels.

Geological evidence of lowered lake levels during the Hypsithermal exists as drowned beaches, erosion surfaces, and peat layers that are found 10 to 27 m below the rebound-adjusted Niagara River sill depth (Lewis, 1999). Hydrochemical evidence exists in heavy oxygen isotopic compositions of ostracods and mollusks that lived between 10 and 7.5 ka (Fritz et al., 1975). These independent lines of evidence suggest that Lake Erie was a hydrologically isolated closed system during the early Hypsithermal, which indicates that the regional climate was warm and dry.

2.2.3. Owasco Lake strandlines: evidence for wetter climate during the Hypsithermal

Owasco Lake is one of the 11 Finger Lakes of upper New York State, which all drain to the north into Lake Ontario and as such are part of the Great Lakes Basin. Dwyer et al. (1996) conclude from the existence of elevated strandlines around Owasco Lake that a relative highstand occurred during the Hypsithermal. Their evidence shows that lake level was peaked ~6.9 ka at about 3 m higher than at any other time in the Holocene. After allowing for glacio-isostatic rebound and drainage channel downcutting, Dwyer et al. (1996) concluded that the elevated strandlines recorded a 2600-year-long period of regionally wetter climate in the last half of the Hypsithermal. Their conclusion is supported by pollen-based estimates of surface moisture that indicate a 50% increase in annual precipitation in central New York State between 9 and 6 ka (Webb et al. (1996). In addition, increases in delivery of land-plant organic matter and of coarse sediment grains to the Rochester Basin of eastern Lake Ontario similarly led Silliman et al. (1996) to conclude that the Hypsithermal was accompanied by a wetter climate in this part of the Great Lakes Basin.

The indications of a wetter climate during the Hypsithermal in central New York State contrast dramatically with evidence for a warmer yet drier climate elsewhere in the Great Lakes Basin ((Krishnamurthy et al., 1995; Lewis, 1999) and in most of North America (Schwalb et al, 1995; Dean et al., 1996; Haskell et al., 1996; Hassan et al., 1997). Locally important changes in the mid-Holocene air mass trajectories that brought moisture to the Great Lake region are the most likely reason for the dramatic differences over such relatively small geographic distances.

2.2.4. Seneca Lake sedimentary calcite: evidence for climate instability at the end of the Hypsithermal

Seneca Lake is the largest and deepest of the Finger Lakes. The present morphology of the Finger Lakes results from deepening of existing stream valleys by the Wisconsin glaciation, which explains why the lakes are narrow and long and why some, such as Seneca, have bottom depths that are below sea level. The narrow and deep basins make the lakes excellent collectors of undisturbed sediment records of environmental changes that have occurred since the ice sheet retreated from this region at approximately 14 ka.

The calcite that precipitates from the surface waters of hard-water lakes like Seneca offers a potentially valuable, high-resolution sedimentary record of environmental changes and particularly those caused by climate changes (Kelts and Talbot, 1990; Hodell et al., 1998; Mullins, 1998). Summertime calcite precipitation events (whitings) are well-known in the modern Great Lakes (Strong and Eadie, 1978; Hodell et al., 1998), which reside in carbonate-rich catchments. Precipitation of calcite occurs when the solubility product of $CaCO_3$ is exceeded (i.e., the water is supersaturated with respect to calcite) and nucleation sites for crystal formation are available. Calcite has retrograde solubility – it becomes less soluble in warmer water. Furthermore, primary productivity affects solubility by removing CO_2(aq), increasing pH, and shifting carbonate equilibria towards CO_3^{2-}, thereby favoring calcite precipitation. The combination of warmer surface waters and longer duration of primary production magnifies Great Lakes whiting events in years when thermal stratification is better developed (Schelske and Hodell, 1991; Hodell et al., 1998). These conditions dominate times of warmer climate.

The calcite contents of lake sediments from the Great Lakes Basin have varied systematically since the end of the last glacial period. Concentrations are highest in sediments deposited during the Hypsithermal in Lake Ontario (Silliman et al., 1996), Seneca Lake (Anderson et al., 1997), and Cayuga Lake (Mullins, 1998). This pattern has been interpreted to result from the warmer summers that persisted during this period of warmer climate. The warmer summers induced earlier seasonal stratification and lengthened the time of algal removal of CO_2(aq) from the surface waters (Mullins, 1998). Greater amounts of calcite consequently precipitated and are recorded as higher concentrations in the sediments that accumulated during the Hypsithermal.

Closely spaced measurements of $CaCO_3$ concentrations in a 5.4 m-long sediment core from Seneca Lake have revealed new, high-resolution evidence of local climate instability during the Hypsithermal and especially its termination (Meyers, 2002). Calcite concentrations fluctuate strongly and regularly between 6 and 14 wt% in sediments deposited between 6 and 4 ka. The durations of these variations are on the order of 2-3 centuries. Interestingly, Steig (1999) documents evidence of increased global-scale climate variability starting around 7 ka in the δD values of the Taylor Dome (Antarctica) ice core that is similar to the Seneca Lake record. This correspondence reminds us that the Great Lakes Basin responds both to global climate forcings and to regional factors.

2.2.5. Seneca Lake calcite δ^{18}O: evidence for early Holocene regional climate modification

The Seneca Lake sediment record provides one of the examples of increased calcite precipitation associated with the warmer climate of the Hypsithermal that was discussed in section 2.2.4. It also illustrates a shift to heavier oxygen isotopic composition of calcite (Fig. 3) that indicates evaporative removal of isotopically lighter water molecules. However, both the calcite concentrations and the calcite δ^{18}O values show reversals of the warming trend between 10 and 8 ka (interval 2 in Fig. 3). Anderson et al. (1997) speculate that this interval of cooler climate in the heart of the Hypsithermal may reflect a pulse of cold glacial meltwater into the Great Lakes that cooled regional summers, which are usually the times of greatest calcite precipitation and lake water evaporation.

This evidence of regional climate modification is an indication that the large areas and volumes of the Great Lakes can exert important effects on the climates of surrounding land areas. The well-known “lake effect” precipitation belts on the downwind sides of the lakes are modern examples of the mini-climates that are created by the lakes. In a broader perspective, this example shows that local and regional factors can overprint and sometimes even overwhelm global agents of climate change. The Hypsithermal was a period of precessionally magnified seasonal contrasts – warmer summer and cooler winters in the northern hemisphere – yet regional cooling in the eastern Great Lakes Basin was superimposed on the hemispheric pattern of warmer summers.

2.2.6. Historic fluctuations in lake levels

Since evolution of the modern Great Lakes about 4 ka, the most important natural influence on lake levels has been climate and its impacts on input and removal of water to the lake basins. Humans have recently affected lake levels by artificially deepening drainage channels and by regulation with artificial spillways (Lakes Superior and Ontario). However, climate changes, or at least year-to-year changes in weather, maintain a strong control over the rises and falls of lake levels.

Highest lake levels usually occur during prolonged periods of greater precipitation, which increases delivery of water to the lakes, and during times of cooler temperatures, which suppresses evaporation of water from the lakes. Conversely, lowest lake levels commonly correspond to diminished precipitation and warmer temperatures. The relatively large surface areas of the lakes makes them especially sensitive to evaporative losses. For example, the lowest recorded level of Lakes Michigan-Huron corresponds to the peak of the Dust Bowl in 1934 (Fig. 4).

The maximum fluctuation in lake levels is less than 2 m, which is small compared to the great depths of most of the Great Lakes (Table 3). However, low lake levels seriously impact coastal marshes and their inhabitants, and they also seriously impact commercial shipping and pleasure boating. High lake levels, on the other hand, increase shoreline erosion. The documented fluctuations in lake level (Fig. 4) show that economically significant impacts on the Great Lakes community are possible, and they suggest that the magnitude of these impacts might increase with future climate change.

2.2.6. Prehistoric fluctuations in lake levels – Lake Superior

Larson (1999) has reconstructed changes in prehistoric levels of western Lake Superior from radiocarbon-dated submerged tree stumps and peat layers in the Apostles Islands area. These reconstructed levels diverge systematically from those expected from simple glacio-isostatic uplift and therefore probably record the influences of climate change. As seen in Figure 5, lake levels were depressed ~1 m from the isostatically adjusted level at about 1300 AD and again at about 1600 AD. The earlier low stand corresponds to the relatively warm climate that existed between the Medieval Warm Period and the Little Ice Age; the later one corresponds to the Little Ice Age. Although it is reasonable to invoke increased evaporation from Lake Superior to explain the low stand at 1300, it is not reasonable to use the same explanation for the one at 1600. Similarly, diminished evaporation cannot be used to explain the high stand preceding the 1600 low stand – the climate presumably was cool. Changes in temperature alone are not sufficient to explain the changes in lake level. Instead, a combination of changes in evaporative removal of water and of its atmospheric delivery is needed to explain the fluctuations in lake level. Depending on the air mass that dominated atmospheric circulation at the times of the two low stands, either evaporation could have been increased or precipitation could have been depressed.

3. PERSPECTIVES FROM THE PAST

Evidence of Holocene climate change is clearly present in the sediment records of the Great Lake Basin. The many lines of evidence show that considerable variation in climate has occurred over time. Where high-resolution records are available, they show fluctuations in climate on the order of decades to centuries during some periods. In view of the short-lived nature of historic fluctuations in lake levels, some of the variations may actually occur over spans of a few years. Future climate change seems inevitable.

The history of climate change in the Great Lakes Basin is complex. The ways in which local climate responded to global forcings was often not uniform across the Basin. Variability exists from place to place and from time to time. This observation indicates that multiple factors are involved in the changes in climate.

A transition from one set of climate conditions to a new one can be unstable and be accompanied by oscillations between the two sets of conditions. The end-Hypsithermal evidence of temperature oscillations provided by the Seneca Lake sediment core shows that the instability is on the order of a few centuries, which could impact human interests.

4. PROSPECTS FOR THE FUTURE

What lies in the future? Uncertainty for sure, and maybe some surprises. Nonetheless, it is possible to speculate on what future changes in climate may occur based on what has happened in the past. One change in climate that has definitely happened over the past century is a global rise in temperature (Fig. 6). Is this pattern something that has happened before - a replication of the Medieval Warm Period of a millennium ago - or is it something new - a response to the documented recent increase in the CO_2 concentration in our atmosphere? The question is complicated by the fact that the Little Ice Age lasted until the beginning of accurate temperature measurements and therefore anchors the increasing trend. Regardless of the cause, the temperature at our planet's surface is increasing, and because the Greenhouse capacity of our atmosphere is growing it is likely to increase further. How will this affect climate?

A possible answer to this question might lie in how the Hypsithermal impacted the climate of the Great Lakes Basin. A probable fallacy in using the Hypsithermal as a harbinger of what is to come from Greenhouse-mediated global warming is that it was a response to precessional amplification of northern hemisphere summer-winter seasonal differences. Greater Greenhouse warming will probably raise temperatures of both summer and winter and in both hemispheres. Still, some lessons can be taken from how the Great Lakes climate responded to this period of warmer summers in the northern hemisphere. The most important one is that different parts of the region evidently experienced different responses. Climate was warmer and drier in most of the Great Lakes Basin, and evaporation was magnified, possibly lowering water levels in Lake Erie to below sill depth. Because isostatic uplift has subsequently changed flow patterns between the lakes, hydraulic isolation of Lake Erie is unlikely to be repeated. However, the water levels of all the lakes could be lowered by many meters, which would have dramatic impacts on water use, shorelines, and navigation.

At the same time that evaporation might increase over most of the Basin, climate-driven changes in atmospheric circulation could make other parts of the Basin wetter. This contrasting response seems to have occurred over central New York in the mid-Holocene.

However, given the fundamental differences between the causes of the Hypsithermal climate change and Greenhouse warming of our planet, an alternative scenario is possible. If the entire planet becomes warmer, then more water will be evaporated from the sea surface and will be available to be transported to the continents by marine air masses. Climate in the Great Lakes Basin may become warmer and wetter, and the lakes may rise to troublesome levels. Flooding and shoreline erosion may become commonplace. Interestingly, climate modeling typically predicts a drier, not wetter, future for the Great Lakes Basin (e.g., Mortsch and Quinn, 1996; Mortsch et al., 2000).

Berger and Loutre (2002) have postulated that the impacts of the fossil-fuel addition of CO_2 to our atmosphere may be farther reaching than generally thought. They point out that mankind has picked a poor time to have its Industrial Revolution – the Milankovitch orbital parameters that have driven global climate change over most of our planet's history are entering a 50-ky period when they essentially cancel each other. The climate of our planet will be especially sensitive to variations in solar output, which is beyond our control, and to the Greenhouse Effect, which we are amplifying. Using three different levels of CO_2, Berger and Loutre (2002) have modeled how long the current interglacial climate of the Earth will last. Using the levels of CO_2 that characterized the last glacial-interglacial transition (210 ppmv for glacial times; 280 ppmv for post-glacial times), they predict a 50 ky interglacial period (Fig. 7), which is substantially longer than most of the interglacials of the past 800 ky. Using the predicted level of 700 ppmv CO_2, the interglacial interval become much warmer and lasts somewhat longer. This prediction indicates that the mid-Holocene Hypsithermal might be a poor model for the kinds of climate change that lie ahead of us and that we could be entering into uncharted climatic territory.

5. RESEARCH NEEDS

Knowledge and understanding about how climate has changed, both globally and in the Great Lakes Basin, have improved sufficiently over the recent decades that research efforts can now be better defined and more focused to the future. Some needs that can be identified include:

1. High-resolution studies of past climate records are rare, and such studies provide the only evidence of how unstable or stable former climate periods may have been. Appropriate sediment accumulations exist in the Great Lakes and in many of the smaller lakes within the Great Lakes Basin that can be subjects of high-resolution paleoclimatological study. Some of these sediment records are varved; their annual layering can reveal incredible details about short-term variations in past climate that can expand understanding of the processes involved in modifying climate. A particular advantage of varved sediments is that they yield multi-century climate records that are far longer than can be provided by meteorological data and therefore are superior measures of climate variations and changes in the past.
2. Multi-proxy studies of past climate records are also rare. Because climate is made of several variables, multiple indicators of climate components should be routinely measured in paleoclimate studies. The list of possible proxies is large (e.g., Table 1) and will probably expand in the future, so careful selection of the parameters appropriate to the questions under study is needed. By measuring proxies of multiple components of climate, improved understanding of the factors that created past climate changes will emerge, and this will refine capabilities to predict future changes.
3. The Great Lakes present unique opportunities to explore climate change dynamics in aquatic systems that respond to continental climate changes yet are large enough to exert significant control over their climate regimes. They are the “Inland Seas”. Study of the modern meteorological phenomena are involved in climate important for their own sake, yet they have the added importance of contributing to explanations of past climate changes and therefore become important to predicting future climate changes. Such studies should be encouraged in the Great Lakes Basin.

4. The links between climate, hydrologic balances, and lake levels in the Great Lakes Basin are complicated. The mechanisms by which former lake levels varied need better understanding so that future lake level changes can be predicted.
5. Modeling of past and future climate changes will ultimately need to be refined. Modeling cannot be successful without an adequate amount of reliable input data and a good understanding of the processes important to climate change. The four needs described above have to be met so that modeling can be improved. At the same time, modeling can point to those areas of the four needs that are more critical, so a synergism exists between modeling and measuring.

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Table 1. Types of information that can be measured in lake sediments to reconstruct paleoclimatic and paleoenvironmental conditions.

Measured Property	Proxy Information Provided	Examples
Pollen	Flowering plants in and around the lake	Leopold et al. (1982); Webb et al. (1997)
Plant macrofossils	Paleo-vegetation; paleo-lake-levels	Hannon & Gaillard (1997); Jackson et al. (1997)
Insect parts	Air and water paleo-temperatures	Elias (1996); Walker et al. (1991)
Grain size distribution	Dynamics of sediment transport	Rea et al. (1980); Silliman et al. (1996)
Ostracod fossils	Water paleo-chemistry	De Decker and Forester (1988); Holmes (1996)
Diatom fossils	Water paleo-chemistry and paleo-temperature	Moser et al. (1996); Pienitz et al. (1995)
$CaCO_3$ concentration	Water paleo-temperatures and stratification	Schelske & Hodell (1991); Mullins (1998)
Calcite $\delta^{18}O$ values	Precipitation-evaporation paleo-ratios	McKenzie & Hollander (1993)
Varve thickness	Seasonal paleo-climate variability	Overpeck (1996); Godsey et al. (1999)
Organic matter concentration	Past abundance of aquatic plants	Dean (1999); Hodell & Schelske (1998)
Organic matter composition	Types of plants in and around the lake	Meyers & Lallier-Vergès (1999); Meyers & Teranes (2001)
Organic matter δD values	Paleohydrologic balance	Krishnamurthy et al. (1995)

Table 2: Summary of late- and post-glacial climate changes that have affected the Great Lakes Basin

Period	Approximate Duration
Maximum extent of last glaciation	20 to 19 ka
Onset of glacial recession	geographically variable, but ~19 ka
Major glacial readvances	15.5, 13.0, 12.8, 10.0 ka
Younger Dryas	11 to 10 ka (last glacial readvance)
Altithermal (or Hypsithermal)	warm period, 9 to 5 ka
Neoglaciation	cool period, 4 ka to present
Medieval Warm Period	~950 to ~1100 AD
Little Ice Age	~1400 to ~1875 AD
“Dust Bowl” Drought	~1930 to ~1935 AD

Table 3: Modern physical and hydraulic features of the Laurentian Great Lakes

Lake	Surface Area (km^2)	Drainage Basin (km^2)	Mean Depth (m)	Greatest Depth (m)	Residence Time (yr)
Superior	82,100	127,700	147	405	185
Huron	59,600	134,000	59	229	30
Michigan	57,800	118,000	85	281	70
St. Clair	1,080	(note 1)	4	6	<1
Erie	25,700	78,000	19	64	2.7
Ontario	18,960	64,030	86	244	8

Note 1: included in Lake Erie drainage basin

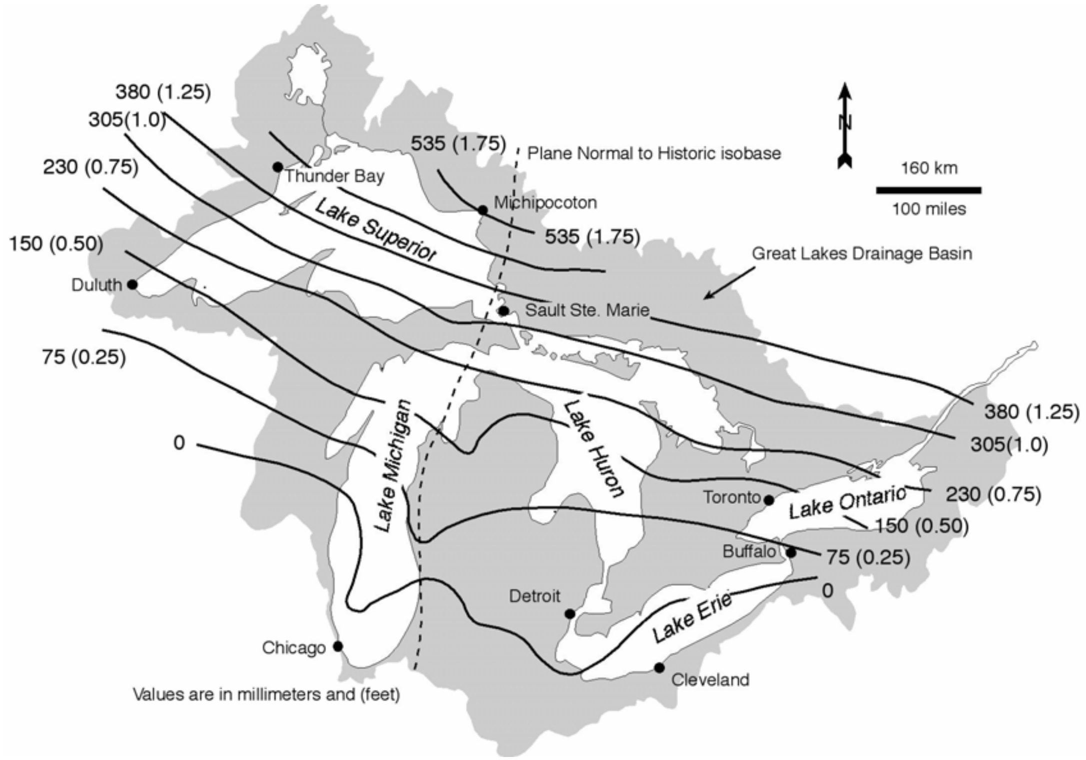

Figure 1: Recent vertical uplift rates per century for the Great Lakes Basin (from Sellinger, 1999). Uplift rates are relative to a datum in the southern edge of the Basin. They increase northwards because the magnitude and duration of glacial weighting were greater in the northern parts of the Basin.

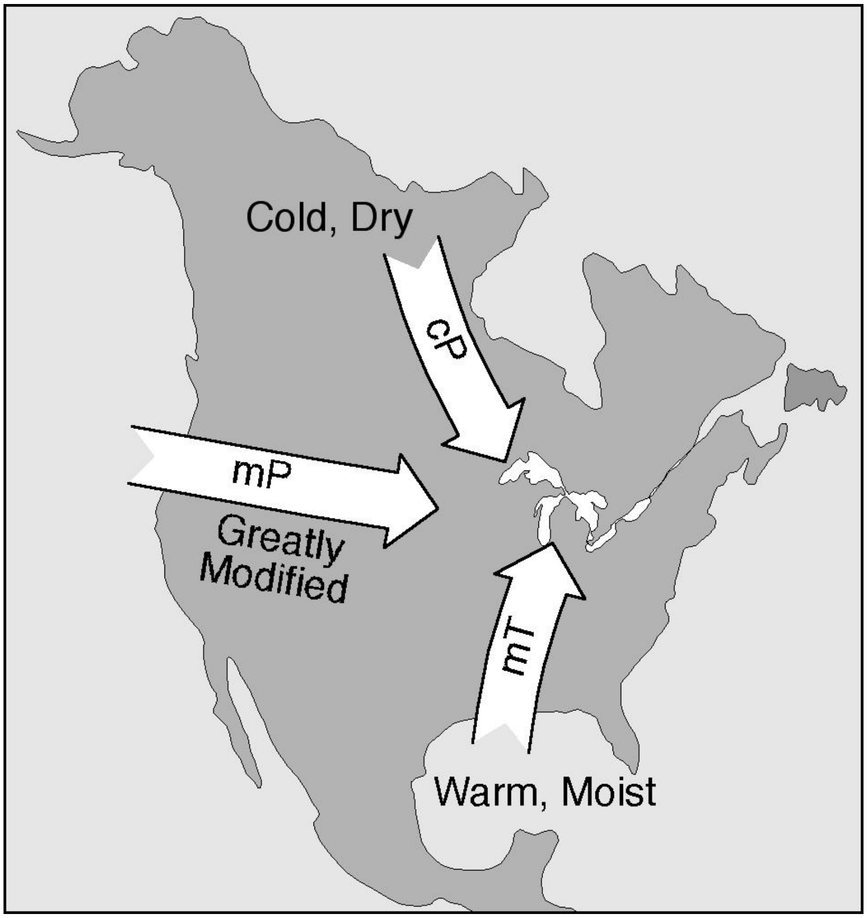

Figure 2: Air masses affecting the Great Lakes Basin. The Pacific air mass (mP) becomes progressively drier and warmer as it crosses North America, the Polar air mass (cP) is cold and dry, and the Gulf of Mexico air mass (mT) is moist and warm.

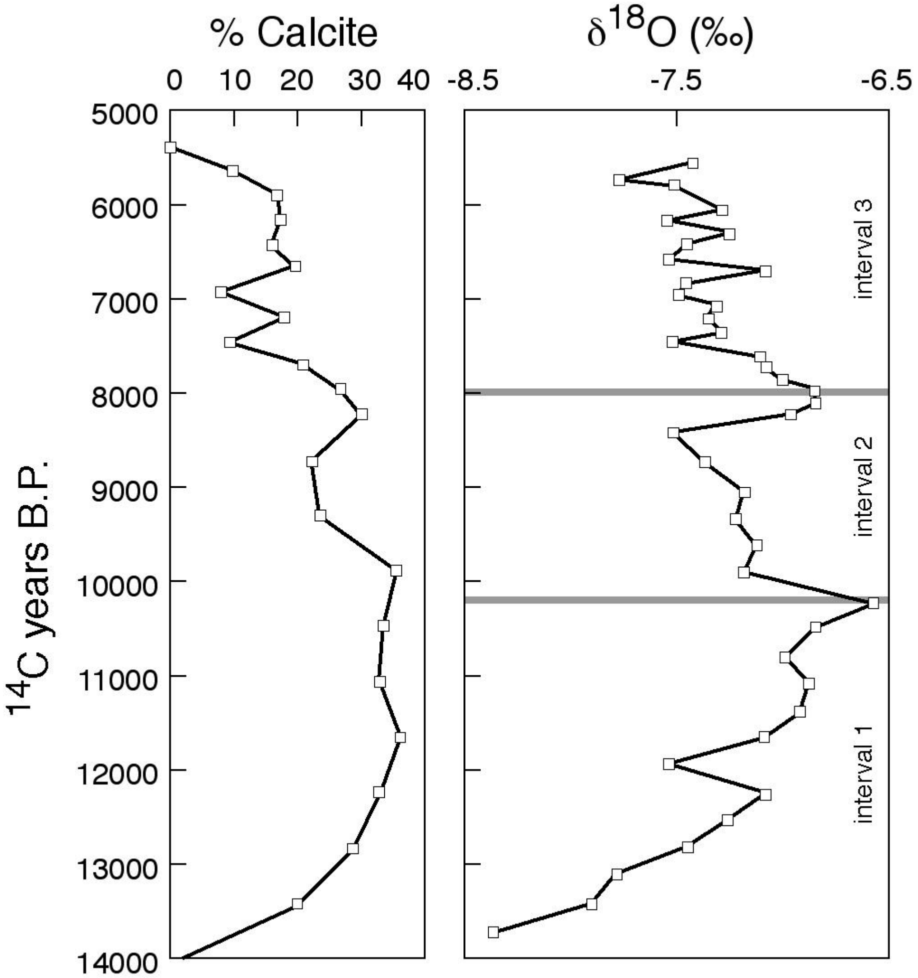

Figure 3: Changes in the concentration of calcite and in the oxygen isotopic composition of calcite in late glacial and early postglacial sediments of Seneca Lake, New York (from Anderson et al., 1997).

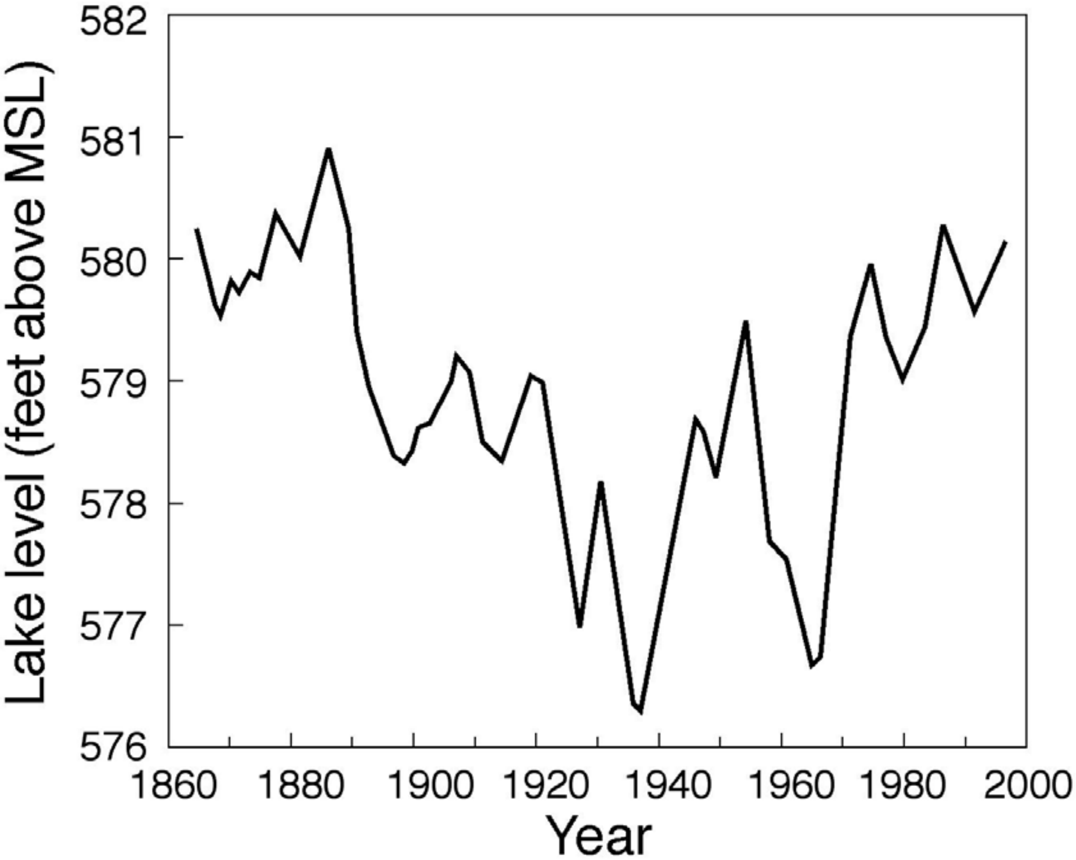

Figure 4: Historic fluctuations in the shared water level of Lake Michigan and Lake Huron (from Lofgren et al., 2000). Note an overall range of nearly five feet (1.5 m).

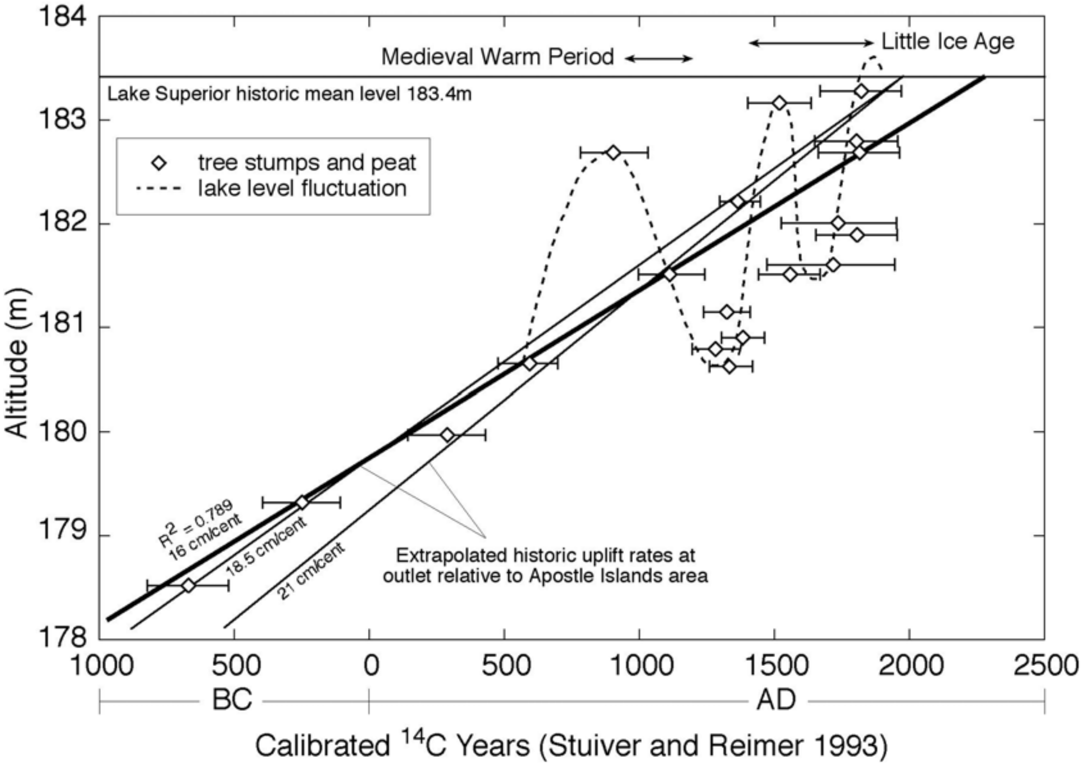

Figure 5: Prehistoric changes in the water level of western Lake Superior relative to mean sea level due to past climate fluctuations as evidenced by radiocarbon dating of drowned trees and peat bogs. Because both the Medieval Warm Period and the Little Ice Age affected lake level, multiple factors are implicated. From Larsen (1999).

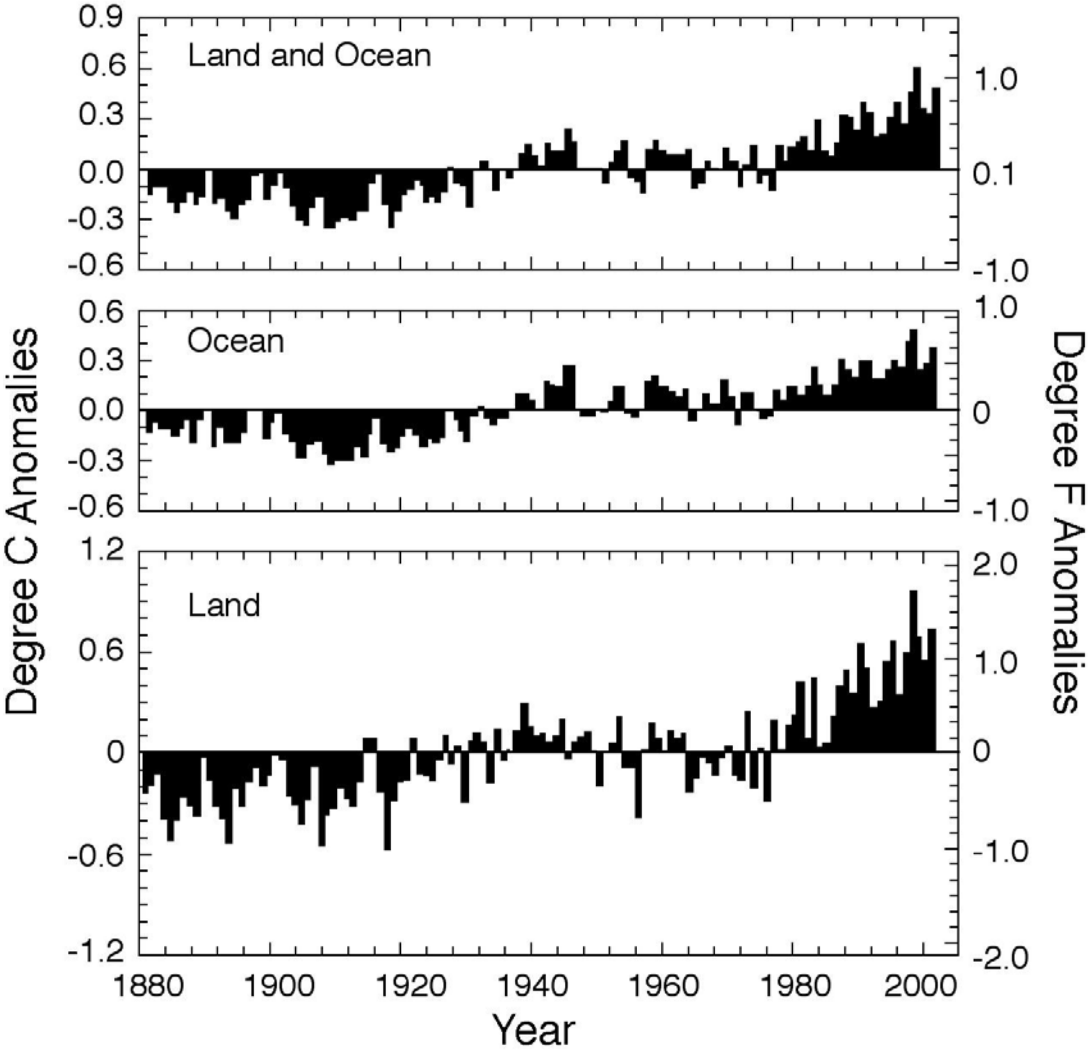

Figure 6: Excursions of continental, marine, whole-Earth mean annual temperature from the 1880-2001 global mean. Global temperatures have increased over the past century and especially since 1980. Source: NOAA National Climate Data Center.

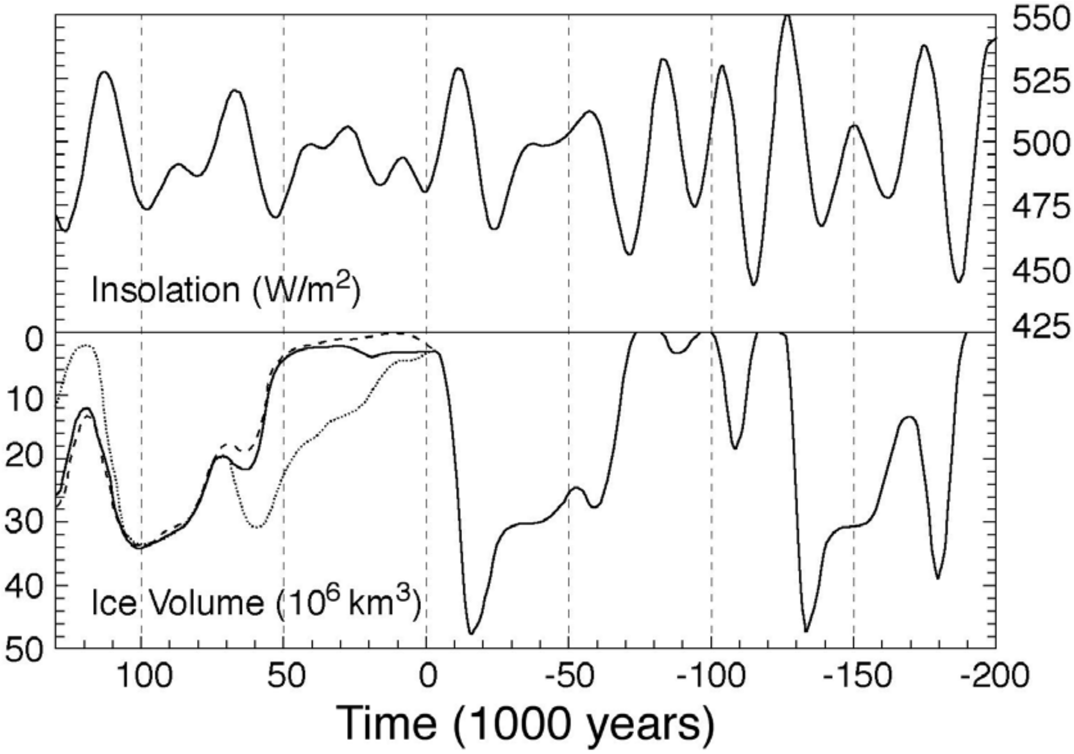

Figure 7: Impacts of natural and human-modified variations in heating of the Earth by the Sun. Long-term orbital variations in summer solstice insolation at 65ºN and simulated northern hemisphere ice volume (glaciations) for the past 200 ka (negative time) and the next 130 ka (positive time). Three future atmospheric pCO_2 conditions are modeled: (1) solid line – last glacial (210 ppmv) and interglacial values (280 ppmv), (2) dashed line – human-induced elevation of pCO_2 to 750 ppmv, and (3) dotted line – a constant pCO_2 of 210 ppmv. Increased pCO_2 extends and amplifies the current interglacial period. Adapted from Berger and Loutre (2002).