Understanding Global Climate Change: Paleoclimate Perspective from the World's Highest Mountains[1]

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ABSTRACT. Glaciers are among the world's best recorders of, and first responders to, natural and anthropogenic climate change and provide a time perspective for current climatic and environmental variations. Over the last 50 years such records have been recovered from the polar regions as well as low-latitude, high-elevation ice fields. Analyses of these ice cores and of the glaciers from which they have been drilled have yielded three lines of evidence for past and present abrupt climate change: (1) the temperature and precipitation histories recorded in the glaciers as revealed by the climate records extracted from the ice cores; (2) the accelerating loss of the glaciers themselves; and (3) the uncovering of ancient fauna and flora from the margins of the glaciers as a result of their recent melting, thus illustrating the significance of the current ice loss. The current melting of high-altitude, low-latitude ice fields is consistent with model predictions for a vertical amplification of temperature in the tropics. The ongoing rapid retreat of the world's mountain glaciers, as well as the margins of the Greenland and Antarctic ice sheets, is not only contributing to global sea level rise, but also threatening fresh-water supplies in many of the most populous regions. More recently, strong evidence has appeared for the acceleration of the rate of ice loss in the tropics, which especially presents a clear and present danger to water supplies for at-risk populations in South America and Asia. The human response to this issue, however, is not so clear, for although the evidence from both data and models becomes more compelling, the rate of global CO_2 emissions continues to accelerate. Climatologically, we are in unfamiliar territory, and the world's ice cover is responding dramatically. The loss of glaciers, which can be viewed as the world's water towers, threatens water resources that are essential for hydroelectric power, crop irrigation, municipal water supplies, and even tourism. As these glaciers are disappearing, we are also losing very valuable paleoclimate archives.

[1] Read 14 November 2008, as part of the symposium "Action Not Words."

THE CLIMATE OF A REGION is defined as the average weather over an extended period, at least in reference to the average human lifespan. It is often measured with respect to variations in temperature and precipitation over interannual to millennial time scales. The world's climate is driven (or "forced") both internally by atmospheric, oceanic, cryospheric, and vegetative changes, and externally by changes in the amount of solar energy reaching the Earth. The variations in the Earth's orbit around the Sun, or orbital parameters, can affect the baseline climate of the entire planet over decades to hundreds of thousands of years. Incoming solar (or insolation) changes influence terrestrial temperatures and oceanic and atmospheric temperatures and circulations, which govern the expansion and retreat of ice sheets and glaciers, the rise and fall of sea levels, and vegetative cover. Recently imprinted on these natural variations are the climatic effects of a human population that has been increasing exponentially since the middle of the nineteenth century, along with the accompanying demands for energy, living space, and food.

Today the popular media refer to climate change primarily with respect to temperature, as demonstrated by the use of the term "global warming" to describe the average rise of 0.11°F per decade over the last century (NOAA State of the Climate Global Analysis 2009, http://www.ncdc.noaa.gov/sotc/?report=global&year=2009&month=13&submitted=Get+Report#trends). Since the late 1970s, this rate has more than doubled to 0.29°F per decade, and 11 of the warmest years on record have occurred in the last 12 years. Since these numbers are based on global averages, they do not reflect regional variations. For example, according to the National Climate Data Center, since 1970 the average annual temperature in the western United States has been rising more rapidly (0.46°F per decade) than in the southeastern part of the country (0.26°F per decade) (http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html). The recent changes are also seasonally inconsistent; for example, on average winters are warming faster than summers in the United States (Meehl et al. 2007). However, the most severe temperature increases appear to be concentrated in the polar regions as well as within the interiors of the large continents. In many of these cases the current changes are unique compared with those over the last several thousand years, in terms of both their rates and their geographic occurrences.

Paleoclimatologists not only strive to reconstruct past climate variations on regional to global scales, but also try to determine the forcing mechanisms, both natural and anthropogenic, that influence climate changes. This information is instrumental for placing the current climate into perspective, and for supplying data for computer models that project future scenarios. It is the role of paleoclimatologists to reconstruct records of temperature and precipitation variability over hundreds to thousands of years from geological and biological "media" that preserve evidence of these variations. Climate proxy data come from a variety of sources, such as written and historical records, corals, tree rings, glacial moraines, and cores. Cores are drilled from ocean and lake sediments and glaciers, and produce continuous climate records that vary from high (seasonal) to low (millennial) resolution.

It is climatic and environmental histories from ice cores that will be discussed in more detail here. A judiciously selected collection from all over the world has provided high-resolution archives of regional and global climate. In addition to the continuous, high-resolution records that glaciers and ice sheets produce, the rapid retreat of their margins also provides some of the most visible evidence for the recent changes.

Mechanisms of Climate Change

Natural forcing mechanisms

Since the dawn of human civilization, climate changes have been governed by both natural and anthropogenic processes; however, until the onset of the Industrial Revolution the natural causes were dominant. The most important natural forcing factor external to the Earth arises from variations in solar energy that reach the atmosphere and the surface. These variations occur in cycles, and the one most relevant to the human life span is the 11–12-year sunspot cycle. Much more influential on the Earth's long-term climate are the orbital variations of the Earth, which at 22,000 to 100,000 years in duration are orders of magnitude longer than the human lifespan and even human civilizations (Milankovitch 1930). These are in large part responsible for both the glacial periods during which large regions at high and middle latitudes are covered by thick ice sheets, and the warm interglacial periods such as the present Holocene epoch, which began about 10,000 years ago (Croll 1864; Milankovitch 1930; Hays et al. 1976).

Under natural conditions, the Earth's temperature is influenced internally by short- and long-term changes in the atmosphere and ocean. Short-term cooling can result from the injection of volcanic dust into the atmosphere following a massive eruption close to the equator, such as the 1991 Mt. Pinatubo event in the Philippines (Minnis et al. 1993). Other widespread but relatively short-lived variations in temperature and precipitation are associated with the linked oceanic/atmospheric system in the equatorial Pacific Ocean known as El Niño-Southern Oscillation. However, some regional climatic changes may last for decades or even centuries, such as the "Little Ice Age," which occurred between the sixteenth and nineteenth centuries (depending on location) and the preceding "Medieval Warming" between the tenth and twelfth centuries. The causes of these events are not completely understood, but they may be related to changes in oceanic circulation that may be triggered by solar intensity anomalies.

Anthropogenic forcing mechanisms

Records of atmospheric CO_2 and methane concentrations over the past several hundred thousand years have been recovered from ice cores drilled through the Antarctic ice sheet. These data show us that the levels of these so-called "greenhouse" gases have never been higher over the last 800,000 years than they are today (Loulergue et al. 2008; Lüthi et al. 2008). Numerous studies, beginning with Arrhenius (1896), have established linkages between atmospheric concentrations of CO_2 and CH_4 and temperature.

Human activity has also altered regional climate in other ways. For example, aerosols such as sulfates, which are the by-products of the burning of fossil fuels in power plants, may have a cooling effect, since they tend to block incoming short-wave solar radiation. Particles known as black carbon result from industrial activity and vegetation burning, which occurs in natural forest fires and during the process of forest clearing, particularly in the equatorial regions. Humans have also caused changes in the planet's reflectivity, or albedo, as darker forest regions are transformed into lighter cropland, grasslands are paved to facilitate transportation, and ice sheets and sea ice melt away to expose darker land and ocean water.

On the relationship between solar output and modern climate warming

When it comes to determining the validity of and causes for anthropogenic climate change, scientists look at the balance of evidence. Some have argued that the variations that we have experienced over recent decades are driven by changes in the Sun's energy output, which are governed by the 11-year sunspot cycle. However, these short-term solar variations are believed to have only minor influence on the Earth's climate, as the irradiance varied by 0.1% over the last two cycles (Fröhlich and Lean 2004). Models predict (and the data show) that in today's world the stratosphere is cooling as the planetary surface warms (Meehl et al. 2007). However, under natural conditions variations in the Sun's energy should cause similar temperature trends in both the troposphere and stratosphere, not the opposite trends that we currently see. In addition, nighttime and winter temperatures have increased at a greater rate than daytime and summer temperatures, which would not be expected if the Sun were driving those changes. High latitudes, which receive less sunlight than low latitudes, have nevertheless experienced greater warming, again the opposite of what would be expected if the Sun were the primary climate forcer.

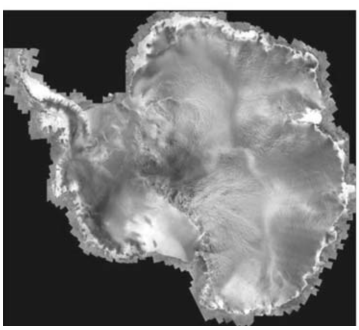
Evidence of Climate Change from Glaciers and Ice Sheets

Glacier ice is one of the most versatile and highly-resolved recorders of the Earth's climate. Although they are restricted to regions where temperatures remain largely below freezing year-round, glaciers and ice sheets occur from the equatorial tropics to the polar regions (fig. 1). They can store anything that is found in the atmosphere, such as precipitation, gases, dust, salts, fallout from volcanic eruptions and aboveground thermonuclear emissions, emissions from biological activity, and even cosmic energy bombardment of chemical species in the atmosphere. Temperature records can be derived from isotopes (atoms of the same element but of different weights) of oxygen and hydrogen, the constituents of water and ice. The large variety of information available from the analysis of glacier ice is listed in figure 2.

Because the Earth is nearly spherical, 50% of the surface lies between 30°N and 30°S, which is the geographical definition of the tropics. It is also a region that contains immense thermal energy that is instrumental in driving the planet's weather systems. Many areas of the tropics are located in monsoon climates, which are characterized by distinct dry winters and wet summers. In glaciated mountain regions, the ice records these seasonal variations as thin dust laminae alternating with thick, cleaner layers (fig. 2). When an ice core is drilled through a tropical glacier, these alternating dark and light layers, constituting yearly cycles, can be counted back in time, so that they are analogous to tree rings. The ice can also record the seasonal variations in atmospheric dust content and variations in the ratio of heavy to light oxygen isotopes ($\delta^{18}O$), which are controlled by a variety of meteorological factors such as temperature and precipitation sources and amounts. Analysis of an ice core produces data showing these seasonal signals, which are useful for establishing a time scale, or chronology, for the climate record. One example of this type of ice core comes from the Dasuopu ice cap in the central Himalayas. A section of the record from this

Polar Regions

Huascaran, Peru



Dasuopu Glacier, Himalayas

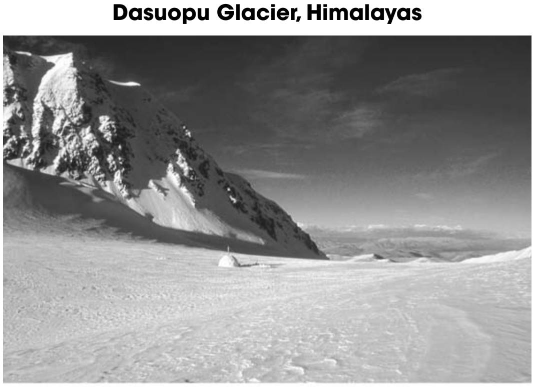


FIGURE 1. Ice cores provide unique climate histories from the polar to the tropical regions. Huascaran (6768 m) is the highest tropical mountain in the Andes of Peru, while Dasuopu (7,200 m) is the highest drill site drilled.

FIGURE 2. Ice cores provide several lines on climatic and environmental data. The longitudinal view of a core (top) shows wet and dry seasons that are recorded as clear and dark layers, respectively. The variety of data that can be recovered from the analysis of the ice is listed. Center: An ice core is extracted from a drill barrel. Photo by Lonnie Thompson. Bottom: The mass of a core section is measured on a balance in a field laboratory. Photo by Ellen Mosley-Thompson.

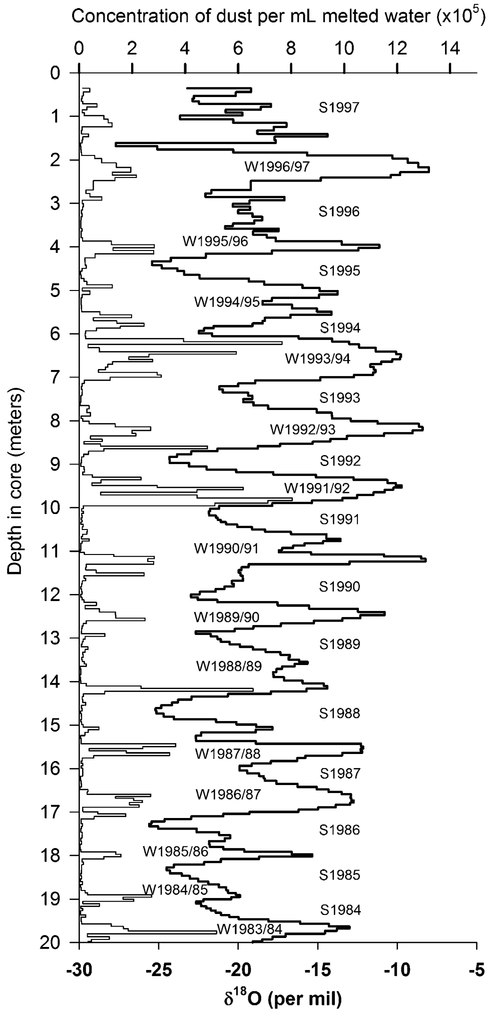


FIGURE 3. Data from the analysis of the top 20 meters of an ice core from the Dasuopu ice cap, Central Himalyas in Tibet, which was drilled in the summer of 1997. The diagram shows wet (summer) and dry (winter) seasonal variations in dust and oxygen isotopic ratios. Using these two measurements, this section of the ice core can be dated by counting the oscillations. Each year is marked on the figure, and the seasons are denoted by "S" (summer) and "W" (winter).

core, which illustrates the regular seasonality of the oxygen isotopic ratios and eolian (windblown) dust is shown in figure 3. The $\delta^{18}O$ shows summer and winter values that oscillate with the concentrations of dust. By counting these annual cycles an ice core can be dated at the top. Using these and other techniques, records can be extracted that document changes in climate and environment over hundreds to thousands of years. Because these records are long, continuous, and of high temporal resolution and contain information on numerous physical and chemical properties of the atmosphere, they are invaluable for providing relatively precise histories of climatic events that occurred during human development, but before humans had a significant influence over their environment.

Evidence from the Ice of Abrupt Climate Change in the Past

According to the National Research Council (2002), abrupt climate change is defined as the condition when "the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause." It "takes place so rapidly and unexpectedly that human or natural systems have trouble adapting to it." Because they produce high-resolution records of climate, ice cores have been valuable in the study of past abrupt climate change. One of the most remarkable examples was a sudden cold, wet event that occurred 5,200 years ago, and left its mark in many paleoclimate records around the world.[2] A record of this event comes from the ice fields atop Mt. Kilimanjaro in Tanzania, which shows a very intense and sudden decrease in the $\delta^{18}O$ levels (Thompson et al. 2002). Such a decrease is indicative of lower temperatures and/or more intense snowfall. This anomalously cold/wet climate lasted a relatively short time (at least in many places), perhaps a few decades, before the climate just as abruptly reverted to its previous state. A possible link to this anomalous cooling is observed in the methane records from the Greenland ice cores, which show that during the Holocene[3] epoch the lowest concentration of this gas occurred 5,200 years ago (Chappellaz et al. 1997; Raynaud et al. 2000). The cause of this methane decrease, and its implied link to the mid-Holocene cold event, are still not fully understood.

Several sudden recent appearances of long-buried fauna and flora resulting from rapidly melting alpine ice confirm the timing and severity of this abrupt climate reversal. Arguably the most famous is "Otzi" or the "Tyrolean ice man," whose remarkably preserved body was discovered in the Alps in 1991 when it was uncovered by a retreating glacier. When his remains were radiocarbon-dated, it was discovered that he died (the forensic evidence suggests he was murdered) and was quickly buried in permanent snow cover around ~5,200 years ago

[2] There are also numerous examples of this event that come from sources other than glaciers. Along the southern margin of Lake Tahoe in the Sierra Nevada Range there are trees preserved underwater. Examination of the trunks shows that that the forest was immersed in rising water about 5,000 years ago. The preserved condition of the trees indicates that the water in the lake has remained high ever since (Lindstrom 1990). The Soreq Cave in Israel contains speleothems that have produced continuous climate records that cover several tens of thousands of years. As in the Kilimanjaro ice-core record, the Soreq Cave record shows that this abrupt cooling also occurred in the Middle East, and that it was the most extreme climatic event in the last 13,000 years (Bar-Mathews et al. 1999).

[3] The Holocene is the warm period since the end of the last ice age, or glacial stage. It is generally considered to cover the last 10,000 years.

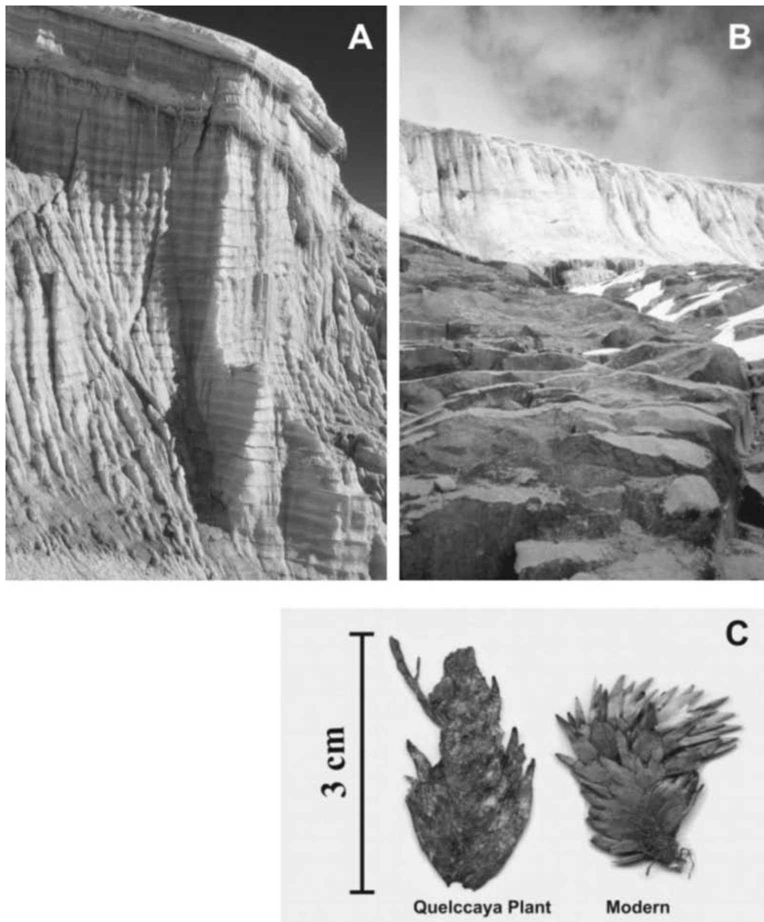


FIGURE 4. The margin of the Quelccaya ice cap in 1977 (A) and in 2002 (B). Photos by Lonnie G. Thompson. The retreat of this ice wall exposed several ancient plants (C, left) which were dated at 5,200 years ago and were identified as *Distichia muscoides*. A modern plant is shown (C, right) (Thompson et al. 2006).

(Baroni and Orombelli 1996). In other locations around the world, plants are being exposed for the first time in 5,200 years as glaciers are melting and shrinking in size. The margin of the Quelccaya Ice Cap in southern Peru is shown in figure 4A as it was in 1977; however, this margin has since melted back, and figure 4B shows that by 2002 a small lake had replaced the ice wall. At the base of the wall, a perfectly preserved wetland plant deposit, which contains no woody tissue, was discovered. It was identified as *Distichia muscoides* (fig. 4C), which today grows in the valleys below Quelccaya, and was radiocarbon-dated at ~5,200 years before present (Thompson et al. 2006). This is strong

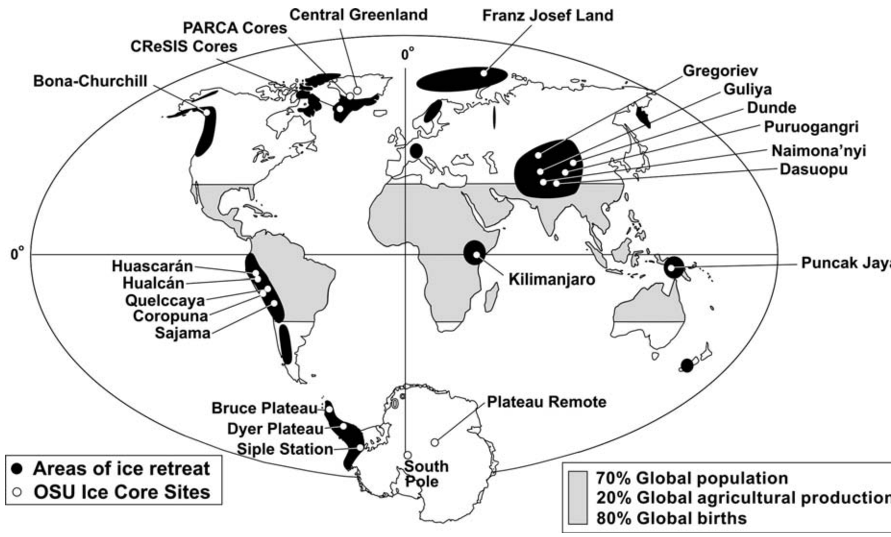


FIGURE 5. Global view of retreating ice over the twentieth to the twenty-first centuries, as shown by dark gray shading. The lighter shading depicts the geographical tropics. Sites where the Ohio State University has conducted ice-core drilling programs are shown.

evidence that this ice cap has not been smaller than its present size for more than five millennia. As the glacier continues to retreat, more plants have been collected and radiocarbon-dated, almost all of which confirm the original findings (Buffen et al. 2009).

Loss of Glaciers in Today's World

The world's cryosphere is in retreat as the tropospheric temperatures warm (fig. 5). Today glaciers cover about 10% of the Earth's surface area, compared with 30% coverage during the coldest part of the last ice age. Because this warming is amplified at high altitude (Bradley et al. 2006), the loss of ice is most drastic in mountainous areas such as the Andes and the Tibetan Plateau. The rising temperatures in the polar regions are especially troubling, as these are the locations of the largest ice sheets in the world.

Ice decline in the polar regions

Ninety-five percent of all the ice on the Earth is located in Antarctica and Greenland.[4] More than 30 years ago the late John Mercer, a professor

[4] This comes to ~14.52×10^6 km^2 of ice cover in Greenland and Antarctica.

at the Ohio State University, predicted that the first consequence of a warming climate linked to atmospheric CO_2 increase would be the breakup of the Antarctic ice shelves in a north to south direction (Mercer 1978). Average temperature on the Antarctic Peninsula has risen 2.5°C in the last 50 years, resulting in the breakup of the ice shelves in just the way Mercer foresaw. One of the most rapid of these deteriorations occurred in 2002, when the Larsen B collapsed in just 31 days. It is not the breakup of these ice shelves that contributes to sea level rise, since they are already floating and thus displacing sea water. However, because they serve as buttresses to land-based glaciers, their disappearance causes the ice flow to increase three to eight fold (Scambos et al. 2004). It is this effect that contributes to sea level rise.

Satellite documentation of the sea ice in the Arctic Ocean extends back three decades. Arctic sea ice cover (measured each September) decreased at a rate of about 8.6% per decade from 1979 to 2007, and in the year between September 2006 and September 2007, 24% of the ice disappeared, although in the last two years it has recovered ~13% (Perovich and Richter-Menge 2009). In 2006 the Northwest Passage was ice-free for the first time in recorded history. This presents advantages for ships, but it poses major problems for the indigenous people and animals of this region. Sea ice reflects solar radiation back to space; thus as sea-ice cover shrinks more dark ocean is exposed, which absorbs more incoming radiation. As this proceeds, a "feedback loop" develops in which the warming water melts more ice, which in turn increases the surface area of the ocean. Eventually one reaches the potential for a "tipping point" from which there may be little chance for recovery.[5]

The Greenland ice sheet has also experienced dramatic ice melt over the recent years, particularly in the Northern Hemisphere summer. There has been an increase in both the number and the size of lakes on the southern part of the ice sheet, and crevices often appear below the lakes. Water has been observed flowing through these crevices (moulins) down to the bottom of the ice sheet, where it acts as a lubricant that speeds the flow of basal ice (Zwally et al. 2002; Das et al. 2008). In the last decade, many glaciers draining Greenland and West Antarctica have accelerated their discharge to the ocean by 20% to 100%, but this has been highly variable over shorter time intervals.[6]

[5] The theory of climatic tipping points or thresholds is relatively new and is a very important line of research for paleoclimatologists and climate modelers to investigate.

[6] None of the most recent reports by the IPCC (2007) took into account these abrupt recent changes in ice flow, which have the potential to cause sea level to rise faster than predicted.

Retreat of alpine glaciers

Tropical atmospheric temperatures tend to remain fairly uniform throughout the year. Alpine glaciers at these latitudes are located in the mid-troposphere (~15,000–20,000 feet above sea level), where persistent warming has been amplified over the last several decades. The smaller, thinner mountain glaciers of the world respond more quickly to changing climate than the massive polar ice sheets, since their surface area to volume ratio is much greater. Although alpine glaciers constitute only 3.6% of the world's ice cover, their rapid rate of melting in comparison with the large polar ice sheets may cause them to contribute more to sea level rise in the short term. Currently, 60% of the land-based ice loss is occurring on the small glaciers and ice caps. The ice loss from mountain glaciers may raise sea level ~0.25 meters by 2100 (Meier et al. 2007). Although global ice retreat at the beginning of the twenty-first century is driven mainly by increasing temperatures, regional factors such as deforestation and precipitation deficits can impact individual glaciers.

There are several documented examples of alpine glacier retreat throughout the world. A study of 67 glaciers in Alaska from the mid-1950s to the mid-1990s shows that all are thinning, and subsequent measurement on 28 of these in the following years shows that the thinning rate has been increasing (Arendt et al. 2002). In the Brooks Range of northern Alaska, 100% of the glaciers are in retreat, while in southeastern Alaska 98% are shrinking (Molnia 2007). When Glacier National Park in Montana was established in 1910, there were 150 glaciers within it. This number is currently down to 26, and it is estimated that by 2030, at the present rate of decrease, no glaciers will remain in the park (Hall and Fagre 2003).

Two of the most carefully documented case studies of alpine glacier retreat are on Kilimanjaro and on the Quelccaya Ice Cap in the Peruvian Andes. Using a combination of terrestrial photogrammetric maps, satellite images, and aerial photographs, it has been determined that the combined ice fields on Kibo, the highest crater on Kilimanjaro, have lost 85% of their surface area since 1912 (Thompson et al. 2009). At the current rate of retreat, it is estimated that Kibo will be ice-free in the next few decades for the first time in 11,700 years. Continued monitoring of these ice fields shows the extent to which their disappearance is accelerating. The deterioration of the Furtwangler Glacier, which lies in the center of Kibo, is shown in figure 6a as a series of aerial photographs from 2000 to 2007, when the glacier actually split into two sections. As it is shrinking in size, it is also thinning rapidly from 9.5 meters in 2000 to 4.7 meters in 2009.

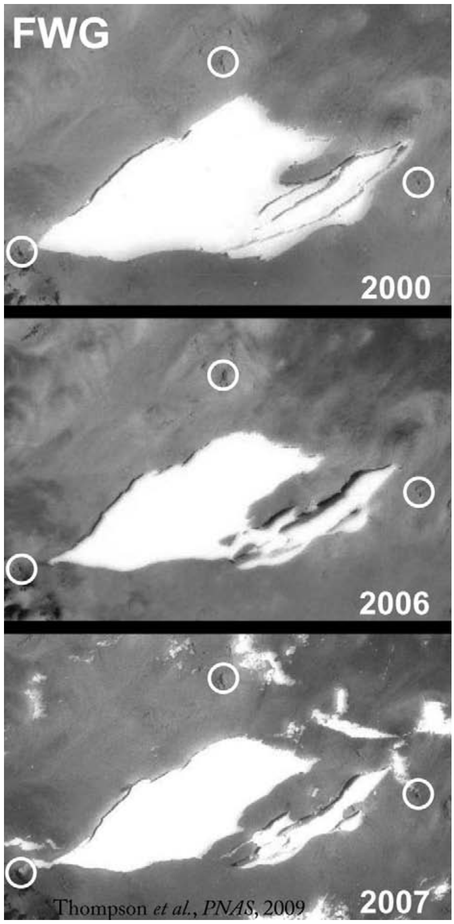
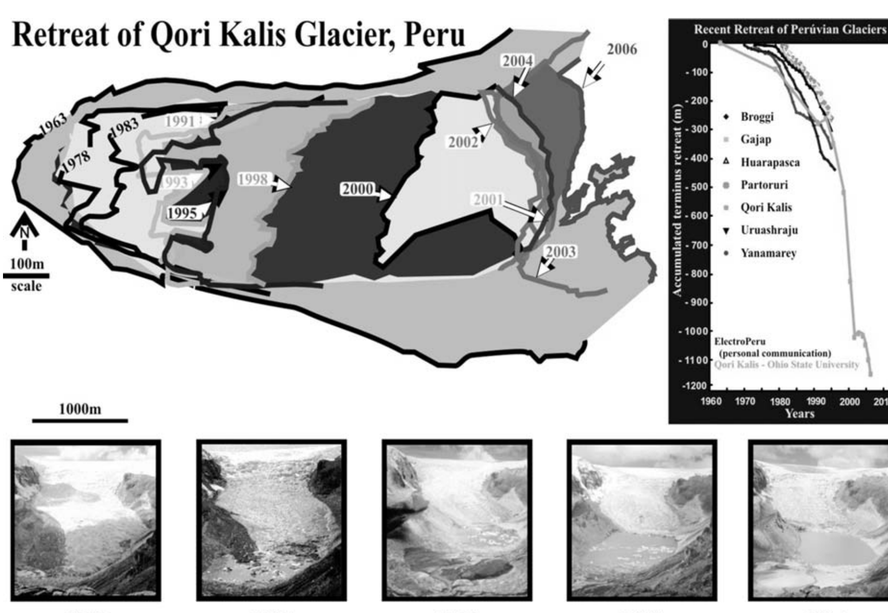


FIGURE 6. The Furtwangler glacier in the center of the Kibo crater on Mt. Kilimanjaro has been vanishing at a rapid rate over the last decade, as shown by the series of aerial photographs on the left. In 2007 the glacier divided into two sections. Qori Kalis, an outlet glacier on the Quelccaya ice cap, has been retreating at an accelerating pace as shown by the map (below) and the plot of ice terminus retreat over time. The melting of the Qori Kalis, and the growth of the forelake, is shown pictorially along the bottom. Photos by paleoclimate ice core team.



The Quelccaya Ice Cap, which is located in southern Peru adjacent to the Amazon Basin, is the largest tropical ice field on Earth. The Qori Kalis outlet glacier has been measured and photographed since 1963. At the beginning of the study the snout of the glacier extended 1,200 meters out from the ice cap, and there was no melt water at the terminus. By the summer of 2008 Qori Kalis had completely retreated to the edge of Quelccaya, and an 84-acre, 60 m deep lake had developed in its place (fig. 6b). The work on this glacier has also documented an accelerating rate of ice loss: from 1963 to 1978 the retreat was calculated as a rate of about 6 m per year, but from 1991 to 2006 it was losing ice ten times faster on average than the initial rate (Thompson et al. 2006). This loss of ice from Quelccaya is not only occurring on the Qori Kalis glacier, but in fact is occurring on the margin of the ice cap itself, as shown in figure 4. Since 1978, 25% of this tropical ice cap has disappeared.

The amount of loss suffered by individual glaciers in many regions has been photographically documented through the twentieth century and into the twenty-first century. An example is the Qoyllur Rit'i glacier in Southern Peru, which is located at the site of an annually observed religious festival. Figure 7A is a photograph of the ice cover in 1935, and figure 7B is a photograph taken at approximately the same location in 2006. The overlap of these two pictures (fig. 7C) provides a view of the extent of the ice retreat over the 71-year interval. The glacier has retreated so much, in fact, that the participants in the religious rites are no longer permitted to carry away pieces of the ice that they regard as sacred (Kormann 2009).

The Himalaya Mountains are home to more than 15,000 glaciers that constitute a very important component of the dry season water supply for India, Nepal, and southern China via the major rivers of the region. Unfortunately, only a few of the glaciers have been monitored over an extended period, so reliable ground observations, which are crucial for determining ice retreat rates, do not yet exist. However, a recent study on an ice core from the Naimona'nyi Glacier in the southwestern Himalayas (Kehrwald et al. 2008) shows that ice is disappearing from the top of the glacier, as shown by the lack of the radioactive bomb horizons from the 1950s and early 1960s that appear in all Tibetan and Himalayan ice-core records (Thompson et al. 1990; 1997; 2000; 2006b).

The glaciologists at the Institute of Tibetan Plateau Research in Beijing have been monitoring 612 glaciers across the High Asian region since 1980. They have found that from 1980 to 1990, 90% of these glaciers were retreating, and from 1990 to 2005, this increased to 95% (Yao et al. 2007). Meteorological records from the Tibetan Plateau and

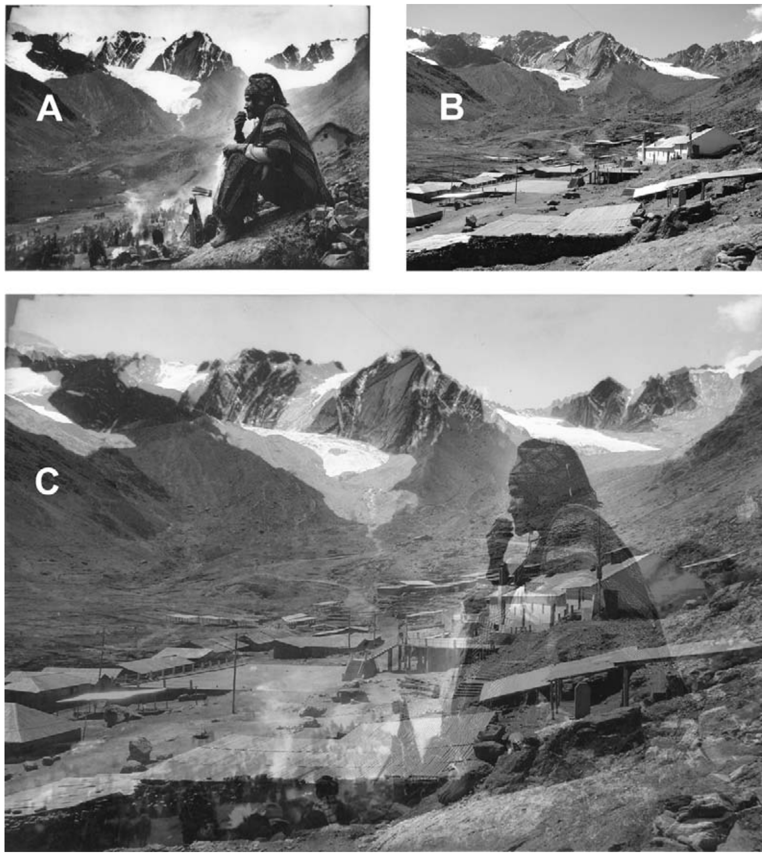


Figure 7. The Qoyllur Rit'i glacier in the Andes of Southern Peru photographed in (A) 1935 (photo by Martin Chambi) and in (B) 2006 (photo by Mary Davis). The extent of the ice retreat over 71 years is shown in the overlap of the two photos (C).

the Himalayas are scarce and of relatively short duration, most beginning in the mid-1950s to early 1960s; however, those that do exist show that surface temperatures are rising, and rising faster at higher elevations than at lower elevations (Liu and Chen 2000). The Tibetan Plateau has been warming at a rate of 0.16°C per decade, with winter temperatures rising 0.32°C per decade. A newly published paper by Matsuo and Heki (2010) shows that from 2003 to 2009 the average ice loss from the Asian high ice fields, as measured by GRACE (Gravity Recovery and Climate Experiment) satellite observations, had accelerated twice as fast as the rate four decades before, but the loss was not consistent over space and time. Ice retreat in the Himalayas slowed slightly, while loss in the mountains to the northwest increased markedly over the last few years.

Thus, taking into consideration the surface temperature measurements, the satellite studies, the ground studies on glaciers, and ice core results, a case can be made that glacier retreat at high elevations is indeed occurring concomitantly with increasing temperatures. This is consistent with the model results discussed in the IPCC report (Giorgi et al. 2001; IPCC 2007), which show not only low-latitude warming but an amplification of that warming at higher elevations where these glaciers are located. A projected planetary scale rise of 2 to 4.5°C between 1990–99 and 2090–99 translates to a 5 to more than 10°C increase over 18,000 feet above sea level (inferred from fig. 1 in Bradley et al. 2006), endangering even the highest alpine glaciers.

Climatological Significance of the Recent Warming and the World's Ice Loss

The loss of ice is accelerating throughout the tropics, and this has been directly observed in the Himalayas, on Kilimanjaro, and in the Andes. Rising temperatures are driven by water vapor feedback in the climate system, which has potential ramifications for the Earth's future climate, since it is linked to the circulation of the Hadley cell. This is the major atmospheric circulation between the equatorial latitudes, where annual precipitation is the highest, and the outer rims of the tropics at ~30°N and ~30°S, where the Earth's major deserts are located. The rising arm of the Hadley cell is located near the equator, and at the surface below this warm air lies the Intertropical Convergence Zone (ITCZ). As the warm, moist air rises and cools, the maximum latent heat release occurs at the 500 mbar level (Webster 2004), the altitude where tropical glaciers are located. There is evidence that over the last 20 years this cell has expanded north and south by about 2° of latitude, which may broaden the desert zones (Seidel et al. 2007; Seidel and Randel 2008) as the dry descending arms move poleward. Under this scenario droughts might become more persistent, not only in the American Southwest, but in the Mediterranean and in the Southern Hemisphere (Australia and parts of South America and Africa).

As recorded in a compilation of ice cores recovered from low-latitude glaciers, the twentieth century was the warmest in the past 2,000 years (fig. 8A) (Thompson et al. 2006a). This is in agreement with Northern Hemisphere temperature reconstructions (Jones and Mann 2004) and more modern meteorological observations (Jones and Moberg 2003) (fig. 8B). That a similar profile can be determined independently by so many different paleoclimate recorders gives us confidence that the warming trend at the end of the twentieth century and the beginning of the twenty-first century is unprecedented in at least the last two millennia. However, individual ice-core records indicate that in

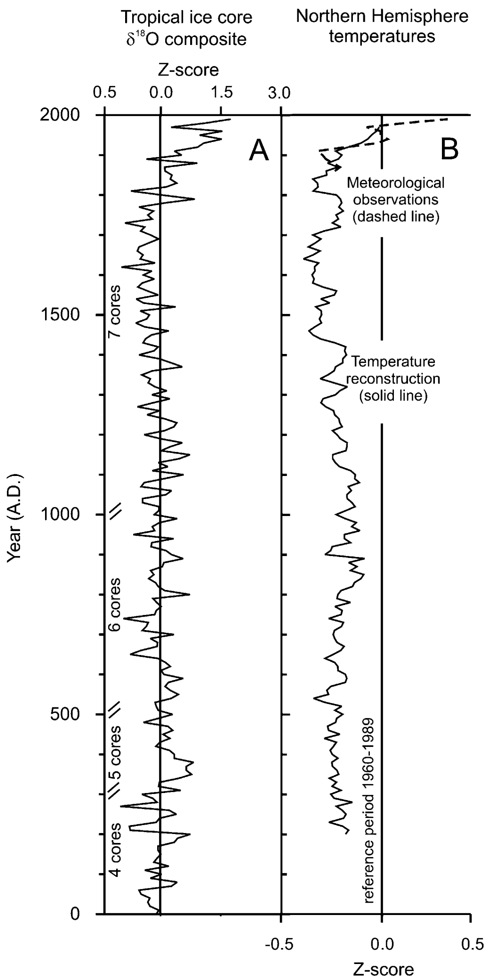


FIGURE 8. (A) 2,000-year record of temperature variations reconstructed from an array of tropical ice cores from the Andes and the Tibetan Plateau (Thompson et al. 2000a). (B) Reconstructed temperature records (Jones and Mann 2004) from a variety of proxy data over a comparable time period, overlain by meteorological data (Jones and Moberg 2003) since the mid-nineteenth century.

some regions the twentieth century was the warmest in more than 5,000 years. The implications of the recent ice loss from Kilimanjaro in Africa and Naimona'nyi in the Himalayas are disturbing, given projections of warming in the twenty-first century at high elevations in these low-latitude regions. The observed rapid glacier flow in Greenland and Antarctica is not predicted by current climate models, which assume a slow, linear response to climate change. Glaciers in most parts of the world are melting within generational timescales, and the consequences could potentially affect billions of people.

Over most of the twentieth century, sea level has risen about 2.0 mm per year, and ~50% of the recorded rise has been caused by thermal expansion of the ocean water. Because they respond to climate change so quickly, the mountain glaciers have contributed about 27%

to global sea level rise between 1993 and 2003, while the more slowly reacting polar ice sheets account for only 15% (IPCC 2007, WGI, table 5.3). Since 1990, sea level has accelerated to a rate of about 3.1 ± 0.7 mm per year, and in the last decade many of the glaciers draining Greenland and Antarctica have accelerated their discharge rate into the world's oceans (IPCC 2007). Since these changes are highly variable, and long records of these variations are lacking, the paths of future trends are unpredictable.

Societal Significance of the World's Ice Loss

Within the geographic tropics reside 70% of the world's 6.8 billion people. For many countries, some of which are in economic peril, alpine glaciers are valuable water resources for hydroelectric power production, crop irrigation, and municipal water supplies. Peru relies on hydroelectric power for 80% of its energy (Vergara et al. 2007), and a significant portion of that comes from mountain streams that are fed by mountain glaciers and ice fields. In Tanzania, the loss of Kilimanjaro's fabled ice cover is already impacting tourism, which is the country's primary source of foreign currency. Even in California, one of the wealthiest regions in the world, the glaciers and snowpacks in the Rocky Mountain Range complex are essential for agriculture.

As discussed above, the rate of average sea level rise, as well as the contribution from melting of alpine glaciers and polar ice sheets, has accelerated over the last 20 years. It would not require the loss of much of the total ice cover before catastrophic consequences ensue. If the Earth lost only 8% of its ice, the effects on some coastal regions would be dramatic. Low-lying areas such as the southern part of the Florida peninsula and much of southern Louisiana would be submerged, and major coastal cities such as New York and Shanghai would be endangered (Overpeck and Weiss 2009). Low-lying continental countries such as the Netherlands and much of Bangladesh find themselves battling flooding at an ever-increasing frequency. Already many small island nations in the western Pacific such as Vanuatu are facing imminent destruction as they are gradually overrun by the rising ocean surface. Currently, Indonesia has more than 17,000 islands, and many of them are at sea level. At the 2007 United Nations Climate Change Conference in Bali, Indonesian environmental minister Rachmat Witoelar stated that 2,000 of his country's islands could be lost to sea level rise by 2030.

Society's options

Over the next twenty years the decisions that our societies make and the actions we take to address the crises of climate change and environmental degradation will be critical for determining the quality of life our descendants experience over the coming centuries. Human societies have three options for dealing with any crisis: mitigate, adapt, or suffer. Mitigation is proactive, and in the case of anthropogenic climate change it involves taking measures to reduce the pace and magnitude of the changes by altering the underlying causes. The obvious and most hotly debated remedies involve those that reduce the emissions of the radiative gases (especially CO_2 and methane) that are involved in trapping the Earth's outgoing longwave radiation, leading to lower atmosphere and surface warming. Another solution that has received recent widespread attention is to enhance the natural carbon sinks through expansion of forests, or by "burying" carbon in the ocean. This latter proposal is an example of several geo-engineering procedures (e.g., Govindasamy and Caldeira 2000; Wigley 2006); however, some of these solutions are considered to be radical and may lead to unintended consequences (Parkinson 2010).

Adaptation is reactive; it involves reducing the potential adverse impacts on societal well-being resulting from the by-products of climate change. This might include construction of sea barriers such as dikes and tidal barriers (similar to those in the Thames River near London), relocation of coastal towns and cities inland, changes in agricultural practices to counteract shifting weather patterns, and strengthening human and animal immunity to climate-related diseases.

The third option is suffering, in which humans are forced to endure the adverse impacts that cannot be staved off by either mitigation or adaptation. Those who are affected most by the environmental and climatic changes that are instigated by wealthy nations are the least likely to have the resources to adapt. It is a cruel irony that so many of these people also live in or near ecologically sensitive areas, such as grasslands (Outer Mongolia), drylands (Sudan and Ethiopia), mountain glaciers (the Quechua of the Peruvian Andes), and coastal lowlands (Bangladesh and the South Sea island region).

Carbon dioxide is a gas that has a very long residence time in the atmosphere. Even if all anthropogenic emissions were to cease immediately, it would take several decades for the tropospheric temperatures to respond. It is estimated that 20% of the CO_2 released today will be impacting the Earth's climate more than 1,000 years from now (Archer and Brovkin 2008). Considering the lack of will among the world's wealthiest and most populous nations (which are also the primary greenhouse gas emitters) to curb their carbon-based fuel consumption, as well as the rapid destruction of carbon sinks such as temperate and tropical forests to make more room for human activities, it would seem that adaptation is the most feasible option for the wealthy, while suffering is the main option left for the world's poor. As challenging as the understanding of climate change is, the human response to the changes can be even more challenging. Often when the subject of climate change arises, it is spoken of in reference to the effects on future generations. What is ignored or disputed is that detrimental effects of changing climate are visible today.

From the late 1980s until the middle of the current decade, the concepts of global-scale warming and climate change were accepted by much of the American media and the general public. This may have been a reaction to a series of extreme weather events, such as deadly summer heat waves affecting North America in 1988, 1995, 1998, 2001, and 2006 and the punishing hurricane seasons of 2005 and 2006. Average winter temperatures in the United States trended noticeably upward from 1980 to 2006. However, since the 2006 Hurricane Katrina disaster Americans have experienced relatively quiet hurricane seasons, and average annual temperatures over the U.S. have decreased over the last two years. This may have lulled many of us into a false sense of security in which we feel that the world's climate is recovering, and thus warnings about anthropogenic climate change can be dismissed as "alarmist hype." However, one glance at a diagram showing annual temperatures over the mainland United States since 1895 (fig. 9) shows that while temperatures have indeed oscillated up and down, the overall trend has been upward, and the next series of oscillations may peak at higher levels.

In the next 20 years the changing climate will become clear to most of us, not just to citizens of some of the less wealthy nations who are already experiencing some of the consequences. Since the concentrations of CO_2 and methane are the highest they have been in 800,000 years, climatologically we are in unfamiliar territory. One of the immediate casualties, the world's ice cover, is responding dramatically. Glaciers, especially tropical glaciers, are the "canaries in the coal mine" for our global climate system as they integrate and respond to most key climatological variables such as temperature, precipitation, cloudiness, humidity, and solar radiation. Many parts of the world will lose their mountain glaciers, which will have swift and adverse impacts on millions of people through seasonal depletion of agricultural and municipal water supplies, hydroelectric power production, and even tourism (e.g., the loss of the famed ice fields of Kilimanjaro). The potential shifting of position and intensity of atmospheric pressure systems, which may result from warming sea surface and lower atmospheric temperatures, could contribute to the migration of jet streams, fronts, and precipitation patterns. If the recently observed expansion of the tropical Hadley cell continues, we might expect droughts in the American

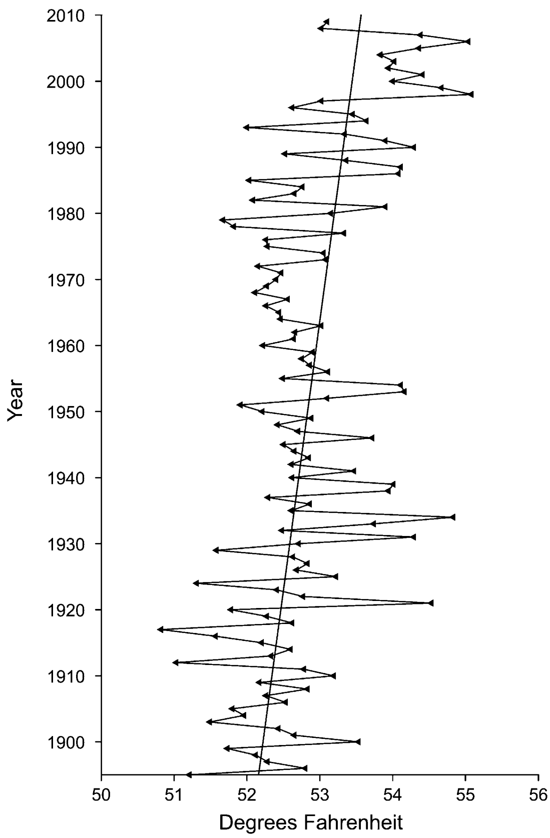


FIGURE 9. Annual average temperatures for the contiguous United States from 1895 to 2009. The straight line shows an upward trend of 0.12°F per decade. Data are from NOAA Satellite and Information Services Climate Monitoring Climate at a Glance Web site. (http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html).

Southwest, Mediterranean Sea region, and Australia to intensify. A hotly debated "wild card" in future climate scenarios is the relationship between Atlantic hurricane frequencies and sea surface temperatures (Vecchi et al. 2008). Considering the current data base and level of understanding of these linkages, we will probably require another 20 years before we are able to come to reliable conclusions about the nature of tropical storms in a changing climate.

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