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Climate Change: The Evidence and Our Options

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Glaciers serve as early indicators of climate change. Over the last 35 years, our research team has recovered ice-core records of climatic and environmental variations from the polar regions and from low-latitude high-elevation ice fields from 16 countries. The ongoing widespread melting of high-elevation glaciers and ice caps, particularly in low to middle latitudes, provides some of the strongest evidence to date that a large-scale, pervasive, and, in some cases, rapid change in Earth's climate system is underway. This paper highlights observations of 20th and 21st century glacier shrinkage in the Andes, the Himalayas, and on Mount Kilimanjaro. Ice cores retrieved from shrinking glaciers around the world confirm their continuous existence for periods ranging from hundreds of years to multiple millennia, suggesting that climatological conditions that dominate those regions today are different from those under which these ice fields originally accumulated and have been sustained. The current warming is therefore unusual when viewed from the millennial perspective provided by multiple lines of proxy evidence and the 160-year record of direct temperature measurements. Despite all this evidence, plus the well-documented continual increase in atmospheric greenhouse gas concentrations, societies have taken little action to address this global-scale problem. Hence, the rate of global carbon dioxide emissions continues to accelerate. As a result of our inaction, we have three options: mitigation, adaptation, and suffering.

Key words: climate, global warming

Climatologists, like other scientists, tend to be a stolid group. We are not given to theatrical rantings about falling skies. Most of us are far more comfortable in our laboratories or gathering data in the field than we are giving interviews to journalists or speaking before Congressional committees. Why then are climatologists speaking out about the dangers of global warming? The answer is that virtually all of us are now convinced that global warming poses a clear and present danger to civilization ("Climate Change," 2010).

That bold statement may seem like hyperbole, but there is now a very clear pattern in the scientific evidence documenting that the earth is warming, that warming is due largely to human activity, that warming is causing important changes in climate, and that rapid and potentially catastrophic changes in the near future are very possible. This pattern emerges not, as is so often suggested, simply from computer simulations, but from the weight and balance of the empirical evidence as well.

THE EVIDENCE

Figure 1 shows northern hemisphere temperature profiles for the last 1,000 years from a variety of high-resolution climate recorders such as glacier lengths (Oerlemans, 2005), tree rings (Briffa, Jones, Schwerngruber,

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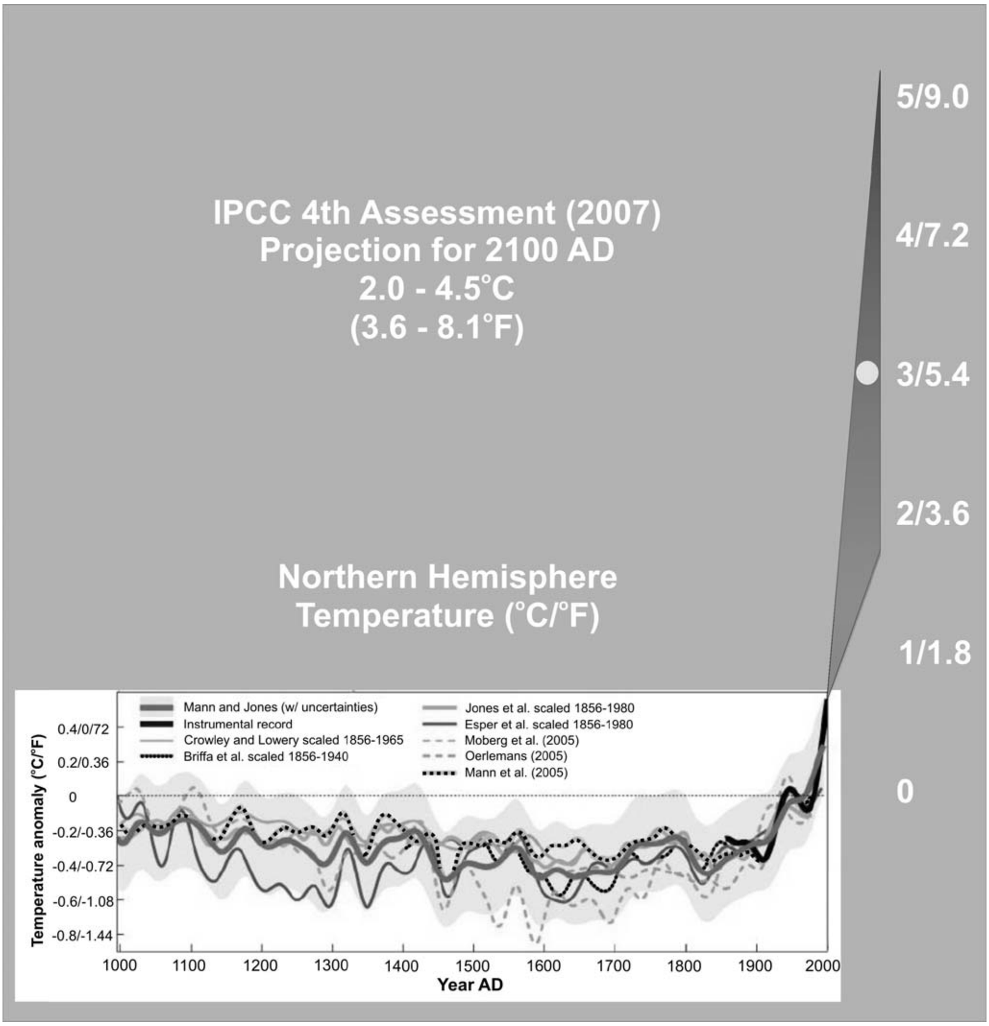

Figure 1. A variety of temperature records over the last 1,000 years, based on a variety of proxy recorders such as tree rings, ice cores, historical records, instrumental data, etc., shows the extent of the recent warming. The range of temperature projected by Meehl et al. (2007) to 2100 AD is shown by the shaded region, and the average of the range is depicted by the filled circle.

Shiyatov, & Cook, 2002; Esper, Cook, & Schweingruber, 2002), and combined sources that include some or all of the following: tree rings, sediment cores, ice cores, corals, and historical records (Crowley & Lowery, 2000; Jones, Briffa, Barnett, & Tett, 1998; Mann, Bradley, & Hughes, 1999; Moberg, Sonechkin, Holmgrem, Datsenko, & Karlen, 2005). The heavy gray line is a composite of all these temperatures (Mann & Jones, 2003), and the heavy black line depicts actual thermometer readings back to 1850 (see National Research Council, 2006, for a review of surface temperature reconstructions). Although the various curves differ from one another, their general shapes are similar. Each data source shows that average northern hemisphere temperatures remained relatively stable until the late 20th century. It is the agreement of these diverse data sets and the pattern that make climatologists confident that the warming trend is real.

Because these temperature numbers are based on northern hemisphere averages, they do not reflect regional, seasonal, and altitudinal variations. For example, the average temperature in the western United States is rising more rapidly than in the eastern part of the country, and on average winters are warming faster than summers (Meehl, Arblaster, & Tebaldi, 2007). The most severe temperature increases appear to be concentrated in the Arctic and over the Antarctic Peninsula as well as within the interior of the large continents. This variability complicates matters, and adds to the difficulty of convincing the public, and even scientists in other fields, that global warming is occurring. Because of this, it may be useful to examine another kind of evidence: melting ice.

Retreat of Mountain Glaciers

The world's mountain glaciers and ice caps contain less than 4% of the world's ice cover, but they provide invaluable information about changes in climate. Because glaciers are smaller and thinner than the polar ice sheets, their ratio of surface area to volume is much greater; thus, they respond more quickly to temperature changes. In addition, warming trends are amplified at higher altitudes where most glaciers are located (Bradley, Keimig, Diaz, & Hardy, 2009; Bradley, Vuille, Diaz, & Vergara, 2006). Thus, glaciers provide an early warning system of climate change; they are our "canaries in the coal mine."

Consider the glaciers of Africa's Mount Kilimanjaro (Figure 2). Using a combination of terrestrial photogrammetric maps, satellite images, and aerial photographs, we have determined that the ice fields on Kibo, the highest crater on Kilimanjaro, have lost 85% of their coverage since 1912 (Thompson, Brecher, Mosley-Thompson, Hardy, & Mark, 2009).

Figure 3 shows a series of aerial photographs of Furtwängler glacier, in the center of Kibo crater, taken between 2000 and 2007, when the glacier split into two sections. As Furtwängler recedes, it is also thinning rapidly, from 9.5 m in 2000 to 4.7 m in 2009 (for more images of Furtwängler's retreat, see http://www.examiner.com/examiner/x-10722-Orlando-Science-Policy-Examiner~y2009m11d2-Mt-Kilimanjaros-Furtwängler-Glacier-in-retreat). If you connect the dots on the changes seen to date and assume the same rate of loss in the future, within the next decade many of the glaciers of Kilimanjaro, a Swahili word meaning "shining mountain," will have disappeared.

The Quelccaya ice cap, which is located in southern Peru adjacent to the Amazon Basin, is the largest tropical ice field on Earth. Quelccaya has several outlet glaciers, glaciers that extend from the edges of an ice cap like fingers from a hand. The retreat of one of these, Qori Kalis, has been studied and photographed since 1963. At the beginning of this study, Qori Kalis extended 1,200 m out from the ice cap, and there was no melt water at the end (Figure 4, map top left). By the summer of 2008, Qori Kalis had retreated to the very edge of Quelccaya, leaving behind an 84-acre lake, 60 m deep. Over the years, a boulder near the base camp has served as a benchmark against which to record the changes in the position of the edge of the ice. In 1977 the ice was actually pushing against the boulder (Figure 5, top), but by 2006 a substantial gap had appeared and been filled by a lake (Figure 5, bottom). Thus, the loss of Quelccaya's ice is not only on the Qori Kalis glacier but also on the margin of the ice cap itself. Since 1978, about 25% of this tropical ice cap has disappeared.

The Himalayan Mountains are home to more than 15,000 glaciers. Unfortunately, only a few of these glaciers have been monitored over an extended period, so reliable ground observations that are crucial for

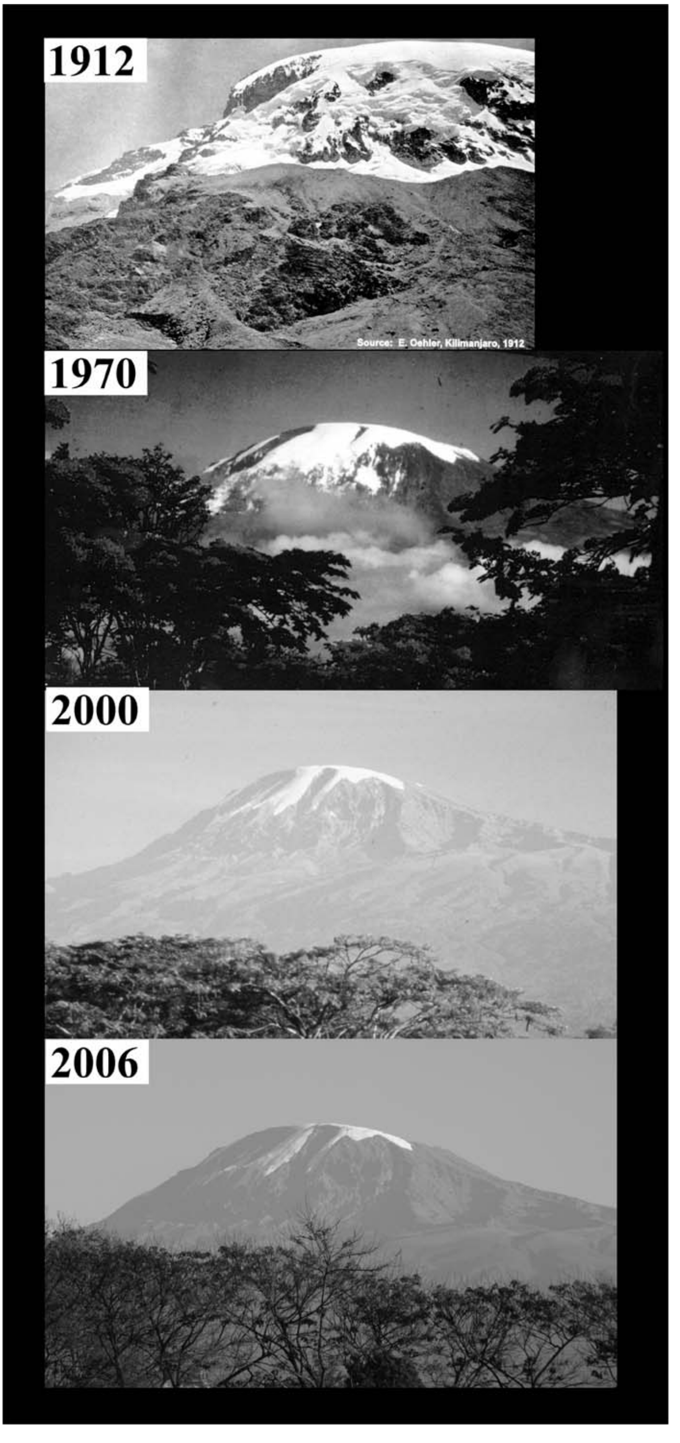

Figure 2. The retreat of glaciers on Mount Kilimanjaro can be seen in the photographs from 1912, 1970, 2000, and 2006; from 1912 to 2006, 85% of the ice has disappeared.

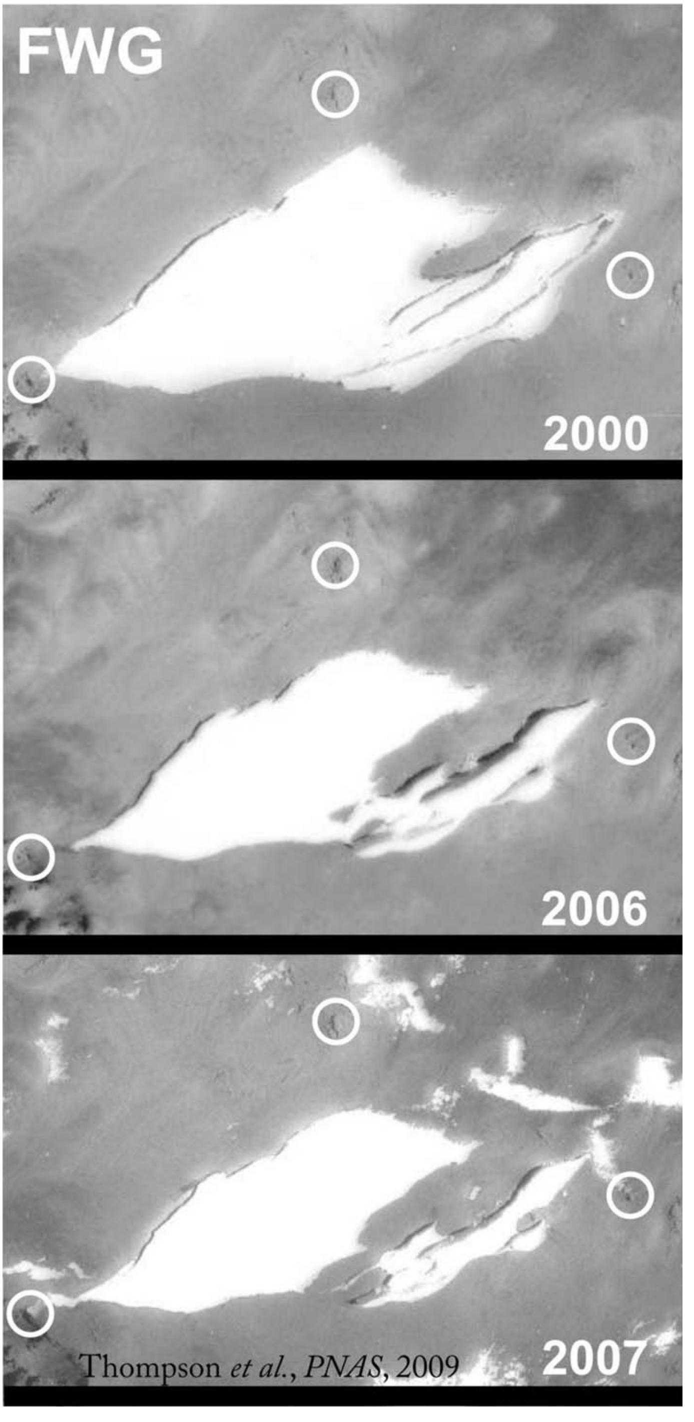

Figure 3. Deterioration of the Furtwängler glacier in the center of Kibo crater on Mount Kilimanjaro. Since 2000 the ice field has decreased in size and thickness and has divided in two.

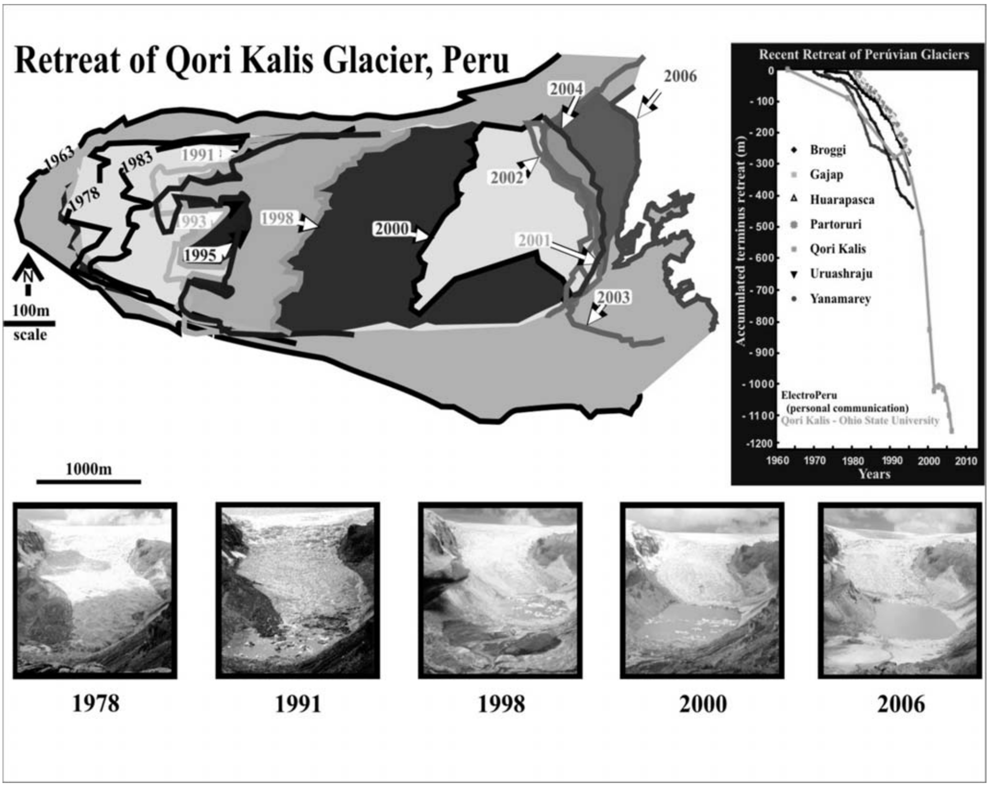

Figure 4. Retreat of the Qori Kalis outlet glacier on the Quelccaya ice cap. Each line shows the extent of the ice. The photos along the bottom provide a pictorial history of the melting of the Qori Kalis outlet glacier and the formation of a lake. The retreat of Qori Kalis is similar to the loss of several Peruvian glaciers, as shown in the graph insert.

determining regional retreat rates do not yet exist. However, a recent study of 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 layers from the 1950s and early 1960s that appear in all Tibetan and Himalayan ice core records (Thompson, 2000; Thompson et al., 1990, 1997, 2006).

Glaciologists at the Institute of Tibetan Plateau Research in Beijing have been monitoring 612 glaciers across the High Asian region since 1980. These scientists found that from 1980 to 1990, 90% of these glaciers were retreating; from 1990 to 2005, the proportion of retreating glaciers increased to 95% (Yao, Pu, Lu, Wang, & Yu, 2007).

A study of 67 glaciers in Alaska from the mid-1950s to the mid-1990s shows that all are thinning (Arendt, Echelmeyer, Harrison, Lingle, & Valentine, 2002). In northern Alaska's Brooks Range, 100% of the glaciers are in retreat, and in southeastern Alaska 98% are shrinking (Molnia, 2007). Glacier National Park in Montana contained more than 100 glaciers when it was established in 1910. Today, just 26 remain, and at the current rate of decrease it is estimated that by 2030 there will be no glaciers in Glacier National Park (Hall & Fagre, 2003). The oldest glacier photos come from the Alps. Ninety-nine percent of the glaciers in the Alps are retreating, and 92% of Chile's Andean glaciers are retreating (Vince, 2010).

The pattern described here is repeated around the world. Mountain

Figure 5. Top: photo taken in 1978 shows a margin of the Quelccaya ice cap pushing against a boulder. Bottom: the same margin is shown in a 2005 photo. The ice has receded and has been replaced by a small lake. The boulder shown in the top photo is located in the center of the white circle to the right.

glaciers nearly everywhere are retreating.

Loss of Polar Ice

Satellite documentation of the area covered by sea ice in the Arctic Ocean extends back three decades. This area, measured each September, decreased at a rate of about 8.6% per decade from 1979 to 2007. In 2007 alone, 24% of the ice disappeared. In 2006 the Northwest Passage was ice free for the first time in recorded history.

As noted earlier, polar ice sheets are slower to respond to temperature rise than the smaller mountain glaciers, but they, too, are melting. The Greenland ice sheet has also experienced dramatic ice melt in recent years. There has been an increase in both the number and the size of lakes in the southern part of the ice sheet, and crevices can serve as conduits (called moulins) that transport meltwater rapidly into the glacier. Water has been observed flowing through these moulins down to the bottom of the ice sheet where it acts as a lubricant that speeds the flow of ice to the sea (Das et al., 2008; Zwally et al., 2002).

The ice in Antarctica is also melting. The late John Mercer, a glacial geologist at The Ohio State University, long ago concluded that the first evidence of global warming due to increasing carbon dioxide (CO_2) would be the breakup of the Antarctic ice shelves (Mercer, 1978). Mean temperatures on the Antarctic Peninsula have risen 2.5° C (4.5° F) in the last 50 years, resulting in the breakup of the ice shelves in just the way Mercer predicted. One of the most rapid of these shelf deteriorations occurred in 2002, when the Larsen B, a body of ice over 200 m deep that covered an area the size of Rhode Island, collapsed in just 31 days (see images http://earthobservatory.nasa.gov/IOTD/view.php?id=2351). An ice shelf is essentially an iceberg attached to land ice. Just as an ice cube does not raise the water level in a glass when it melts, so a melting ice shelf leaves sea levels unchanged. But ice shelves serve as buttresses to glaciers on land, and when those ice shelves collapse it speeds the flow of the glaciers they were holding back into the ocean, which causes sea level to rise rapidly.

Just days before this paper went to press, a giant ice island four times the size of Manhattan broke off the Petermann glacier in Greenland. This event alone does not prove global climate change, because half of the ice loss from Greenland each year comes from icebergs calving from the margins. It is the fact that this event is part of a long-term trend of increasing rates of ice loss, coupled with the fact that temperature is increasing in this region at the rate of 2° C (3.6° F) per decade, that indicates that larger scale global climate change is underway.

The loss of ice in the Arctic and Antarctic regions is especially troubling because these are the locations of the largest ice sheets in the world. Of the land ice on the planet, 96% is found on Greenland and Antarctica. Should all this ice melt, sea level would rise over 64 m (Church et al., 2001; Lemke et al., 2007), and of course the actual sea level would be much higher due to thermal expansion of the world's oceans as they warm.

Although research shows some variability in the rate of ice loss, it is clear that mountain glaciers and polar ice sheets are melting, and there is no plausible explanation for this but global warming. Add to this the laboratory evidence and the meteorological measurements, and the case for global warming cannot be denied. So what causes global temperatures to rise?

CAUSES OF GLOBAL WARMING

Climatologists strive to reconstruct past climate variations on regional and global scales, but they also try to determine the mechanisms, called *forcers*, that drive climate change. Climatologists recognize two basic categories of forcers. Natural forcers are recurring processes that have been around for millions of years; anthropogenic forcers are more recent processes caused by human activity.

One familiar natural forcer is the earth's orbit around the sun, which gives us our seasons. In the northern hemisphere, June is warm because the sun's rays fall more directly on it, and the sun appears high in the sky; in the southern hemisphere, June is cool because the sun's rays hit the earth at a deep angle, and the sun appears low in the sky.

Less obvious natural forcers include short- and long-term changes in the atmosphere and ocean. For example, when Mount Pinatubo erupted in the Philippines in 1991, it spewed millions of tons of sulfuric gases and ash particles high into the atmosphere, blocking the sun's rays. This lowered global temperatures for the next few years. Another natural forcer is the linked oceanic and atmospheric system in the equatorial Pacific Ocean known as the El Niño-Southern Oscillation (ENSO). ENSO occurs every 3 to 7 years in the tropical Pacific and brings warm, wet weather to some regions and cool, dry weather to other areas.

Other natural forcers include periodic changes in energy from the sun. These include the 11- to 12-year sunspot cycle and the 70- to 90-year Wolf-Gleissberg cycle, a modulation of the amplitude of the 11-year solar cycle. These changes in solar energy can affect atmospheric temperature across large regions for hundreds of years and may have caused the "medieval climate anomaly" in the northern hemisphere that lasted from about 1100 AD to 1300 AD. Solar cycles may also have played a role in the cause of the "little ice age" in North America and Europe during the 16th to 19th centuries. These changes in climate, which are often cited by those who dismiss global warming as a normal, cyclical event, affected large areas, but not the Earth as a whole. The medieval climate anomaly showed warmth that matches or exceeds that of the past decade in some regions, but it fell well below recent levels globally (Mann et al., 2009).

The most powerful natural forcers are variations in the orbit of the Earth around the Sun, which last from 22,000 to 100,000 years. These "orbital forcings" are partly responsible for both the ice ages (the glacial periods during which large regions at high and midddle latitudes are covered by thick ice sheets), and for the warm interglacial periods such as the present Holocene epoch which began about 10,000 years ago.

There is consensus among climatologists that the warming trend we have been experiencing for the past 100 years or so cannot be accounted for by any of the known natural forcers. Sunspot cycles, for example, can increase the sun's output, raising temperatures in our atmosphere. We are seeing a temperature increase in the troposphere, the lower level of our atmosphere, and a temperature decrease in the stratosphere, the upper level. But this is the exact opposite of what we would get if increased solar energy were responsible. Similarly, global temperatures have increased more at night than during the day, again the opposite of what would occur if the sun were driving global warming. In addition, temperatures have risen more in winter than in summer. This, too, is the opposite of what would be expected if the sun were responsible for the planet's warming. High latitudes have warmed more than low latitudes, and because we get more radiation from the sun at low latitudes, we again would expect the opposite if the sun were driving these changes. Thus, changes in solar output cannot account for the current period of global warming (Meehl et al., 2007). ENSO and other natural forcers also fail to explain the steady, rapid rise in the earth's temperature. The inescapable conclusion is that the rise in temperature is due to anthropogenic forces, that is, human behavior.

The relatively mild temperatures of the past 10,000 years have been maintained by the greenhouse effect, a natural phenomenon. As orbital forcing brought the last ice age to an end, the oceans warmed, releasing CO_2 into the atmosphere, where it trapped infrared energy reflected from the earth's surface. This warmed the planet. The greenhouse effect is a natural, self-regulating process that is absolutely essential to sustain life on the planet. However, it is not immutable. Change the level of greenhouse gases in the atmosphere, and the planet heats up or cools down.

Greenhouse gases are captured in ice, so ice cores allow us to see the levels of greenhouse gases in ages past. The longest ice core ever recovered (from the European Project for Ice Coring in Antarctica) takes us 800,000 years back in time, and includes a history of CO_2 and methane levels preserved in bubbles in the ice (Loulergue et al., 2008; Lüthi et al., 2008). The CO_2 and methane curves illustrated in Figure 6 show that the modern levels of these gases are unprecedented in the last 800 millennia.

Globally, CO_2 concentrations have varied between 180 and 190 parts per million per volume (ppmv) during glacial (cold) periods and between 270 and 290 ppmv during interglacial (warm) periods. However, since the onset of the Industrial Revolution, when fossil fuel use (chiefly coal and oil) began to burgeon, CO_2 concentration has increased about 38% over the natural interglacial levels (Forster et al., 2007). Between 1975 and 2005, CO_2 emissions increased 70%, and between 1999 and 2005 global emissions increased 3% per year (Marland, Boden, & Andres, 2006). As of this writing, the CO_2 concentration in the atmosphere is 391 ppmv (Mauna Loa CO_2 annual mean data from the National Oceanic and Atmospheric Administration, 2010), a level not seen at any time in 800,000 years. Climatologists have identified no natural forcers that could account for this rapid and previously unseen rise in CO_2.

Methane raises temperature even more than CO_2, and the amount of methane in the atmosphere, like that of CO_2, is also at a level not seen in 800 millennia. Two thirds of current emissions of methane are by-products of human activity, things like the production of oil and natural gas, deforestation, decomposition of garbage and sewage, and raising farm animals.

Many people find it difficult to believe that human activity can affect a system as large as Earth's climate. After all, we are so tiny compared to the planet. But every day we tiny human beings drive cars; watch television; turn on lamps; heat or cool our houses and offices; eat food transported to us by planes, ships, and trucks; clear or burn forests; and behave in countless other ways that directly or indirectly release greenhouse gases into the air. Together, we humans emitted eight *billion* metric tons of carbon to our planet's atmosphere in 2007 alone (Boden, Marland, & Andres, 2009). (CO_2 weighs 3.66 times more than carbon; that means we released 29.3 billion metric tons of CO_2.) The evidence is overwhelming that human activity is responsible for the rise in CO_2, methane, and other greenhouse gas levels, and that the increase in these gases is fueling the rise in mean global temperature.

A global temperature rise of a few degrees may not seem such a bad thing, especially to people living in harsh, cold climates. But global warming does not mean merely that we will trade parkas for T-shirts or

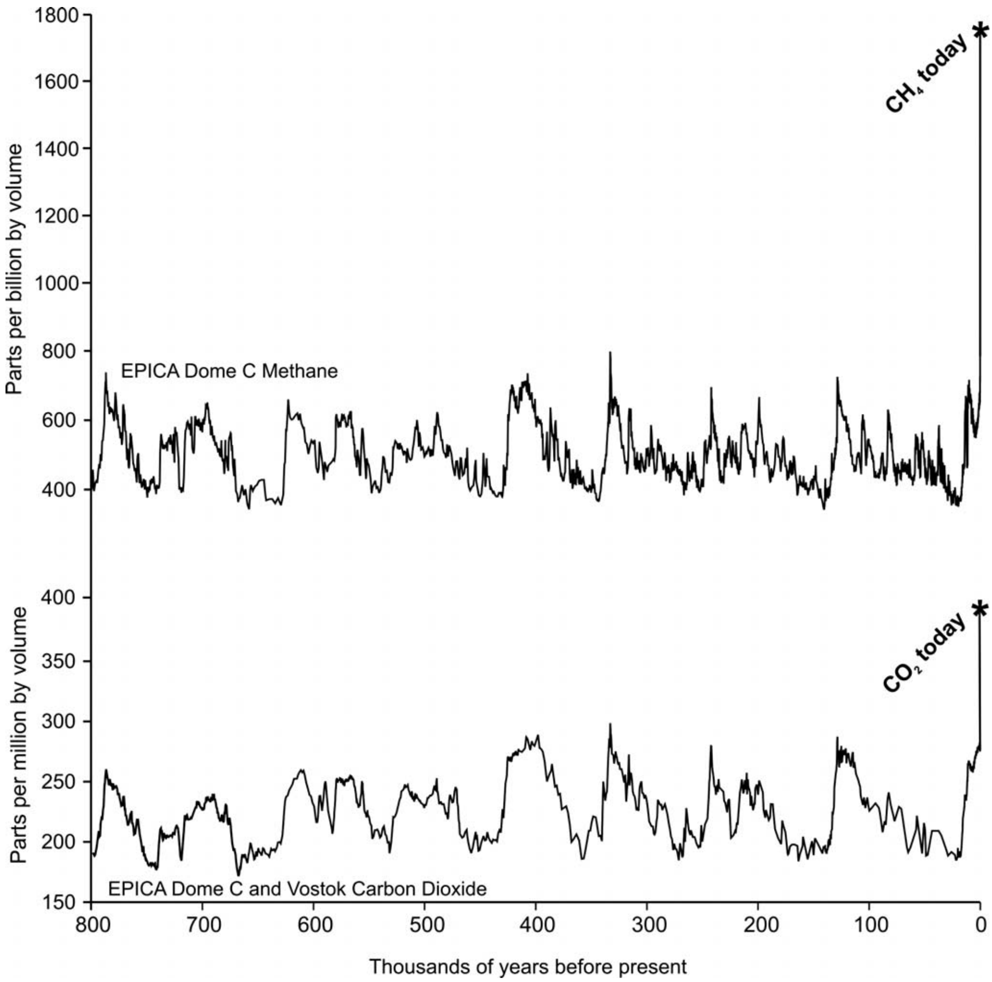

Figure 6. Concentrations of carbon dioxide (CO_2) and methane (CH_4) over the last 800,000 years (eight glacial cycles) from East Antarctic ice cores. Data from Loulergue et al. (2008) and Lüthi et al. (2008). The current concentrations of CO_2 and CH_4 are also shown (Forster et al., 2007).

turn up the air conditioning. A warming planet is a changing planet, and the changes will have profound consequences for all species that live on it, including humans. Those changes are not just something our children and grandchildren will have to deal with in the future; they are taking place now, and are affecting millions of people.

EFFECTS OF GLOBAL WARMING

One effect of global warming that everyone has heard about is a rise in sea levels. About half of this rise is due to thermal expansion: Ocean temperatures are rising, and as water warms it expands. Put a nearly full cup of water in a microwave and heat it, and the water will spill over the cup.

In addition to thermal expansion, the oceans are rising because ice is melting, and most of that water inevitably finds its way to the sea. So far, most of that water has come from mountain glaciers and ice caps (Meier et al., 2007). As global temperatures increase, sea level rise will mainly reflect polar ice melt. So far, ocean rise has been measured in millimeters, but there is enough water in the Greenland ice sheet alone to raise sea levels by about 7 m, West Antarctica over 5 m, and East Antarctica about 50 m (Lemke et al., 2007). If the Earth were to lose just 8% of its ice, the consequences for some coastal regions would be dramatic. The lower part of the Florida peninsula and much of Louisiana, including New Orleans, would be submerged, and low-lying cities, including London, New York, and Shanghai, would be endangered (to see the effects of various magnitudes of sea level rise in the San Francisco Bay area, go to http://cascade.wr.usgs.gov/data/Task2b-SFBay/data.shtm).

Low-lying continental countries such as the Netherlands and much of Bangladesh already find themselves battling flooding more than ever before. Many small island nations in the western Pacific (e.g., Vanuatu) are facing imminent destruction as they are gradually overrun by the rising ocean. Indonesia is an island nation, and many of its 17,000 islands are just above 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. At current rates of sea level rise, another island nation, the Republic of Maldives, will become uninhabitable by the end of the century (http://unfcc.int/resource/docs/napa/mdv01.pdf). In 2008, the president of that country, Mohamed Nasheed, announced that he was contemplating moving his people to India, Sri Lanka, and Australia (Schmidle, 2009). One of the major effects of continued sea level rise will be the displacement of millions of people. Where millions of climate refugees will find welcome is unclear. The migration of large numbers of people to new territories with different languages and cultures will be disruptive, to say the least.

In addition to the danger of inundation, rising sea levels bring salt water into rivers, spoil drinking wells, and turn fertile farmland into useless fields of salty soil. These effects of global warming are occurring now in places like the lowlands of Bangladesh (Church et al., 2001).

People on dry land need the fresh water that is running into the sea. In the spring, melting ice from mountain glaciers, ice caps, and snowfields furnish wells and rivers that provide fresh water for drinking, agriculture, and hydroelectric power. For example, in the dry season, people in large areas of India, Nepal, and southern China depend on rivers fed by Himalayan glaciers. The retreat of these glaciers threatens the water supply of millions of people in this part of the world. Peru relies on hydroelectric power for 80% of its energy (Vergara et al., 2007), a significant portion of which comes from mountain streams that are fed by mountain glaciers and ice fields. In Tanzania, the loss of Mount Kilimanjaro's fabled ice cover would likely have a negative impact on tourism, which is the country's primary source of foreign currency. The glaciers and snow packs in the Rocky Mountains are essential for farming in California, one of the world's most productive agricultural areas.

Global warming is expanding arid areas of the Earth. Warming at the equator drives a climate system called the Hadley Cell. Warm, moist air rises from the equator, loses its moisture through rainfall, moves north and south, and then falls to the Earth at 30° north and south latitude, creating deserts and arid regions. There is evidence that over the last 20 years the Hadley Cell has expanded north and south by about 2° latitude, which may broaden the desert zones (Seidel, Fu, Randel, & Reichler, 2008; Seidel & Randel, 2007). If so, droughts may become more persistent in the American

Southwest, the Mediterranean, Australia, South America, and Africa.

Global warming can also have effects that seem paradoxical. Continued warming may change ocean currents that now bring warm water to the North Atlantic region, giving it a temperate climate. If this happens, Europe could experience a cooling even as other areas of the world become warmer.

Accelerating Change

It is difficult to assess the full effects of global warming, and harder still to predict future effects. Climate predictions are made with computer models, but these models have assumed a slow, steady rate of change. Our best models predict a temperature rise in this century of between 2.4° and 4.5° C (4.3° and 8.1° F), with an average of about 3° C (5.4° F; Meehl et al., 2007; Figure 1). But these models assume a linear rise in temperature. Increasingly, computer models have underestimated the trends because, in fact, the rate of global temperature rise is accelerating. The average rise in global temperature was 0.11° F per decade over the last century (National Oceanic and Atmospheric Administration, 2009). Since the late 1970s, however, this rate has increased to 0.29° F per decade, and 11 of the warmest years on record have occurred in the last 12 years. May, 2010, was the 303rd consecutive month with a global temperature warmer than its 20th-century average (National Oceanic and Atmospheric Administration, 2010).

The acceleration of global temperature is reflected in increases in the rate of ice melt. From 1963 to 1978, the rate of ice loss on Quelccaya was about 6 m per year. From 1991 to 2006, it averaged 60 m per year, 10 times faster than the initial rate (Thompson et al., 2006). A recent paper by Matsuo and Heki (2010) reports uneven ice loss from the high Asian ice fields, as measured by the Gravity Recovery and Climate Experiment satellite observations between 2003 and 2009. Ice retreat in the Himalayas slowed slightly during this period, and loss in the mountains to the northwest increased markedly over the last few years. Nevertheless, the average rate of ice melt in the region was twice the rate of four decades before. In the last decade, many of the glaciers that drain Greenland and Antarctica have accelerated their discharge into the world's oceans from 20% to 100% (Lemke et al., 2007).

Increasing rates of ice melt should mean an increasing rate of sea level rise, and this is in fact the case. Over most of the 20th century, sea level rose about 2 mm per year. Since 1990, the rate has been about 3 mm per year.

So, not only is Earth's temperature rising, but the rate of this change is accelerating. This means that our future may not be a steady, gradual change in the world's climate, but an abrupt and devastating deterioration from which we cannot recover.

Abrupt Climate Change Possible

We know that very rapid change in climate is possible because it has occurred in the past. One of the most remarkable examples was a sudden cold, wet event that occurred about 5,200 years ago, and left its mark in many paleoclimate records around the world.

The most famous evidence of this abrupt weather change comes from Otzi, the "Tyrolean ice man" whose remarkably preserved body was discovered in the Eastern Alps in 1991 after it was exposed by a melting glacier. Forensic evidence suggests that Otzi was shot in the back with an arrow, escaped his enemies, then sat down behind a boulder and bled to death. We know that within days of Otzi's dying there must have been a climate event large enough to entomb him in snow; otherwise, his body would have decayed or been eaten by scavengers. Radiocarbon dating of Otzi's remains revealed that he died around 5,200 years ago (Baroni & Orombelli, 1996).

The event that preserved Otzi could have been local, but other evidence points to a global event of abrupt cooling. Around the world organic material is being exposed for the first time in 5,200 years as glaciers recede. In 2002, when we studied the Quelccaya ice cap in southern Peru, we found a perfectly preserved wetland plant. It was identified as *Distichia muscoides*, which today grows in the valleys below the ice cap. Our specimen was radiocarbon dated at 5,200 years before present (Thompson et al., 2006). As the glacier continues to retreat, more plants have been collected and radiocarbon dated, almost all of which confirm the original findings (Buffen, Thompson, Mosley-Thompson, & Huh, 2009).

Another record of this event comes from the ice fields on Mount Kilimanjaro. The ice dating back 5,200 years shows a very intense, very sudden decrease in the concentration of heavy oxygen atoms, or isotopes, in the water molecules that compose the ice (Thompson et al., 2002). Such a decrease is indicative of colder temperatures, more intense snowfall, or both.

The Soreq Cave in Israel contains speleothems that have produced continuous climate records spanning tens of thousands of years. The record shows that an abrupt cooling also occurred in the Middle East about 5,200 years ago, and that it was the most extreme climatic event in the last 13,000 years (Bar-Matthews, Ayalon, Kaufman, & Wasserburg, 1999).

One way that rapid climate change can occur is through positive feedback. In the physical sciences, positive feedback means that an event has an effect which, in turn, produces more of the initial event. The best way to understand this phenomenon as it relates to climate change is through some very plausible examples:

Higher global temperatures mean dryer forests in some areas, which means more forest fires, which means more CO_2 and ash in the air, which raises global temperature, which means more forest fires, which means …

Higher global temperatures mean melting ice, which exposes darker areas (dirt, rock, water) that reflect less solar energy than ice, which means higher global temperatures, which means more melting ice, which means …

Higher global temperatures mean tundra permafrost melts, releasing CO_2 and methane from rotted organic material, which means higher global temperature, which means more permafrost melting, which means …

Positive feedback increases the *rate* of change. Eventually a tipping point may be reached, after which it could be impossible to restore normal conditions. Think of a very large boulder rolling down a hill: When it first starts to move, we might stop it by pushing against it or wedging chocks under it or building a barrier, but once it has reached a certain velocity, there is no stopping it. We do not know if there is a tipping point for global warming, but the possibility cannot be dismissed, and it has ominous implications. Global warming is a very, very large boulder.

Even if there is no tipping point (or we manage to avoid it), the acceleration of warming means serious trouble. In fact, if we stopped emitting greenhouse gases into the atmosphere tomorrow, temperatures would continue to rise for 20 to 30 years because of what is already in the atmosphere. Once methane is injected into the troposphere, it remains for about 8 to 12 years (Prinn et al., 1987). Carbon dioxide has a much longer residence: 70 to 120 years. Twenty percent of the CO_2 being emitted today will still affect the earth's climate 1,000 years from now (Archer & Brovkin, 2008).

If, as predicted, global temperature rises another 3° C (5.4° F) by the end of the century, the earth will be warmer than it has been in about 3 million years (Dowsett et al., 1994; Rahmstorf, 2007). Oceans were then about 25 m higher than they are today. We are already seeing important effects from global warming; the effects of another 3° C (5.4° F) increase are hard to predict. However, such a drastic change would, at the very least, put severe pressure on civilization as we know it.

OUR OPTIONS

Global warming is here and is already affecting our climate, so prevention is no longer an option. Three options remain for dealing with the crisis: mitigate, adapt, and suffer.

Mitigation is proactive, and in the case of anthropogenic climate change it involves doing things to reduce the pace and magnitude of the changes by altering the underlying causes. The obvious, and most hotly debated, remedies include those that reduce the volume of greenhouse gas emissions, especially CO_2 and methane. Examples include not only using compact fluorescent lightbulbs, adding insulation to our homes, and driving less, but societal changes such as shutting down coal-fired power plants, establishing a federal carbon tax (as was recently recommended by the National Academy of Sciences), and substantially raising minimum mileage standards on cars (National Research Council, 2010). Another approach to mitigation that has received widespread attention recently is to enhance the natural carbon sinks (storage systems) through expansion of forests. Some have suggested various geo-engineering procedures (e.g., Govindasamy & Caldeira, 2000; Wigley, 2006). One example is burying carbon in the ocean or under land surfaces (Brewer, Friederich, Peltzer, & Orr, 1999). Geoengineering ideas are intriguing, but some are considered radical and may lead to unintended negative consequences (Parkinson, 2010).

Adaptation is reactive. It involves reducing the potential adverse impacts resulting from the by-products of climate change. This might include constructing sea barriers such as dikes and tidal barriers (similar to those on the Thames River in London and in New Orleans), relocating coastal towns and cities inland, changing agricultural practices to counteract shifting weather patterns, and strengthening human and animal immunity to climate-related diseases.

Our third option, suffering, means enduring the adverse impacts that cannot be staved off by mitigation or adaptation. Everyone will be affected by global warming, but those with the fewest resources for adapting will suffer most. It is a cruel irony that so many of these people live in or near ecologically sensitive areas, such as grasslands (Outer Mongolia), dry lands (Sudan and Ethiopia), mountain glaciers (the Quechua of the Peruvian Andes), and coastal lowlands (Bangledesh and the South Sea island region). Humans will not be the only species to suffer.

Clearly mitigation is our best option, but so far most societies around the world, including the United States and the other largest emitters of greenhouse gases, have done little more than talk about the importance of mitigation. Many Americans do not even accept the reality of global warming. The fossil fuel industry has spent millions of dollars on a disinformation campaign to delude the public about the threat, and the campaign has been amazingly successful. (This effort is reminiscent of the tobacco industry's effort to convince Americans that smoking poses no serious health hazards.) As the evidence for human-caused climate change has increased, the number of Americans who believe it has decreased. The latest Pew Research Center (2010) poll in October, 2009, shows that only 57% of Americans believe global warming is real, down from 71% in April, 2008.

There are currently no technological quick fixes for global warming. Our only hope is to change our behavior in ways that significantly slow the rate of global warming, thereby giving the engineers time to devise, develop, and deploy technological solutions where possible. Unless large numbers of people take appropriate steps, including supporting governmental regulations aimed at reducing greenhouse gas emissions, our only options will be adaptation and suffering. And the longer we delay, the more unpleasant the adaptations and the greater the suffering will be.

Sooner or later, we will all deal with global warming. The only question is how much we will mitigate, adapt, and suffer.

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