GLOBAL ISSUES

GLOBAL WARMING

Natalie Goldstein

Foreword by Kerry Harrison Cook
Professor of Climate System Science, University of Texas at Austin

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Introduction

HISTORICAL BACKGROUND

It is the suddenness that makes it so unsettling. They were building a large wall in a magnificent capital city of the greatest empire the world had ever known. It is as if the whistle blew and all the workers knocked off for lunch—only they never came back. The wall was simply left, unfinished. Massive basalt blocks lay half shaped on the ground; stoneworking tools lay where the workers dropped them before they decamped, never to return. The site—in Tell Leilan, a capital city of the ancient Akkadian Empire in Mesopotamia—is eerie and unnerving and makes you wonder what awful event could have led to such a rapid departure.

Around 2200 B.C.E., the Akkadian Empire crumbled into ruin. So traumatic was the event that brought down the empire, the disaster is commemorated in the ancient Lamentation, "The Curse of the Akkad":

> *For the first time since cities were built and founded,*
> *The great agricultural tracts produced no grain . . .*
> *The gathered clouds did not rain, the* masgurum *did not grow . . .*
> *He who slept on the roof, died on the roof.*
> *He who slept in the house, had no burial.*
> *People were flailing at themselves from hunger.*[1]

What had happened at Tell Leilan?

Archaeologist Harvey Weiss (1945–) unraveled the mystery. In 1978, Weiss got permission from the Syrian government to excavate the Tell Leilan site. Over the next decade, Weiss and his team unearthed parts of the buried city. In 1993, when Weiss came upon the unfinished wall, he was a bit flummoxed. Why had the Akkadians not completed the wall? At first, Weiss thought that perhaps, some time later, local people had pilfered some of the stone to build their own walls. Weiss left it at that. Then, one day in 1999 while he was driving across the desert, Weiss had a revelation. He suddenly realized that the wall had not been dismantled, it had been abandoned—quickly. It was as if "Someone gave the order, and [the workers] moved out, probably in a matter of days."[2]

This realization helped explain an odd soil layer the archaeologist had found during the excavations. Older, lower soil layers contained the usual bits of pottery, grain, pollen, and other artifacts and biotic traces that are commonplace in soil. Yet the soil layer that dated to the time the wall was abandoned, around 2200 B.C.E., contained none of these. This layer of soil not only lacked signs of human activity, it did not contain one trace of even a single earthworm. The one-meter (3-ft.) thick layer of soil that had accumulated over the course of 300 years was totally lifeless. It struck Weiss that the Akkadian Empire had collapsed due to an intense and prolonged—300-year-long—drought. Weiss was convinced that sudden climate change had led to the downfall of the Akkadian Empire.

Weiss's published findings generated a storm of controversy. Traditional archaeologists understood that drought affected civilizations but had never before been asked to accept that climate change could undo them. Archaeologists published counterarguments to show that it had to be one of the usual suspects, such as barbarian invasions, economic collapse, or bureaucratic corruption, that had led to the Akkadian downfall. Traditional archaeologists insisted that a civilization would adapt to a severe drought and that the artifacts of their adaptation would be found at the dig site. Weiss countered by saying, "They did adapt; they left. . . . [Leaving] is a fundamental cultural adaptation to conditions that cannot sustain life. Adaptation does not mean staying in one place regardless of what happens."[3] Thus, as the severe drought set in, when death from starvation and dehydration was imminent, those who were able to leave Tell Leilan took off in search of more hospitable territory.

It took years, but over time Weiss's view of Akkadian demise was borne out by scientific research into climate change. Paleoclimatologists are able to confirm what happened so long ago by drilling cores out of mile-deep ice sheets or seafloor sediment. Core drilling can be compared to slowly twisting a plastic straw down through the top of a marble cake. As the straw moves downward, cake enters the hollow straw. When the straw is pulled out, it is filled with a cylinder of cake that shows the interior pattern of yellow cake and chocolate cake. In the same way, an ice core reveals patterns of the chemical composition of the many layers of ice it has passed through. Analysis of these layers tells scientists when and under what conditions the ice formed. The same is true for sediment cores.

Paul Mayewski (1946–), of the University of Maine, analyzed an ice core from Greenland to see if Weiss's conclusion was supported by scientific evidence. Mayewski's analysis revealed that there was, in fact, a terrible, three-century-long drought in the Middle East from about 2200 B.C.E. to about 1900 B.C.E. Mayewski determined that the drought had been caused by a weakening of the air circulation over the North Atlantic Ocean that sends the most abundant rains to Mesopotamia.

Other supporting evidence came from deep-sea sediment cores. Peter deMenocal (1960–) of Columbia University's Lamont-Doherty Earth Observatory (LDEO) drilled sediment cores from the Gulf of Oman, downwind from Syria. He analyzed the cores, layer by layer, looking for dolomite, the signature mineral in Mesopotamian dust. DeMenocal knew that during a long-term drought, a lot of dolomite-rich dust would have blown off the land and eventually ended up as sediment in the gulf. At first, deMenocal looked for a modest spike in dolomite dust. Instead, he found a whopping 400 percent increase in dust in the layer of sediment laid down between 2200 B.C.E. and 1900 B.C.E. He was astounded—and impressed by Weiss's insight.

Further confirmation came from ice core researchers in South America, who found that during this ancient period the Amazon region endured the worst drought in more than 17,000 years, and scientists in Africa, who revealed that the ice atop Mount Kilimanjaro also showed a sudden and dramatic increase in dust content during this time. More confirmations flooded in, from lakebed sediments in Minnesota to stalactite formations in Israeli caves. To climate scientists, the evidence was clear: Prolonged drought caused by global climate change was the curse that had killed the Akkadians.

DeMenocal explained what happened in Tell Leilan and its relevance to people today:

> *Year-to-year variations [in rainfall] were a real threat, and so [the Akkadians] obviously needed to have grain storage and to have ways to buffer themselves. . . . And they were good at that. They could manage that. . . . The thing they couldn't prepare for was the same thing that we won't prepare for, because in their case they didn't know about it and because in our case the political system can't listen to it. And that is that the climate system has much greater things in store for us than we think.*[4]

The curse of Akkad is instructive in several ways. It shows that dramatic changes in the global climate can occur abruptly—like flipping a switch—in just a few years. It is also an object lesson in humankind's vulnerability to abrupt climate change.

The human species evolved during times of great climate upheaval. Human ancestors thrived on the warm African savanna before their descendants dispersed to colonize most of the globe. Humans survived the last ice age, about 12,800 years ago, in part because they were nomads, wandering hunter-gatherers who could move from a less habitable location to a more habitable one as conditions changed. During the collapse of Mesopotamian civilizations 4,200 years ago, it was the nomads who were best able to live through the terrible drought because they could follow sources of food and water or move their flocks to greener, less arid pastures. It was the people embedded in a complex society—with its specialization and large population of city dwellers—who suffered the most. It is a given that the more complex and urban a society is, the more at risk it is to climate change disruptions because its population is fixed in place.

The Akkadians did not cause the drought that destroyed them, but their complex, urbanized way of life—their dependence on the import of food and goods into the cities—made most of them mortally vulnerable to it. Today, societies are so complex nearly everyone is exposed to the devastating shocks that climate change can bring. Many people today are aware of their vulnerability in the face of climate change. Young people worry about conditions they will face as adults. Older people are concerned about what type of world their children and grandchildren will inherit. The difference between then and now is that people today are causing climate change and they have it within their power to come to grips with it and take decisive action to limit its impact before it is too late.

THE SCIENCE OF CLIMATE CHANGE

Natural Climate Changes and Cycles

The Akkadians were felled by a natural change in the global climate. Global warming—the topic of this book—refers to how human activity is changing the global climate. Most of the few remaining global warming skeptics admit that the global climate is warming but insist that this warming is part of a natural climate cycle, so there is nothing humankind can or should do about it. To fully grasp how people are changing the climate today, it is first important to understand natural climate cycles and how what is happening today differs from natural climate changes.

SHORT-TERM CLIMATE VARIATIONS

The Akkadians would no doubt be highly indignant at the idea that the climate change that finished them off was barely a blip in the paleoclimate record. The ancient, 300-year-long drought is hardly discernible when compared with longer-term, major climate changes. In other words, short-term climate events are insignificant on a geologic timescale; on a human timescale they are full-fledged, long-lasting disasters. Short-term natural climate variations result from a variety of factors.

Air circulation over the North Atlantic has far-reaching climatic effects, influencing the climate (or more briefly and locally, the weather) over much of the globe. The Akkadian drought arose from air pressure changes that weakened the normally forceful winds over the North Atlantic Ocean—the North Atlantic Oscillation (NAO). When it is in its strong, "positive" mode, the NAO sends abundant precipitation to the Middle East in the winter and spring. For reasons that are not fully understood, the NAO periodically flips into its weak or "negative" phase. When, 4,200 years ago, the NAO flipped into reverse and entered a rather lengthy "negative" phase, Mesopotamia remained parched for three centuries.

The Arctic Oscillation (AO) is a vortex of air over the Arctic region that also intensifies and weakens in a cyclic pattern. When air circulation in the vortex is powerful (or strongly positive), cool air is prevented from flowing out of the Arctic to cool north temperate regions, and extremely hot, dry summers ensue. When the AO is negative, it brings the Northern Hemisphere (NH) cool summers and exceptionally stormy winters.

Both the NAO and its Pacific Ocean counterpart, the Pacific Decadal Oscillation (PDO), reflect changes in atmospheric pressure over the northern regions of these two oceans. Historically, both the NAO and the PDO cycles lasted between 10 and 20 years, though as Akkadians would attest, they can also get stuck in a rut for far longer periods.

Short-term climate variations have had other historically important impacts. The Medieval Warm Period (ca. 900–1300) resulted from a strengthening of the NAO, which brought Europe mild weather, long summers, and abundant rainfall. This benign climate enabled farmers to reap record harvests and led to a population explosion in Europe. It was so balmy during this period that some of Europe's best wines were grown in England! However, when the NAO became too strongly positive, rain soaked Europe almost continually from 1315 to about 1322. Year after year during this "great hunger," sodden crops rotted in the fields.

Only three or four years later, the NAO abruptly flipped into reverse (negative phase), and the Little Ice Age began. Starvation stalked Europe again, but this time it was from the cold. Hunger haunted Europe as crops failed and long, warm, sunny summers became a distant memory. The Little Ice Age lasted for more than five centuries. Both the Medieval Warm Period and the Little Ice Age resulted from relatively minor (geologically speaking) climate variations that had a traumatic impact on humans.

Conditions on the Sun also have short-term effects on Earth's climate. The Sun goes through an 11-year cycle of high and then low energy. During a solar maximum, or period of high energy, the surface of the Sun is often dotted with sunspots, which are signs of high, often violent, solar activity and energy output. When a solar maximum occurs, the more energetic Sun emits more solar radiation, some of which reaches Earth. It is undeniable that increased solar radiation during a solar maximum may raise Earth's average global temperature slightly. (However, scientists studying the last solar maximum in 2000 determined that the additional solar radiation reaching Earth accounted for less than 30 percent of the global warming detected at that time.) During a solar minimum, when the Sun's radiation is weakest, less solar energy, and therefore heat, reaches Earth, and the planet experiences some temporary cooling. The weakest solar activity ever recorded occurred during the Maunder Minimum at the end of the Little Ice Age (ca. 1645–1715). Few or no sunspots were reported during this time.

El Niño is a climate-altering event that normally occurs every three to seven years. An El Niño is initiated when the westward-blowing trade winds of the tropical Pacific Ocean weaken or cease. This phenomenon is related to a periodic seesawing of air pressure in the southern Pacific Ocean, called the Southern Oscillation. Normally, pressure is high over the eastern Pacific and low over the western Pacific. Periodically, this pressure gradient flattens out or reverses (low pressure in the east, high pressure in the west). This reversal of atmospheric pressure occurs in concert with changes in the tropical Pacific Ocean. When air pressure flips and the trade winds stop blowing, the huge pool of warm water that normally sits in the western equatorial Pacific sloshes eastward toward the central Pacific. Sea-surface temperature (SST) has an enormous influence on precipitation, so the movement of the warm water pool has dramatic effects on rainfall. Because these air and sea phenomena occur together, this climate pattern is generally known as the El Niño–Southern Oscillation, or ENSO. ENSO causes aberrant and often costly (and deadly) changes in rainfall patterns (including monsoons) around the world, with the greatest effects felt in South America, Australia, and India.

THE GRAND CLIMATE CYCLE

The discovery of Earth's grand climate cycle arose from the 19th-century obsession with ancient ice ages. It was only 200 years ago that scientists first dared speculate that ancient ice ages may have occurred, particularly in the Northern Hemisphere. Geologic formations, such as Alpine valleys and the elongated gouges of the Finger Lakes in upstate New York, seemed to hint

that some enormous force—perhaps a mile-thick ice sheet?—must have carved these deeply incised depressions.

In the late 1830s, Swiss geologist Louis Agassiz (1807–73) began accumulating evidence of ancient glacier activity. He concluded that in the geologic past, Earth had experienced at least one ice age. Agassiz's revelation inevitably led to a burst of scientific creativity and discovery.

In the late 1840s, French scientist Joseph Leverrier (1811–71) studied the changes in the shape of Earth's orbit, called its eccentricity. Eccentricity is a measurement of how "out of round" an orbit is. A non-eccentric orbit is a perfect circle; a highly eccentric orbit is very flattened, or elliptical. On average, Earth's orbit is about 155 million kilometers (93 million mi.) from the Sun. When it is positioned in the "flat" part of its most eccentric orbit, Earth is 5 million kilometers (3 million mi.) closer to the Sun than when its orbit is more circular. Leverrier showed that this seemingly slight difference affects the amount of solar radiation striking Earth, and thus the global climate. Leverrier calculated that Earth's eccentricity varies during a 100,000-year cycle; that is, it takes 100,000 years for Earth's orbit to change from its greatest eccentricity to its least eccentricity and back again.

Nineteenth-century scientists knew that Earth rotates on its axis and that the axial tilt, or inclination, is 23.5 degrees off vertical. Leverrier found that the planet Jupiter exerts a gravitational pull on Earth that causes its inclination to vary over a period of 41,000 years. Thus, every 41,000 years Earth's axial tilt changes from its minimum tilt of 21.5 degrees off vertical to its maximum tilt of 24.5 degrees off vertical. The degree of Earth's inclination affects which parts of the globe get the strongest sunlight. So inclination, too, affects the global climate.

The final piece of the climate cycle puzzle concerns the way Earth wobbles on its axis, like a slightly off-balance spinning top. In the mid-1800s, a French mathematician studied this phenomenon, called precession, and its effect on climate. He found that it takes, on average, 8 million daily rotations—or about 22,000 years—for the Earth to complete one entire "wobble circuit," or precession cycle. Precession amplifies the effects of inclination, so it too has an impact on climate.

The Milankovitch Cycle

These were all interesting, even crucial, parts of the climate puzzle, but what did they have to do with ice ages? Serbian mathematician Milutin Milankovitch (1879–1958) put all of the puzzle pieces together. By the 1930s, Milankovitch had spent three tedious decades calculating the amount of sunlight every part of the Earth receives during all the changes the planet goes through as it orbits the Sun. Milankovitch concluded that an extreme of axial tilt or precession away from the Sun would lessen the amount of solar radiation hitting one part of the Earth, cooling that hemisphere sufficiently to initiate an ice age. Precession often acts as an amplifier of inclination, so an ice age is likely to occur when together they position a hemisphere so that it gets less solar radiation.

Milankovitch determined that an ice age results when Earth is farthest from the Sun, positioned at the outer edge of its most eccentric orbit. Thus, Earth undergoes a grand climate cycle every 100,000 years—the time it takes to complete one full orbital cycle. It takes a long time to build an ice sheet, but a relatively short time to melt one. Over 90,000 years or so the vast ice-age ice sheets build to their maximum extent. During this period, the more frequent cyclical ice-age triggers kick in, with ice volume peaking every 41,000 years (from inclination) and every 22,000 years (from precession). Then, within 10,000 years, the ice sheets melt and the climate enters a warm, interglacial period, which usually lasts for about 10,000 years but may persist for up to 25,000 years. This 100,000-year grand climate cycle is also known as the Milankovitch cycle.

Milankovitch also revealed the crucial role that snow cover plays in the lead-up to an ice age. Milankovitch showed that it was not cooler winter temperatures during the climate cycle that led to ice ages, as most scientists then believed, but cooler summer temperatures. When the amount of solar radiation hitting a high-latitude region of the planet is very weak during the summer, the winter snows do not completely melt away. Some snow stays on the ground all summer. More snow is added the next winter, and more of that survives the following summer. Snow reflects light (and heat) away from the globe, so the more snow remains on the ground, the cooler the region gets. Year after year, the extent of snow cover increases and the regional climate cools. Milankovitch showed that after just a few years, this process leads to the formation of an ice sheet and the onset of an ice age.

MID-TERM CLIMATE CYCLES AND EVENTS

Climatologists long thought that since the last ice age Earth experienced a period of climate stability. However, ice and sediment core research has shown that in the modern geologic epoch (the Holocene), climate has fluctuated wildly and been about as far from humdrum stability as it can get.

These newly discovered climate fluctuations generally arise during times of climatic transition, usually at the end of an ice age, and may have dramatic effects on the ocean. Most of these changes are too complex to address here; suffice it to say that when they are graphed they produce a spiky scrawl of jagged sawtooth lines, each indicating a dramatic and abrupt climate shift from warm to cool and vice versa. Climatologist Richard Alley (1957–) described these extreme variations in the climate cycle this way:

> *[If you can] imagine the spectacle of some really stupid person … bungee-jumping off the side of a moving roller coaster car, you can begin to picture the climate—the roller coaster rides the orbital rails of the ice ages, with the bungee-jumping maniac [the fluctuating climate] bouncing up and down [warm climate, cool climate] past it.*[5]

Where Are We Now?

All these up-and-down climate cycles can make a person dizzy, so let's pause to see where on this crazy roller coaster ride of a climate cycle we are today and how we got here.

About 20,000 years ago, Earth was in a cold part of its orbital cycle. Then, about 12,800 years ago, as the climate began to warm, the planet entered a short but intense ice age (due to a midterm climate event) called the Younger Dryas (named after the pretty *Dryas* flower that flourished during this frigid period). At the dawn of the Younger Dryas, average temperatures in many parts of the world plunged by an astonishing 15°C (27°F) in less than 10 years. Then the climate switch flipped, and the Younger Dryas ended. About 10,000 years ago, it really warmed up (except for one extreme cold snap 8,200 years ago), giving us today's relatively mild and stable climate. Earth's present axial tilt of 23.5 degrees is fairly extreme and accentuates seasonal temperature differences. However, the planet's current precession and the favorable roundness of its eccentricity offset the tilt's tendency toward a cooler climate. All in all, Earth is currently in what Richard Alley calls a climatic "sweet spot."[6] We have been basking in that rare and most comfortable of climate regimes—the 10,000- to 25,000-year span of the warmest weather between ice ages.

People and Climate

People have been affecting the global climate since the agricultural revolution. Their primary contribution to climate change then—as now—came from the quantities of heat-trapping gases, such as carbon dioxide (CO_2) and methane, they emitted into the atmosphere.

PREINDUSTRIAL IMPACTS

For hundreds of thousands of years, our ancient ancestors had little effect on the climate. They were mainly nomadic hunter-gatherers who sought food supplies wherever they happened to be. But once our species, *Homo sapiens,* appeared on the scene about 100,000 years ago, the climate was in for a change. This change did not begin with the Industrial Revolution (ca. 1750), but predated it by thousands of years.

Humans had little effect on the climate until they began to live in permanent settlements about 11,500 years ago, at the dawn of agriculture. As people became more adept at growing their own food, settlements grew from tens to hundreds of inhabitants. More food was needed for the growing population, so forests were cleared to free up more land for farming. Forests are carbon sinks—trees absorb CO_2 from the atmosphere during photosynthesis—and act as carbon reservoirs that keep carbon out of the atmosphere. So cutting down forests for agriculture inevitably increased atmospheric CO_2 concentrations. Then, around 3,000 years ago, the Chinese started burning coal as a fuel, and Europeans began digging up and burning peat (a coal precursor) to keep warm. Both these fuels added CO_2 to the atmosphere. Climatologists have calculated that between 8,000 years ago and the beginning of the Industrial Revolution, forest clearing, primarily for agriculture and fuel, released an estimated 300 billion tons of CO_2 into the atmosphere—at a rate of 0.04 billion tons per year over 7,750 years.[7]

Methane is a powerful heat-trapping gas that occurs in far lower concentrations than CO_2. About 5,000 years ago, atmospheric methane concentrations, too, began rising. These ancient increases in atmospheric methane are generally attributed to greater numbers of domestic (and flatulent) livestock and, most important, to irrigation of rice paddies in Asia. Land flooded with water to grow rice drowns natural vegetation, which dies and decays, a process that emits large quantities of methane.

Finally, these ancient alterations of the atmosphere and climate were exacerbated by the large increase in the human population that the agricultural revolution made possible. More people eat more food, which requires more forest clearing or rice growing (not to mention fuel burning and house building). Scientists estimate that between 7000 B.C.E. and 1750 C.E., the human population doubled about every 1,000 to 1,500 years.[8] Thus, a population of a few million or tens of millions 6,000 years ago grew to 200 million by 2,000 years ago and 650 million by 1700.[9] As is happening today, population growth magnified humanity's impact on the climate. Today, however, the human population is growing exponentially, adding new billions at an accelerating rate and creating unsustainable strains on the natural environment.

THE INDUSTRIAL REVOLUTION

The slow and steady human impact on climate that characterized the 10 millennia prior to 1750 was nothing compared with the changes brought about by the Industrial Revolution. Some historians locate the start of the Industrial Revolution in 1769, when Scottish inventor James Watt (1736–1819) patented the first steam engine. Watt's steam engine burned coal to boil water, which generated steam, which powered an engine. Watt's steam engine could be used to power just about anything—to turn the gears of almost any large mechanical device. Watt adapted the steam engine and sold it to industrialists eager to profit from its efficiency. The coal-burning steam engine powered nearly every industry—from textiles to transportation—for almost 150 years.

The world's first oil well was drilled in Titusville, Pennsylvania, in 1858 by an Abe Lincoln look-alike named Edwin L. Drake. In August 1859, Drake struck oil. Soon, the well was producing 10 to 35 barrels of oil a day, "almost doubling the world's [oil] production."[10] By the mid-1900s, Pennsylvania provided nearly all U.S. petroleum.

Petroleum was used to power a variety of machinery. When John D. Rockefeller's Standard Oil Company controlled most of it, oil became more widely used, though it still lagged behind coal as the fuel of choice. Rockefeller's oil refineries quickly and profitably sold all the oil they produced. What the refineries could not sell was a lighter, more volatile by-product of oil refining—light petroleum—which was just dumped as (toxic) waste. Then, in 1860, destiny provided light petroleum with its raison d'être. The first internal combustion engine mixed light petroleum—gasoline—with air to produce a controlled explosion in a chamber containing a moving piston. The automobile age had begun. By 1904, motorcars were in production; within 10 years, the automobile had made petroleum one of the most important sources of energy in the world.

The rest, as they say, is history. Both coal and petroleum products were ubiquitous in industrialized countries, powering billions of machines and millions of cars, heating countless buildings, and pouring enormous quantities of CO_2 into the air.

FOSSIL FUELS

Coal and petroleum products are fossil fuels, so called because they formed from the long-dead, decayed bodies of ancient (fossil) organisms. Coal formed from plants that lived during the Carboniferous period, more than 300 million years ago, when much of the planet was covered by lush, tropical vegetation. Over millions of years, vast layers of dead plants were continually buried by yet more decaying vegetation. The weight and pressure of overlying layers transformed the carbon-based plants into coal. Petroleum is a hydrocarbon that also formed over hundreds of millions of years, but it was created by the dead and decaying bodies of tiny marine organisms, or algae. Oil formed when countless algae died and sank to the sediments on the ocean floor. Over millions of years, the layers of dead algae accumulated, and the pressure of overlying layers and ocean water compressed them until they became a type of liquefied carbon—oil.

Both coal and oil are carbon-based materials that release CO_2 during combustion. For eons, these enormous amounts of ancient carbon were tucked away safely—or sequestered—beneath Earth's surface. But, beginning with the Industrial Revolution, millions of years' worth of stored carbon was being "exhumed" and burned—adding colossal quantities of carbon, in the form of CO_2, to the atmosphere. Surely, all this added carbon was having some effect on the balance of carbon in the atmosphere and the oceans. Where was all this carbon going?

THE GREENHOUSE EFFECT

It was a combination of pure luck and the intervention of his mentors that saved Joseph Fourier (1768–1830) from losing his head to the guillotine in 1794. For an egghead mathematician, Fourier had an incredibly adventurous life. After being imprisoned three times during the turbulent years of the French Revolution, Fourier found himself accompanying Napoléon to Egypt. It was in the furnace of the Egyptian desert that Fourier first turned his professional attention to the movement, or diffusion, of heat.

Back in France in the 1820s, Fourier began thinking about what kept the Earth warm. He formulated a hypothesis, published in 1824, in which he suggested that some solar radiation bounces off Earth's surface and back into space. But some of it is held near the surface by the atmosphere, which acts as a heat-trapping envelope that reradiates solar energy back toward the ground. He compared the atmosphere to a greenhouse that allows solar energy to enter, but contains gases that trap some heat inside. The concentrations of these heat-absorbing gases—whatever they were—determine how much solar energy, in the form of infrared radiation, is reradiated to the planet's surface. As often happens, Fourier's important paper sank into obscurity. Only when the Industrial Revolution was running at full throttle would Fourier's paper be unearthed and its climatic implications considered.

Several decades later, in 1859, geologist John Tyndall (1820–93) identified two of the heat-trapping gases—or greenhouse gases (GHGs)—whose existence Fourier had postulated: CO_2 and water vapor. Like most climate researchers of his time, Tyndall was fascinated by ice ages. Tyndall showed that as the levels of these gases in the atmosphere dropped, the planet would enter an ice age. (Tyndall did not consider the flip side of that coin—global warming from increases in these gases.)

Svante Arrhenius (1859–1927) was a Swedish chemist who, like Tyndall, was intrigued by ancient ice ages. By 1896, Arrhenius had calculated that halving CO_2 concentrations in the atmosphere would lower Europe's temperature by 4–5°C (7–9°F) and initiate an ice age. It looked good on paper, but Arrhenius was not even sure that atmospheric levels of CO_2 could change. He turned to his colleague Arvid Högbom (1857–1940), who had spent years studying how increases in industrial CO_2 emissions were affecting the carbon cycle and the atmosphere. Using Högbom's findings, Arrhenius calculated that if CO_2 emission rates continued or increased, Earth's climate would warm by 5–6°C (9–11°F). Perhaps it was because both scientists hailed from icy Sweden that this prospect did not in any way concern them.

By 1908, however, when Arrhenius published his findings in book form, the rate of coal burning had increased dramatically. In his book, Arrhenius speculated that increasing CO_2 emission rates would, at some unknown future time, cause the global climate to warm. Arrhenius's work was rejected by the scientists of his time and then ignored until the 1990s, when global warming became a pressing issue.

In Arrhenius's day, scientists firmly believed that the global climate system was self-regulating. Nearly everyone in that era accepted that the balance of nature—the essential goodness and harmony of the natural world—would always manage to smooth out any changes human activity might cause.

This attitude irked English engineer Guy Stewart Callendar (1898–1964) who took it upon himself to investigate whether human emissions of CO_2 were accumulating in the atmosphere and changing the climate. Callendar gathered data from 200 weather stations around the world for the years 1880 to 1934. Not only did his analysis show a huge increase in atmospheric CO_2, it also revealed an overall warming of the climate. Callendar explained why the oceans—the panacea of the natural balance believers—would not absorb limitless quantities of CO_2 but, as CO_2 levels increased, would actually give back into the atmosphere some of the CO_2 they temporarily took from the air. Callendar's calculations were incomplete and very crude by today's climate model standards, but his insights and urgent warnings about climate change were on target.

It took two world wars and cold war paranoia for official interest and the necessary technology to finally vindicate Arrhenius and Callendar. The breakthrough came at the dawn of the nuclear age and was subsidized by U.S. agencies tasked with guarding the country's security interests. Specifically, national security officials were extremely keen on any technology or research that would help them detect radioactivity (from nuclear bomb testing) in the air or the oceans. To this end, scientists had developed a method for detecting—and dating—substances by the amount of an isotope of carbon (C) they contained. Once scientists figured out exactly how long it takes for the radioactive isotope C-14 to decay into "normal" C-12 (many millennia) and the rate at which it decays, they could precisely date carbon-based materials based on how much C-14 they contained.

In 1955, chemist Hans Suess (1909–93) used C-14 dating techniques to show that fossil fuel carbon was present in the atmosphere. (Fossil fuel carbon is identifiable because it is so old it contains no C-14.) Roger Revelle (1909–91) of the Scripps Institution of Oceanography heard about Suess's work and immediately hired him. Together they would find out if carbon from fossil fuel combustion was being absorbed and retained by the oceans. Revelle was an expert in ocean chemistry, and he knew that some chemicals in the ocean buffered the effects of additions of other chemicals, such as CO_2. Revelle analyzed the amounts of C-12 and C-14 in ocean water and found that seawater's buffering mechanisms would prevent it from retaining all the CO_2 emissions it had absorbed. In fact, Revelle's calculations showed that the ocean surface absorbed barely $\frac{1}{10}$ of the amount of CO_2 scientists had predicted. Most of the CO_2 absorbed by the ocean's surface was evaporated back into the air before ocean circulation could safely sequester it at the sea bottom. So, scientific faith in the ocean as the savior of the climate was misplaced. Most of the CO_2 emissions people were putting into the atmosphere were staying there. As Revelle and Suess stated in their seminal paper: "[Carbon dioxide] may become significant during future decades if industrial fuel combustion continues to rise. . . . [H]uman beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years."[11]

Keeling's Curve

Geochemist Charles David Keeling (1928–2005) loved nature, and as a scientist he pursued studies that kept him outdoors as much as possible. Dave Keeling was determined to find out if global CO_2 levels were rising. In 1955, a manic Keeling spent months rushing from one wild, remote site in California to another with his homemade "air-trapping" sphere to capture and then analyze the amount of CO_2 in each sample. Keeling realized that in order to verify that CO_2 levels were rising, he needed to find a baseline with which to compare these levels over time.

When Keeling analyzed his trapped air samples, he found that each one contained a CO_2 concentration of 315 ppm (parts per million). A jubilant Keeling realized that the gas he was collecting represented the condition of the global atmosphere and was not distorted by "noise" from local air pollutants. Further, his 315 ppm concentration could be used as a baseline with which to compare future changes in CO_2 levels.

In 1957, Keeling attended the International Geophysical Year (IGY) conference in Washington, D.C., where he met Revelle. Keeling was a man with a mission, and his passion for his research convinced Revelle to bring him to Scripps. There, Keeling got the funding he needed to build a more sophisticated apparatus for measuring the components of air.

In early 1958, Keeling hauled his new, far more precise device up to the desolate summit of 4,170-meter (13,680-ft.) tall Mauna Loa in Hawaii. Mauna Loa was the perfect site for analyzing the global atmosphere. Mauna Loa is surrounded by thousands of miles of open ocean, is uncontaminated because it towers above the air pollution lower in the atmosphere, and is in the path of the trade winds so it is swept by air that has traveled most of the globe. Here, Keeling set up shop and began his analyses. By 1960, Keeling's data confirmed that the upward trend in the level of atmospheric CO_2 was in accord with Revelle's prediction of low oceanic uptake. Year after year, Keeling monitored and recorded the data his apparatus gave him about atmospheric CO_2 concentrations. His famous graph of increasing atmospheric CO_2 levels is known as the Keeling curve.

Trends in CO_2 Concentrations, Mauna Loa, Hawaii, for Selected Years

YEAR	CO_2 CONCENTRATION (SEASONALLY ADJUSTED) (PPM/VOLUME)
1960	316.5
1970	324.7
1980	337.9
1985	344.9
1990	353.0
1995	359.5
1996	361.1
1997	362.3
1998	367.9
1999	368.94
2000	369.30
2001	372.18
2002	374.73
2003	376.65
2004	378.43
2005	381.0
2006	382.61
2007*	386.04

* April 2007

Note how, beginning in 2000, increases jump from tenths of a unit to several full units.

Source: Scripps Institution of Oceanography. Available online. URL: http://www.scrippsco2.ucsd.edu/data/data.html.

The Natural and Enhanced Greenhouse Effect

Since Tyndall's time, scientists have understood the basics of the greenhouse effect, which describes how greenhouse gas molecules trap solar radiation (heat) near Earth's surface. Some solar radiation never reaches Earth's surface because it is reflected out into space by clouds and dust high in the atmosphere. Some solar radiation is reflected back into space by Earth's ice- and snow-covered surfaces, which have high reflectivity, or albedo. Some solar radiation is absorbed by the land and the oceans.

The solar radiation that is neither reflected away from the planet nor absorbed by the planet's surface is sent back toward space as infrared radiation. Some of this infrared radiation escapes into space. However, some of it is absorbed by GHGs in the atmosphere and then reradiated back to Earth's surface, where it warms the planet. Thus, the more GHGs there are in the atmosphere, the warmer the planet's surface will be.

The greenhouse effect is not necessarily negative. In fact, every living thing on Earth owes its life to the *natural* greenhouse effect. Without heat-trapping gases in its atmosphere, Earth would be a frozen, lifeless wasteland. The GHGs that are emitted naturally into the atmosphere (water vapor from evaporation; volcanic CO_2, for example) maintain the world's warm, life-sustaining climate. The main naturally occurring GHGs are water vapor, CO_2, and methane. (The primary components of the atmosphere—nitrogen and oxygen—are thermally neutral and have no impact on the greenhouse effect.)

The *enhanced* greenhouse effect refers to GHGs that have been added to the atmosphere by human activity. The enhanced greenhouse effect leads to global warming because the additional GHGs reradiate more infrared radiation and heat back to Earth's surface.

Carbon dioxide is not the only GHG in Earth's atmosphere. Water vapor and methane have been mentioned as vital GHGs. Methane levels in the atmosphere increase with the number of livestock raised and the amount of rice grown. In the 1980s, it was found that deforestation also adds methane to the atmosphere. These activities have resulted in an increase in atmospheric methane concentrations from 791 ppb (parts per billion) in 1850 to 1,847 ppb in 2004.[12]

CFCs (chlorofluorocarbons) are a thoroughly anthropogenic (human-made) source of greenhouse warming. CFCs are a family of chemicals that were used as propellants (in aerosol cans such as hairspray) and as refrigerants in air conditioners and refrigerators from the 1950s to the 1980s. After it was discovered that CFCs destroy stratospheric ozone, creating an annual "ozone hole" over Antarctica, in 1987 nearly all the nations of the world signed on to the Montreal Protocol, an international agreement to phase out production and use of CFCs. However, CFCs are thousands of times more

potent than CO_2 at trapping heat and they remain in the atmosphere for centuries. So CFCs (and to some extent the hydrofluorocarbons, or HFCs, that replaced them) continue to act as GHGs. Nitrous oxide (N_2O), coming mainly from fertilizers and disturbed soil, was identified in the 1970s as another powerful GHG. All in all, by 1985 more than 30 trace gases were found that amplify the greenhouse effect. Most occur in minute amounts, but together they can cause significant warming.

Though it is not listed among the GHGs that are affected by human activity, water vapor is one of the most potent GHGs on Earth. The heat-trapping capacity of water vapor is largely responsible for the natural greenhouse effect that created the life-giving warmth of Earth's climate. The intimate relationship between air temperature and the amount of water vapor in the air (via evaporation) is one vital mechanism that drives global warming. Further, water vapor amplifies the effects of atmospheric CO_2; thus it has a major impact on climate change. However, its short residence in the atmosphere (about 10 days), among other factors, means that water vapor has not been assigned a numerical global warming potential (GWP), comparing its heat-trapping capacity to that of carbon dioxide. This lack of designation should not lead one to underestimate the potency of this important GHG.

As scientists gained more understanding of climate cycles and the greenhouse effect, pressing questions arose: How do minor changes in the amount of sunlight reaching Earth cause climate changes as drastic as ice ages? What relationship, if any, does CO_2 have to climate changes caused by orbital variations? Is there some trigger or strong feedback mechanism that provides the necessary push to propel a small change due to orbital or axial variations into a major climate shift?

Earth's climate is a nonlinear system in which seemingly insignificant, step-by-step changes can suddenly cross a threshold and snowball to cause dramatic climate shifts. Even relatively small alterations in some aspect of the climate can initiate feedbacks that amplify the effects of these changes. Once a feedback mechanism begins, it may send the climate hurtling over a threshold that causes irreversible climate change. Scientists speculate that CO_2 might be one of the triggers that flips the sensitive and delicately balanced climate into a new regime. Ice and sediment core studies would reveal how closely coupled CO_2 and shifts in Earth's climate system really are.

Core Confirmations

Even back in the 1950s and 1960s, it seemed logical to some observers to correlate higher CO_2 concentrations with fossil fuel burning—where else could all that extra carbon be coming from? Yet there was no conclusive evidence either that human activity was solely responsible for the excess CO_2 or that global warming was a bad thing. Maybe a warming climate would keep the next ice age at bay and save civilization.

Until incontrovertible evidence showed that a warming climate was dangerous and undesirable and that it was being caused by human burning of fossil fuels, societies would resist the economic and lifestyle disruptions that abandoning fossil fuels would entail. After all, everything in modern industrial society is powered by fossil fuels, from electricity generation (mostly coal powered) to home heating (mainly oil) to transportation (gasoline). Obviously, more research was needed. That research delved deep into Earth's ice and sediment.

ICE CORES

One way to determine if today's climate changes are the result of human activity is to dredge up data from ancient climates and then compare what happened then with what is happening now. If paleoclimate conditions resemble what is happening today, then the argument that a natural cycle is causing today's observed warming is supported. If climate conditions observed today, particularly in terms of the rate and degree of atmospheric CO_2 increase, are absent from the paleoclimate record, then the climate changes currently observed can likely be attributed to human activity.

Ice sheets are a perfect place to look for clues about ancient climates. When snow falls on an ice sheet and is compacted into ice, it contains minute bubbles of the air through which it fell. So every snowflake that has fallen on an ice sheet over time deposits in the ice a minute sample of Earth's air at the time the snow fell. Scientists can analyze those ice-bound air bubbles to find out the chemical composition of the atmosphere in the distant past.

To travel really far back in time, scientists must analyze ice from an enormously thick ice sheet. That is why most ice core research is conducted in Greenland or Antarctica. Greenland's ice sheet is several kilometers thick, and its lower layers formed hundreds of thousands of years ago. The miles-thick ice sheets in Antarctica contain ice more than a million years old.

To get at ancient ice, intrepid teams drill into the ice to remove a core that is usually a 10–12 centimeter- (4–5 in.) diameter cylinder of ice. The first ice core, drilled in 1961 at Camp Century in Greenland, was only a few feet long and revealed little about ancient climates. By 1966, advances in drilling technology allowed these researchers to extract an ice core 1.4 kilometers (0.87 mi.) long, representing 100,000 years of Earth's climate. Two years later, a 1.6 kilometer- (1-mi.) long ice core was removed from the Ross Ice Shelf in Antarctica. By the late 1980s, scientists in Greenland were able to extract cores of increasing length (and therefore age), as were drilling teams in Antarctica, especially at the research station at Lake Vostok.

Removing a cylinder of ice from a glacier is not simply a matter of drilling a hole and yanking out a core. As ice is removed from the depths, it must be lifted with extreme care or the lessening of pressure on the ice as it nears the surface will cause it to explode. After refrigerating and examining the core, scientists carve it up into thin slices that are easy to handle and whose microscopic characteristics can be minutely analyzed.

Scientists first assess a core's visible characteristics. For example, ice is laid down in layers that are comparable to tree rings. Scientists can measure the size of each layer to determine which periods got more or less snow and the opacity of the layers to see which layers contain the most dust (indicating dry, windy conditions or volcanic eruptions). Unfortunately, for a number of years, two of the most important clues held in the ice—the chemical composition of its air bubbles and the temperature at which it formed—were technologically impossible to unravel.

Then in the 1960s, Danish paleoclimatologist Willi Dansgaard (1922–) discovered a way to use isotopes of oxygen to determine the temperature at which ancient ice formed. Scientists knew that a rare isotope of oxygen, oxygen-18, is heavier than "normal" oxygen-16. When the climate is cold, O-18 will condense before O-16, and O-18 will also precipitate out of clouds before O-16. Dansgaard showed that it is possible to determine the precise temperature at which various ratios of O-16 to O-18 will occur. An analysis of the ratio of O-16 to O-18 in ice tells scientists the atmospheric temperature at the time the ice was laid down. Determining temperature at the time of ice formation was further refined by Jeffrey Severinghaus (1959–), who, in 1999, showed that analyzing the amounts of argon and nitrogen isotopes in the air bubbles enabled scientists to date changes in surface temperature at the time of ice formation to within a decade—a remarkable achievement and a key to understanding abrupt climate change.

In the 1970s, scientists developed a dependable way to retrieve and analyze the air bubbles trapped in ancient ice. The method involved crushing a squeaky-clean ice sample in a vacuum chamber that contained gas-analyzing equipment. The equipment was able to accurately analyze the chemical composition of the tiny, rapidly exploding air bubbles.

Using these two vital analytical tools, climatologists finally were able to conduct the crucial analyses of past climates that would put our own changing climate into perspective. What they found was momentous, astonishing, and troubling.

In 1985, researchers in central Antarctica published their study of a 2-kilometer- (1.24-mi.) long ice core taken from the huge ice sheet at Lake Vostok. This core contained a record of the temperature and composition of the atmosphere over the past 150,000 years (a grand climate cycle of ice age, warm period, ice age). Significantly, the study results showed that the globally averaged temperature rose and fell in step with concentrations of CO_2 in the atmosphere. These results prompted one expert to conclude that there is an "emerging consensus that CO_2 is an important component in the system of climatic feedbacks" and that future research would "require treating climate and the carbon cycle as parts of the same global system rather than as separate entities."[13]

Scientists were impressed by these findings, but hesitated to use them to declare that "global warming is real." Though the data were compelling, they revealed only one grand climate cycle. Perhaps, scientists speculated, this grand climate cycle was in some way abnormal. So instead of claims of certainty, climatologists called for more and longer cores to reveal conditions through several grand climate cycles.

It was not long before deeper ice cores were drilled and subjected to the same analyses. By 1987, a Vostok core dating back more than 160,000 years showed the same CO_2-temperature coupling. A few years later, the Vostok team removed an ice core dating back 420,000 years that revealed the climate through four grand climate cycles. Analysis of this core showed that during the coldest part of the four previous ice ages, atmospheric concentrations of CO_2 leveled out at about 180 ppm. During the warmest part of the four interglacial periods, CO_2 concentrations never exceeded 280 ppm. Antarctic drilling teams continued to pull longer and older ice out of the ice sheet. All the Antarctic cores—from 600,000 years ago, from 850,000 years ago—confirmed the CO_2 concentration data. At no time during the last eight interglacial warm periods had CO_2 concentrations topped 280–300 ppm. At the time these scientists were conducting their analyses, the air they were breathing contained CO_2 concentrations of 345–382 ppm—truly unprecedented elevations of CO_2.

These studies revealed that CO_2 was a significant factor in amplifying the changes in the global paleoclimate caused by orbital variations. The research underscored the crucial difference between natural climate variations in the ancient past and climate change today. During past grand climate cycles, as the ice age waned, the ocean warmed along with the climate. The warmer ocean emitted to the atmosphere large quantities of CO_2, which amplified the natural climate change, but did not induce it. In our current situation, CO_2 is a causative factor that is enhancing the greenhouse effect and warming the global climate at a rate and to a degree not seen before. Based on their ice core study, the Vostok scientists stated that continued emissions of CO_2 would produce "a warming unprecedented in the past million years, and [would occur] much faster than previously experienced by natural ecosystems."[14]

The Research in Context

Carbon dioxide is linked in a stepwise manner to Earth's globally averaged temperature. From ice core and other research, climatologists know that the difference in the globally averaged temperature between the depth of an ice age and the warmest part of the interglacial period that follows is between 5° and 6°C (9°–11°F).[15] Normally, this change in globally averaged temperature occurs over a period of 100,000 years.

As of 2005, when CO_2 levels hit 380 ppm (the highest level to that time in nearly 1 million years), the globally averaged temperature had risen about 1°C (1.8°F) since the Industrial Revolution. If humans continue to pump CO_2 into the atmosphere at current (or accelerating) rates, CO_2 concentrations are expected to rise to 880–1,000 ppm within a century or two, creating a heat-trapping capacity in the atmosphere not seen in 30–40 million years and raising the globally averaged temperature 5°–6°C (9°–11°F) or more in only 200 years. As Richard Alley describes it, Earth would return to the "saurian steambath" of the dinosaur-dominated Cretaceous period.[16]

How would the planetary climate respond to such unprecedented changes in the atmosphere? Is it even possible for Earth's climate to change so quickly and drastically?

Comparison of Changes during Natural Climate Cycles and for Global Warming (Business as Usual Scenario)

	NATURAL CLIMATE CYCLE	CLIMATE CHANGE OCCURRING IN TODAY'S INTERGLACIAL CLIMATE (BUSINESS AS USUAL [BAU])
Temperature difference between the depth of an ice age and the following warm interglacial period	5° to 6° C (9° to 11° F)	4.5° C to 6.4° C (8.1° to 11.5° F)
Time frame within which this temperature change occurs	50,000 to 90,000 years	100 to 200 years
Difference between ice age and interglacial atmospheric CO_2 concentrations	180 ppm (ice age) 300 ppm (interglacial warm)	280 ppm (pre-industrial) 384 ppm (2007)
Time frame within which this change in CO_2 concentration occurs	50,000 to 90,000 years	250 years
Highest atmospheric CO_2 concentration during warm periods in last 1 million years	280 to 300 ppm	384 ppm now; likely rising to 880 to 1,000 ppm under BAU scenario

Abrupt Climate Change

Early drilling teams who shivered in their parkas atop ice sheets were not investigating climate change. For the first decade or so, ice core researchers sought evidence that would either support or debunk Milankovitch's astronomical theory of climate cycles and unravel the mysteries of past ice ages.

At the end of the 19th century, scientists believed that Earth's climatic norm was long, stable warm periods (like ours) punctuated by rare and brief episodes of glaciation, which were also marked by warm and cold periods. Studies of land surface features had convinced early geologists that there had been exactly four ice ages in Earth's past. The advent of radiocarbon dating and other techniques for analyzing ancient time and temperature convinced scientists to abandon this view and accept Milankovitch's ideas.

Radiocarbon dating allowed researchers to use proxies—representative evidence—to study ancient climates. For example, in the 1950s, chemist Harold Urey (1893–1981) was combining radiocarbon dating with analysis of isotopic oxygen uptake to create a time line for ancient marine animals. Urey's proxies were the fossils of tiny, shelled marine organisms called foraminifera, or forams for short. Urey showed that the ratio of O-18 to O-16 in foram shells revealed the temperature of the water at the time the ancient shells were constructed.

Urey's work was advanced by Cesare Emiliani (1922–95), who studied deep-sea sediment cores hundreds of meters long. In 1955, Emiliani announced that he had picked through the muck of a sediment core dating back 300,000 years. His analysis of foram shells fossilized in the mud revealed that there had been dozens of glacial periods—not just four—and that the warm-cold climate swings seemed to occur rapidly and unpredictably. Emiliani's findings were dismissed until, years later, researchers confirmed them in studies of warm- and cold-loving foram species. Each foram species occurred in sediment cores at intervals correlating exactly with Emiliani's many glaciations.

In 1960, Wallace Broecker (1931–), along with colleagues at LDEO, reported that deep-sea and lakebed sediment cores revealed extreme climate shifts of between 5°–10°C (9°–18°F) in less than 1,000 years. Broecker speculated that such rapid shifts might have something to do with ocean circulation. His subsequent sediment core research led Broecker to postulate that climate regimes shifted abruptly and erratically. His findings correlated well with the graph of sawtooth climate fluctuations revealed by ice cores from both Greenland and Antarctica, in which abrupt, large-scale changes in a climate regime were interspersed with equally rapid and erratic shorter-term "flickers" from warm to cold and back again. Other climatologists used a variety of proxies—from fossil pollen and beetle shells to tree rings—to confirm that the global climate seemed to lurch out of relatively stable periods via "catastrophic discontinuities" as it transitioned to a different climate regime.[17] Willi Dansgaard's Greenland core research supported these findings, revealing rapid and "violent" temperature shifts at the end of the Younger Dryas.

The more climate scientists learned, the clearer it became that the climate could change faster than anyone had thought possible. Changes believed to take millennia in the 1970s were found to take only centuries in the 1980s, and decades in the 1990s. Then one day in midsummer 1992, Richard Alley and other climatologists working on the Greenland glacier were thunderstruck by the data they uncovered. They were analyzing part of an ice core that had formed at the end of the Younger Dryas when they found a clear and visible change in the ice. That change, consisting of only three layers of ice, showed that the climate had shifted dramatically in only three years. These results indicated "a twofold change in three years, with most of that change in one year, and with a 'flicker' when the climate bounced up and down. . . . [T]he change was fast—not over a century, not even over a human generation, but maybe over a congressional term [two years] or less."[18]

These sobering results were supported by sediment core studies done that same year in the Norwegian Sea. In the years following, analyses of sediments from California to the Arabian Sea confirmed that an extreme, global climate shift had occurred in only three years at the end of the Younger Dryas. Clearly, the global climate can change abruptly and dramatically.

Abrupt climate change can be compared to a person leaning over in a canoe. As the person leans to the left one inch at a time, the canoe adjusts and remains stable. If the canoe were a linear system, the person could lean left inch by inch until his or her left ear was touching the water and the canoe rested stably on its side. But neither the canoe nor the climate is a linear system. As nonlinear systems, they do not remain stable throughout incremental changes. The person in the canoe can lean left just so many inches before the entire "canoe system" reaches a literal "tipping point," becomes unstable, and finds a new equilibrium—with the canoeist dumped overboard beside the capsized canoe.

The climate works the same way. Up to a point, the climate seems to adjust to incremental changes and remains stable. But as these incremental changes add up, at some crucial point, the changes abruptly tip the climate into a new type of equilibrium, or new climate regime.

The rapid changes discovered in the ice core described above are not about to happen now: They were among the midterm climate events mentioned earlier and occur during the transitional period at the end of an ice age. They are important because they show how quickly the global climate can flip into a completely new regime. A climate historian describes the innate instability of Earth's climate and compares it to the human experience: "The entire rise of human civilization since the end of the Younger Dryas ha[s] taken place during a period of warm, stable climate that [is] unique in the long record. The climate known to history seem[s] to be a lucky anomaly."[19]

THE OCEAN AND ABRUPT CLIMATE CHANGE

As late as the 1970s, scientists bemoaned the fact that we knew more about the surface of the Moon than we did about our own planet's oceans. Through the first half of the 20th century, most ocean research focused on either navigation and shipping (surface currents) or fisheries. The general feeling was that the ocean was too complex to be studied thoroughly and analytically and, further, that ocean processes were so drawn out—taking many hundreds of years—that they lacked relevance to human enterprise. They certainly discouraged scientific inquiry. Analyzing the ocean's effect on climate would be, scientists thought, like a meteorologist waiting an entire lifetime for a single cold front to pass by and then having to predict the weather from that one event. What was the point?

The cold war (again) proved to be the impetus oceanographic research needed. Atmospheric testing of nuclear bombs spewed radioactive material into the air and the oceans. Spurred by popular anxiety about radioactive fallout, governments began tracking the released radioactive material as it was carried around the world by ocean currents. Tracing the radioactive material initially indicated that ocean water moves from Antarctica north across the surface of the Atlantic Ocean, then sinks to the depths in the North Atlantic before wending its way south again, and eventually flowing into the mid-Pacific. (Scientists continue to unravel the complexities of ocean circulation, sometimes in unorthodox ways. In 1992, shipping containers holding 29,000 rubber duckies and other buoyant bathtub toys spilled into the Pacific Ocean. Plotting the site where each toy was found washed ashore has greatly expanded oceanographers' understanding of surface ocean currents.) Based on the radioactive tracers, scientists' preliminary calculations showed that a complete ocean circulation cycle—the ocean's turnover rate—takes at least 1,000 years. Since Revelle established that only a fraction of absorbed CO_2 enters the deepwater circulation, climate scientists began to seriously question if the timescale of ocean circulation would permit deep-ocean absorption of sufficient quantities of CO_2 at the rate humans were producing it.

Several deep-sea drilling projects greatly expanded the data derived from ocean sediments. Studies of ancient, fossilized shells suggested that the North Atlantic Ocean circulation had changed drastically at the time of the Younger Dryas. Studies of microfossils on the seafloor supported the finding: A dramatic alteration of ocean circulation had occurred during the last glacial period when the "deep waters of the North Atlantic had apparently grown cold and still."[20] Termination of the North Atlantic circulation had affected all the world's oceans and Earth's climate. Both ice and sediment cores show a correlation between this cold event, and the later warm-up, with atmospheric concentrations of CO_2. Increasingly, scientists began to wonder if there was a connection: Could CO_2 be a push that changes the pattern of ocean circulation in response to changes in the Milankovitch cycle? Could atmospheric warming due to increasing concentrations of CO_2 affect ocean circulation?

The North Atlantic Deep Water Circulation

Wallace Broecker is sometimes regarded as the Renaissance man of climatology. His obsession with unraveling the secrets of abrupt climate change has led him to study ocean biochemistry, marine plankton, coral cores, ocean sediment cores, lake sediment cores, ice cores, fossil pollen, and any other proxy he could get his hands on that might help him untangle this slippery problem. Broecker synthesized all the data then available, and, in a landmark 1985 paper, he and colleagues at LDEO revealed that the pattern of ocean circulation was akin to a vast "conveyor belt," an illustrative simplification of the complex patterns of ocean currents that span the world. The researchers showed that the enormous current of water (of which the Gulf Stream is a part) flowing northward in the Atlantic carries a stupendous amount of heat to northwestern Europe and that therefore a shutdown of the North Atlantic conveyor belt would affect the global climate. Since the entire conveyor belt system takes 1,000 years to complete a cycle, such a collapse would have dire long-term effects on the climate.

Broecker and others showed why the North Atlantic Ocean—in particular, the North Atlantic Deep Water (NADW) circulation—is the Achilles' heel of the global climate. As the immense Atlantic current sweeps northward from Antarctica, its salinity (salt content) increases. By the time the current reaches the North Atlantic, it is saltier (but only by about 7 percent) and a lot colder (under the influence of the Arctic). The colder, saltier water is denser—or heavier—than surrounding waters, so it sinks to the ocean bottom, where it pushes unimaginably huge amounts of water (about 19 billion liters/sec [5 billion gal./sec]) south toward the equator.[21] In this way, the NADW is the driver, or engine, behind the global oceanic conveyor belt, also called the thermohaline circulation (THC) (thermo = heat; haline = salt), or the meridional overturning circulation (MOC), a recent coinage that reflects the complex dynamics of ocean circulation.

If something happens to dilute the NADW—to reduce its salinity—or to raise the temperature of the water at the site where the NADW engine keeps the machinery of ocean circulation going, the NADW, and global ocean circulation, can collapse. Some scientists believe that it has happened before.

About 20,000 years ago, the world was in an ice age. Over thousands of years, the climate started to warm and the mile-thick ice sheets that covered most of North America began to melt. Some meltwater escaped by creating the Mississippi, Susquehanna, and Hudson Rivers. But a stupendous amount of water was dammed up behind accumulated blocks of ice at the mouth of today's St. Lawrence River, creating a lake that covered more than 225,300 square kilometers (140,000 mi.^{2}). Inevitably, the ice dam broke, and a superflood of truly biblical proportions swept into the North Atlantic. The flood of freshwater rapidly reduced the salinity, and thus the density, of the ocean water in the NADW's engine room. The THC collapsed. Heat was no longer carried northward by the Gulf Stream, and the world was plunged into another ice age—the Younger Dryas. A similar outflow of freshwater occurred as the world was thawing out of the Younger Dryas ice age (about 8,200 years ago): This time, the ice-dammed floodwaters and a huge flotilla of icebergs surged out of Hudson Bay—and another, though less severe and prolonged, ice age occurred. These cataclysmic changes are among the mid-term climate cycles discussed above.

These revelations regarding the abruptness with which a catastrophic, though perfectly normal, event could shut down global ocean currents and alter the world's climate really began to worry climate scientists. Richard Alley compared the global climate to a drunk: "When left alone, it sits; when forced to move, it staggers."[22] When the floods overpowered the NADW, the stagger set the climate reeling. Climate research has been providing increasingly convincing evidence that anthropogenic CO_2 emissions might act as a similar knockout punch for the oceans and climate. The reason for this has to do with what are called climate feedbacks.

FEEDBACKS AND OTHER EFFECTS

Shipwrecked people bobbing in a lifeboat on the open ocean must remember one crucial lesson: No matter how thirsty you get, don't drink seawater. Seawater is salty and will kill you. But the people are desperate, so they drink the seawater. The salt makes them even thirstier. So they drink more seawater, get more unbearably thirsty, drink even more seawater—and then they die. Seawater's effect on the body is an example of a positive feedback, a situation in which one action sets in motion ongoing and self-perpetuating reactions, like a loop that goes round and round and gets bigger and bigger as it feeds on itself.

There are negative feedbacks, too. For example, when people exercise, their body heat rises, which makes them sweat. As sweat evaporates from the skin, the body cools off. When the body has regained its normal internal temperature, it stops sweating. A negative feedback, then, is a response intended to stabilize a system after some type of change.

Earth's climate system contains myriad extremely complex feedbacks, both positive and negative. In general, negative climate feedbacks are long-term stabilizers of the climate. Positive feedbacks occur in much shorter time frames and tend to cause more abrupt and dramatic climate changes. Present-day global warming is setting in motion quite a few positive feedbacks that are changing the climate. One of the most worrying involves changes in the THC.

Increasing concentrations of CO_2 and other GHGs are warming both the atmosphere and the ocean's surface. Warmer air leads to higher rates of evaporation, which adds increasing concentrations of water vapor to the atmosphere. The temperature-water vapor feedback is perhaps the most important feedback in climate change. Water vapor is a very powerful GHG, so the additional water vapor warms the atmosphere, which increases evaporation, which adds even more water vapor to the air, and so on in a classic feedback cycle.

Water vapor also rises to form clouds, which eventually unload their accumulated water as rain. Rain is freshwater. Scientists have documented that increasing precipitation over the NADW is reducing the salinity of—or freshening—the deepwater current that drives the THC. As the climate warms, increased precipitation reduces the salinity—and therefore the density—of the NADW. The lower the density of the NADW, the weaker the deepwater current becomes. This positive feedback is weakening the engine that drives ocean circulation.

Global warming is also reducing the extent of Arctic sea ice. As the ice melts, its freshwater flows south into the North Atlantic, further freshening and weakening the NADW that drives ocean circulation. By 2005, more than 101 million hectares (250 million ac) of permanent (year-round) Arctic sea ice had melted.[23]

Another aspect of ice-melt feedback is being observed with increasing alarm in Greenland. The warming climate is causing the Greenland ice sheet to lose enormous quantities of freshwater, which are pouring into and diluting the crucial engine in the North Atlantic. As reported in 2006 by climatologists from the University of Colorado, Boulder, Greenland lost 237 cubic kilometers (57 mi.^{3}) of ice annually between 2002 and 2005; this loss increased to 342 cubic kilometers (82 mi.^{3}) annually by 2006. Overall, Greenland is losing far more ice mass to melting than it gains via snowfall each year.[24]

Generally, scientists are uncertain about the effect the freshening of the NADW will have on the THC and global climate. Though the NADW has weakened, scientists question if current degrees of freshening will have sufficient impact to cause another Younger Dryas-like ice age. Extensive melting of the Greenland ice sheet is the event most likely to cause a THC collapse. However, sea ice extent and the many other arcane factors that affect the NADW, and thus the THC, are extremely complex, and exactly how they will play out is still not clear.

Ice, or lack thereof, generates another positive feedback cycle. Ice has a high albedo, so it reflects solar radiation away from the planet, cooling it. That is why the Arctic is often called the "air conditioner" of the global climate. As the climate warms, ice melts and the regional extent of ice cover dwindles. Water has a low albedo; it absorbs solar radiation and heat. As the extent of north polar ice decreases, less heat is reflected away from the planet, and more heat-absorbing water is exposed. As more heat is absorbed, more ice melts. It is a vicious cycle in which loss of ice cover exposes more water, which causes more heat absorption, which hastens even greater loss of ice, and so on. This positive feedback cycle is one reason why the north polar regions are warming far faster and more dramatically than other regions of the planet.

The Arctic is the site of yet another positive feedback that may also have dire consequences for the global climate. A huge swath of subpolar regions (about 2.25 billion hectares [~5.5 billion acres]) is permafrost, or land that is permanently frozen. In much of Siberia, the permafrost extends about a mile beneath the surface; in other parts of the Arctic, such as Alaska, its depth varies from a few hundred to several thousand feet.

Because of global warming, permafrost throughout the Arctic is melting. Visitors to these northern regions are now confronted by forests of "drunken" trees that are listing precariously as the once-frozen ground beneath them thaws. However, "inebriated" trees are the least of the problems associated with melting permafrost. Scientists estimate that there are at least 500 billion tons of methane stored within the permafrost. As the permafrost thaws, the methane (a GHG 21 times more potent than CO_2) is released to the atmosphere where it accelerates climate warming, which intensifies permafrost thawing, which releases more methane, and so on. In some places, methane emissions from thawing permafrost have increased 60 percent in recent decades. Scientists predict that, if all the stored methane in permafrost were to enter the atmosphere, there would be a huge spike in global temperatures. As one expert remarked, "I think it's just a time bomb, waiting for . . . warmer conditions."[25]

There are numerous other effects that a warming climate will likely have on Earth and its people, though not all involve feedbacks. Some of these have been well documented and widely reported. These include:

- Disappearance of mountain glaciers whose spring meltwaters maintain rivers on which people and ecosystems depend for survival. Some of the largest and most important rivers in the world are fed by glacial meltwater. If these glaciers melt completely, their associated river systems would dry up. There is incontrovertible evidence that because of global warming, mountain glaciers are retreating everywhere in the world. The loss of these glaciers and the rivers they sustain would have truly catastrophic consequences.
- Rising sea levels from thermal expansion of ocean water and melting ice will add to the oceans' volume, resulting in the inundation of most of the world's major coasts and port cities.
- Alterations in precipitation patterns that may affect agriculture, the availability of drinking water, and desertification. One serious concern is the potential desiccation and disappearance of the Amazon rain forest due to drought. Some climate models predict that the destruction of the Amazon rain forest might affect precipitation patterns in the Western Hemisphere, if not beyond. Destruction of the Amazon would also increase atmospheric CO_2 concentrations due to the loss of a vital carbon sink and reduced CO_2 uptake via photosynthesis. Reduced photosynthesis could also conceivably lower the oxygen content of the atmosphere.
- Persistent ENSO conditions in the tropical Pacific induced by global warming, which would change global patterns of rainfall and drought.
- Melting of the frozen methane beneath the seafloor would release unimaginable quantities of this GHG into the atmosphere, causing a huge, long-lasting spike in global temperatures. Scientists have documented a slight rise in the temperature of deep-ocean waters. Though many scientists believe it is unlikely, they admit that it is possible that if global warming continues unabated, the deep ocean might warm sufficiently to thaw out and release the frozen methane beneath the sea.
- Possible collapse of the NADW if most or all of the Greenland glacier melts. The fresh meltwater would flow into the North Atlantic and could conceivably lead to a severe weakening or collapse of the THC. If the Gulf Stream stops flowing, the world could enter another ice age.

TIPPING POINTS

For the first time in 2005, scientists began using the term *tipping point* to describe what might be happening to the global climate. A tipping point is a threshold that, once crossed, there is no going back. It is a point of no return; a point at which the climate has changed irreversibly and positive feedbacks are self-sustaining. Scientists view a collapse of the Greenland and/or West Antarctic ice sheets, the potential shutdown of the THC, loss of Arctic sea ice, rising sea levels, and the release of methane held in permafrost as the events that are most likely to send the global climate over the edge. A Russian researcher who watched as methane bubbled out of once-frozen tundra described it as an "ecological landslide that is probably irreversible and is undoubtedly connected to climatic warming."[26]

Record ice melt in the Arctic in September 2007 (the height of melt season) has climatologists concerned that we may be nearing a tipping point sooner than expected. For the first time in history, the fabled Northwest Passage linking the Atlantic and Pacific Oceans opened due to unprecedented loss of sea ice. Historically, this polar sea route has been perpetually icebound. The Arctic's sea ice extent shrank to 4.13 million square kilometers (1.6 million mi.^{2}) in 2007, more than 20 percent below its previous all-time low in 2005. Both James Hansen of NASA (National Aeronautics and Space Administration) and climatologists at Germany's Potsdam Institute for Climate Impact Research stated that the Arctic has already hit or is very near a tipping point that will irreversibly change the global climate.[27]

Global Response

The first intimations that something was awry in Earth's climate originated with scientists at the IGY conference in 1957–58. Those early researchers were among the first to study and collect data to document what came to be known as global warming.

In 1967, climate scientists formed the Global Atmospheric Research Program (GARP), which sponsored some climate research and symposia. In 1971, GARP held the Stockholm Study of Man's Impact on Climate conference, one of the first venues where the risks of global warming were openly addressed and reported.

A turning point was reached at a global climate conference held in Villach, Austria, in 1985. Scientists at this meeting reached consensus on global warming and issued a public statement of their concern: ". . . in the first half of the next century a rise of global mean temperature could occur which is greater than any in man's history. . . . While some warming of climate now appears inevitable due to past actions, the rate and degree of future warming could be profoundly affected by governmental policies."[28] This was unprecedented—a scientific community not only reached unanimous agreement on the reality of climate change, its members actively demanded that governments take action to curb it. In 1987, most nations adopted the Montreal Protocol to phase out the manufacture and use of CFCs. This success in Montreal would, it was hoped, serve as a model for future climate treaties.

In 1988, when the worst heat wave and drought since the 1930s Dust Bowl hit the United States, the public began to take notice. The weather became the "hottest" story covered by the press, and suddenly global warming was on the lips of citizens and their government representatives alike. Though a one-year drought and heat wave cannot be attributed to climate change, for the first time, the state of the climate became a political issue. Conservatives, climate skeptics, and business interests began to worry that global warming would become the sole province of an elite international group of climate scientists over whom they had no control.

To prevent this, U.S. politicians urged the formation of an entirely new entity, under the auspices of the UN. The new agency—the Intergovernmental Panel on Climate Change (IPCC), created in 1988—would be composed of government representatives from national laboratories and scientific agencies, as well as the scientists who worked at them. This unique hybrid organization would periodically gather climate research data from scientists the world over. It would then meet to reach consensus before issuing reports on the state of the global climate.

The first IPCC report was issued in 1990. It concluded that the global climate was, indeed, warming and that the enhanced greenhouse effect would likely raise globally averaged temperatures several degrees by 2050. The second IPCC report was published in 1995. By this time, the evidence for human-induced climate change was more compelling, so government representatives put up stiffer resistance to making the scientific findings public. After intense negotiations, consensus was reached. The most quoted statement in the final report reads: "The balance of evidence suggests that there is a discernible human influence on global climate."[29] This rather tepid statement reflects the sometimes acrimonious negotiations that led to its formation. Yet it still conveys the unmistakable message that human emissions of GHGs are changing the climate. *Science* magazine gave the report its imprimatur with the simple announcement, "It's official."[30]

The 1995 report stated that emissions of GHGs would raise global temperature between 1.5° and 4.5°C (2.7°–8.1°F) sometime around 2050. The landmark report made headline news around the world. The IPCC's conclusions impelled the international community to convene to try to figure out how to address this urgent problem. The groundwork had been laid at the 1992 Earth Summit in Rio de Janeiro, where 150 nations had signed on to the United Nations Framework Convention on Climate Change (UNFCCC). The goal of the framework was the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[31]

The third meeting of the parties to the Convention was convened in Kyoto, Japan, in 1997. Despite heated debate, the outcome of this meeting was a document that committed all Annex I (industrialized nation) members to GHG reductions of 6–10 percent below 1990 levels by 2012. This document is known as the Kyoto Protocol. The Kyoto Protocol would go into effect only when nations that were collectively responsible for 55 percent of the world's GHG emissions ratified it. Since 1997, all European nations and many other industrialized and nonindustrialized nations have ratified the Kyoto Protocol, but the United States—which emits 25 percent of the world's GHGs—has refused to ratify it. It was not until 2004, when Russia ratified it, that the Kyoto Protocol entered into force.

In 2001, the IPCC issued its third assessment of the global climate. This report stated unequivocally that global warming was underway and would get worse as the effects of past, current, and future GHG emissions kicked in. The report concluded that it was *likely* (66–90 percent certain) that the unprecedented rate of observed warming was due to anthropogenic emissions of GHGs.

PRESENT AND FUTURE CLIMATE CHANGE

The following section provides an overview of current climate change science. It is largely based on the latest 2007 IPCC Assessment Report (AR4), though it also contains other current and pertinent research. The AR4 is the most comprehensive report to date on the state of the global climate. The AR4 data reveal a dangerously warming world, but one that can still be saved from future climatic catastrophe by swift and decisive action.

Computer Models: Power in Numbers

Fear not—no attempt will be made to explain the mathematical complexities of computer climate models here. However, it is important to know a bit about these models in order to understand why they are considered so reliable.

The earliest climate models were crude approximations of the climate, omitting key factors if they were poorly understood. For example, early models omitted ocean processes (a very serious limitation). Today's climate models not only include ocean processes, they incorporate highly variable factors such as cloud cover, water vapor, the carbon cycle, aerosols, ice cover, and complex feedbacks throughout the climate system (though some knotty problems, such as vegetation's effect on climate, are still being researched). They analyze climatic factors on ever-smaller scales, giving them a far more accurate cumulative picture of the world climate.

AR4 coordinates and incorporates data from 18 supercomputer climate models from around the world. By comparing the results from each computer simulation, IPCC scientists can predict climate change with various levels of confidence based on the consensus among models. The number of computer models used to derive data for AR4 is unprecedented and provides the most realistic and reliable analysis yet made of the global climate.

Climate models analyze outcomes for various scenarios, or conditions. For example, a BAU model predicts the climatic response if GHG emissions rates continue unabated. Other scenarios predict what will happen for various degrees of mitigation, such as different reductions in GHGs (20 percent, 50 percent, or 80 percent by 2050, for example). Worst-case scenarios predict the climatic consequences of accelerating rates of GHG emissions if developed countries ignore mitigation and developing countries increase their fossil fuel use as they develop economically.

RADIATIVE FORCING

One way climate models analyze the global climate is by measuring the radiative forcing (RF), or simply "forcing," of all the factors affecting the climate. The term *forcing* refers to something that pushes the climate away from its normal state. So radiative forcing is a fancy way of describing whether something warms or cools the climate. For example, something that warms the climate—a GHG—is said to have positive forcing. Something that cools the planet—volcanic particles—has negative forcing.

A climate factor's RF is calculated as its temperature effect, measured in watts, on one square meter of Earth's surface, written as Wm^{-2} (or W/m^2). Using this measure, scientists can calculate the RF of every GHG and many other climatic factors. For the first time in AR4, the RF for all anthropogenic climate inputs has been calculated. Knowing the RF for each climate factor gives scientists, and a knowledgeable public, the power to describe precisely the degree of each source's forcing. Anyone who knows a climate factor's forcing can use the numbers to explain why, for instance, increased solar radiation cannot be the cause of global warming.

Confidence and Likelihood Terminology Used in the 2007 IPCC Assessment Report (AR4)

CONFIDENCE TERMINOLOGY	**DEGREE OF CONFIDENCE IN BEING CORRECT**	**LIKELIHOOD TERMINOLOGY**	**LIKELIHOOD OF THE OCCURRENCE OR OUTCOME**
Very high confidence	At least 9 out of 10 chance	*Virtually certain*	> 99% probability
High confidence	About 8 out of 10 chance	*Extremely likely*	> 95% probability
Medium confidence	About 5 out of 10 chance	*Very likely*	> 90% probability
		Likely	> 66% probability
		More likely than not	> 50% probability
		About as likely as not	33%–66% probability
		Unlikely	< 33% probability
		Very unlikely	< 10% probability

Source: Solomon, S., et al. "Technical Summary." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC.* Cambridge: Cambridge University Press, 2007, pp. 22–23.

The Atmosphere: Observed and Projected Changes

Emissions of CO_2, the most important GHG, increased 80 percent between 1970 and 2004. Fossil fuel combustion has been putting about 27 gigatons (Gt: billion tons) of CO_2 into the atmosphere annually. In 2007, despite isolated efforts to reduce emissions, concentrations of atmospheric CO_2 grew 0.6 percent, or 19 billion tons; methane levels rose in 2007 for the first time since 1998. Without mitigation, increased demand and economic development are expected to raise emissions 57 percent from current levels to about 42 Gt by 2030.[32]

In the 8,000 years prior to industrialization, CO_2 concentrations had risen by only 20 ppm. Today's emissions have raised atmospheric CO_2 concentrations by more than 30 percent above preindustrial (ca. 1750) levels of about 280 ppm to a February 2008 level of 386.6 ppm. Increased CO_2 concentrations are responsible for a RF of $+1.6\ Wm^{-2}$. It is *very likely* that the rate of increase of emissions of long-lived GHGs (LLGHGs) and their total forcing is unprecedented in more than the last 10,000 years.[33] A 2008 study revealed that CO_2 emissions were increasing 35 percent faster than previously thought. About half of that increase was attributed to growing inefficiency in fossil fuel combustion (e.g., U.S. cars and Chinese coal-fired power plants); the other half results from the declining ability of natural carbon sinks to absorb CO_2.[34]

Eleven of the last 12 years (1995–2006) were the warmest years on record (since 1850), with 1998 and 2005 the hottest on record. Globally averaged temperatures have risen by 0.74°C (1.3°F), with greater warming occurring over land (0.27°C/0.48°F per decade) than over the oceans (0.13°C/0.23°F per decade). The rate of temperature rise in the last 50 years is double that in the previous 100 years. Regional temperature increases since 1950 vary, ranging from no change to 1.0°C (1.8°F). The temperature difference between day and night, called the diurnal temperature range, has flattened out in recent decades, with the greatest consequences for hot nighttime temperatures during summer heat waves. Similarly, there has been a significant reduction in the number of very cold days and nights and an increase in the number of extremely hot days and nights, with a concomitant increase in the number of warm extremes and far fewer cold extremes.[35] In sum, there is *very high confidence* that the net effect of human activities since 1750 has been one of warming, and it is *very likely* that the increase in globally averaged temperature is due to anthropogenic emissions of GHGs.[36]

Global warming has affected air circulation patterns, producing a persistent positive NAO/AO in the Northern Hemisphere and a similar pattern in the Southern Hemisphere. The low pressure created by these air circulation patterns has shifted extratropical, midlatitude storm tracks and jet streams poleward. This poleward shift brings more hot, tropical air over a wider belt of midlatitude regions.[37] As a result, larger swaths of land north and south of the equator will become hotter, and some (U.S. Southwest, Mexico, North Africa) may see increasing and prolonged drought. Research published in 2007 revealed that the tropics are moving poleward at a faster rate than climate models predicted. Over the last 25 years, the tropics have expanded by 2.5 degrees to 4.8 degrees of latitude, or up to 500 kilometers (311 mi.); that is 200 kilometers (124 mi.) per decade. Accelerating warming is expected to hasten this tropical expansion.[38]

Precipitation patterns have been rather variable, depending on region, though overall precipitation has increased, particularly over eastern North and South America, northern Europe, and northern and central Asia. It is *likely* that a significant amount of precipitation has fallen during heavy precipitation events, and these events occur more infrequently during longer dry periods. More intense and likely more numerous North Atlantic hurricanes (and storms elsewhere) have also occurred due to rising SSTs. Notable reductions in precipitation are occurring over the Sahel, the Mediterranean region, southern Africa, and parts of southern Asia. Globally, the area affected by drought has *likely* increased since the 1970s. Droughts have also been observed to be more intense and of longer duration, particularly in the tropics and subtropics, since the 1970s.[39]

Higher SSTs are leading to significant increases in atmospheric water vapor. The positive temperature-water vapor feedback arises from GHG heating of the planet's surface, which increases evaporation, which adds more water vapor to the air, which further warms the planet, and so on. Several studies have revealed larger amounts of water vapor in both the upper and lower troposphere. One study predicted a 20 percent increase in water vapor in the lower troposphere by century's end, with a 100 percent increase in the upper troposphere.

Upper atmospheric water vapor was shown to have the greatest positive feedback for accelerated global warming in the future.[40] Public health professionals expressed concern that higher humidity near the surface will lead to a significantly higher death toll during intense summer heat waves, especially in cities. One study revealed that urban heat-related deaths could rise 95 percent above current levels if sufficient air-conditioning is not available.[41]

All global warming projections depend on what, if any, mitigating measures humankind takes to curb climate change by reducing GHG emissions. Therefore, computer models project the climate into the future for an array of different scenarios, each representing a different human response to the crisis, from do nothing (BAU) to making immediate and drastic cuts in GHG emissions. Thus, climate projections are given as a range of possible outcomes, each of which depends on what people are willing and ready to do to curb global warming. However, since the GHGs already emitted to the atmosphere will stay there for quite some time and continue to trap heat, the scientific consensus is that we can expect a minimum of 0.2°C (0.36°F) warming per decade for the foreseeable future. Without immediate and large-scale replacement of fossil fuels, GHG emissions are expected to increase 25–90 percent by 2030, and it is *very likely* that coming changes in the climate system will be greater than those seen during the 20th century. Among the many computer models running the major climate scenarios, the *likely* temperature increase relative to a 1980–99 baseline is between 1.8° and 4.0°C (3.2° and 7.2°F) by 2090 to 2099. However, warming substantially greater than 4.5°C (8.1°F) cannot be ruled out, especially under a BAU scenario and if positive feedbacks kick in sooner and are more powerful than computer models suggest.[42] If the climate warms this much, the negative

effects become so much worse that all bets are off in terms of accurately predicting outcomes.

Land: Observed and Projected Changes

Land use changes have an important impact on climate change because, normally, plants and soil are carbon sinks: they absorb CO_2 from the air. The precise interactions between plants, soil, and the atmosphere are highly complex and not fully understood, but observations and the most advanced computer models have revealed a great deal about how the land affects climate.

Plants remove CO_2 from the air during photosynthesis. In recent decades, deforestation, especially in the tropics, has reduced this CO_2 uptake. Thus, conversion of forest to crop- or pastureland reduces the flux, or movement, of CO_2 out of the air and into vegetation. Scientists have calculated that land use changes during the 1990s resulted in a net flux of CO_2 to the atmosphere of about 1.6 Gt carbon per year.[43] Data from the more recent and extensive deforestation of the Amazon rain forest are not yet available, but will certainly raise this figure considerably.

Studies have shown that though most plants initially flourish as atmospheric CO_2 concentrations increase, when CO_2 levels rise above a certain level (> 450 ppm), some plants not only do not absorb and use the additional CO_2 but actually begin to outgas it back into the air. In addition, at some point too much CO_2 begins to retard plant growth. Data reveal that at 1°C (1.8°F) of warming, net productivity (growth) of many plants decreases 1.3 percent, and the plants begin to outgas 6.2 percent more CO_2 than they would under cooler conditions.[44]

Land use changes also affect albedo: leafy forested land has a higher albedo than pasture or cropland. Thus, as forest is cleared for agriculture, the land reflects less light and heat away from the planet's surface and instead absorbs more heat. In 1750, only 5–7 percent of the globe was under crop cultivation; by 1990, 39 percent of the planet was cleared for agriculture, with more than 11 million square kilometers (4.2 million mi.^{2}) coming from forest clearing.[45]

Soils also play an important role in climate feedbacks. As soils warm, microbial activity increases, with more rapid breakdown of organic matter into carbon and methane, which are released in greater amounts into the atmosphere. Higher temperatures may eventually change soils from net carbon sinks to carbon emitters. As soils stop absorbing CO_2 and begin outgassing it, global warming will intensify, which will further accelerate the chemical processes in soil, which will add more GHGs to the air, and so on.

Overall, "climate change alone will tend to suppress both land and ocean carbon uptake, increasing the fraction of anthropogenic CO_2 emissions that remain airborne and producing a positive feedback to climate change."[46]

Ice: Observed and Projected Changes

Ice loss is a worldwide phenomenon. Nearly everywhere ice is found, it is melting due to global warming.

ANTARCTICA

Though the East Antarctic ice sheet seems to be fairly stable for now, West Antarctica, including the Antarctic Peninsula, is losing increasing amounts of ice. Average summer temperatures around the West Antarctic Ice Sheet (WAIS) have risen about 2.5°C (4.5°F) in the last decade or so. The AR4 reports ice loss from this region of about 136–139 Gt/yr, and that loss rate appears to be accelerating.[47] It is *very likely* that ice melt from Antarctica has contributed to the observed global rise in sea level between 1993 and 2003. (The volume of the entire Antarctic ice sheet is equivalent to about 57 meters [187 ft.] of sea level rise.)[48]

More recent research paints a picture of a more rapidly deteriorating WAIS. One NASA study measured ice flow along 85 percent of West Antarctica's coastline and documented a 20 percent increase in net ice loss to 196 Gt/yr in 2006. Melting of this amount of ice nearly doubled West Antarctica's contribution to sea level rise to 0.5 millimeters/yr (0.2 in.) in 2006. The study revealed that Antarctic ice loss has increased 75 percent in the last decade due to accelerated glacier flow.

Warmer SST melts and thins ice shelves that buttress the glaciers behind them. Though some Antarctic melting arises from warmer air temperatures, higher Southern Ocean SST, which has increased 1–2°C (1.8–3.6°F) in the last 50 years (double the global average), has undermined ice shelves by melting them from below. In some cases, ice shelves have collapsed and inland glaciers have rocketed toward the sea.[49]

A worrying increase in melting was observed on the Ross Ice Shelf, which acts as a major brake on inland glaciers.[50] The Pine Island glacier, a mass of ice the size of Texas, has increased its melting rate from 1 percent/yr in the 1990s to 5 percent/yr in 2008. The glacier is retreating at a rate of 3.5 meters (11.5 ft.) per year across its entire 30-kilometers-long (18.6-mi.) outer edge. Disintegration of this glacier could raise sea level by 25 centimeters (10 in.).[51]

A NASA analysis of 20 years of Antarctic ice data revealed that in 2005 the area of snowmelt on the WAIS, much of which lies below sea level, had moved at least 805 kilometers (500 mi.) inland from the ice sheet margins along the coast. Ice melt was also noted for the first time at an altitude of 1.9 kilometers (1.2 mi.) above sea level in the Transantarctic Mountains.[52]

Increasing air and ocean temperatures will further undermine the WAIS, and a total collapse would raise sea levels by about five–six meters (16.5–19.7 ft.). Ongoing warming, however, is predicted to increase Antarctica's contribution to sea level rise by 0.7–0.9 millimeters/year (0.3–0.4 in./yr.) for the foreseeable future.[53] Scientists are closely watching outflow of ice streams and the development and spread of melt ponds on the WAIS. Melt ponds are small lakes of melted ice on the surface of an ice sheet or glacier. If melt ponding spreads across the ice sheet, it could lead to an event similar to the rapid disintegration and collapse of the Larsen B Ice Shelf, a mass of ice the size of Rhode Island. In a 2008 study, scientists determined the long-term behavior of WAIS glaciers and revealed that they are thinning at an accelerating rate. Pine Island glacier thinned about four centimeters a year (1.6 in.) during the past 14,500 years; since the 1990s, it's been thinning at 1.6 meters (5.2 ft.) annually.[54]

AR4 projections include substantially accelerated ice discharge from West Antarctica and potential collapse or weakening of ice shelves due to surface melting and/or basal thinning, especially at SST increases of 1°C (1.8°F) or more. Surface temperature warming of 5°C (9°F) could cause breakup of the WAIS.[55]

THE ARCTIC

Melting of Arctic sea ice will not affect sea levels because the ice forms on water (in the same way that ice cubes melting in a glass of water do not raise the water's level). The AR4 predicted a possible large-scale loss of summer Arctic sea ice by 2030–2050. The report cited reductions in annual mean Arctic sea ice of about 2.7 percent per decade and a decline in Arctic summer ice cover of about 7.4 percent annually.[56] The report predicted that summer sea ice in the Arctic would disappear completely by 2100.[57] By the time the IPCC report was published, however, new research showed that its predictions were far too conservative.

In September 2007, the extent of Arctic sea ice had dwindled to a record low of 4.13 million square kilometers (1.50 million mi.^{2}), more than 2.6 million square kilometers (1 million mi.^{2}) lower than the previous record (2005). At the current rate of summer melting (about 8 percent/yr), the Arctic is expected to be ice free in summer by 2013. Scientists say that "In the end, it will just melt away quite suddenly."[58]

The dramatic acceleration of sea ice loss was attributed to several factors, most importantly record high SST. Once sea ice begins melting, a positive feedback cycle is set in motion, with less sunlight reflected away from the surface by the dwindling ice and more heat absorbed by the exposed water, which has a far lower albedo. Heat absorption by the greater expanse of Arctic water raised SST in 2007 to 5°C (9°F) above normal—a high never before observed. Air temperatures were 3.5°C (6.3°F) above normal and 1.5°C (2.7°F) above the previous record.[59]

Record-breaking ice loss was not limited to the summer melt season, however, as declines in Arctic sea ice extent set records for March 2007 as well. March is the month that usually sees the greatest extent of winter sea ice; in March 2007, the rate of sea ice decline was three times the previously predicted rate of 1.8 percent per decade.[60]

Warming of the Arctic Ocean is also thinning sea ice. German researchers found that in 2007, vast stretches of Arctic sea ice were only one meter (3 ft.) thick, a thinning of 50 percent since 2001. The warmer water on which the sea ice floats is melting and thinning it from below. To make matters worse, scientists at the University of Colorado, Boulder, found that "there has been a nearly complete loss of the oldest, thickest ice and that 58 percent of the remaining perennial ice is thin and only 2 to 3 years old." Twenty years ago, only 35 percent of the ice was that young; today, only 5 percent of multiyear ice is seven years old, down from 21 percent in 1988. The finding is significant because younger sea ice is more vulnerable to rapid melting.[61]

Another problem plaguing the Arctic comes from what is called black carbon (BC), soot that comes from fossil fuel burning, forest fires, and industrial emissions. Air currents carry BC to the poles, where it falls on ice and significantly reduces its albedo. This reduces the ability of the ice to reflect light and heat away from the planet, exacerbating global warming. The BC also absorbs more of the heat that hits the soot-covered ice, warming it and accelerating melting. BC may also compromise regrowth of winter Arctic ice.

Many scientists are coming to the conclusion that the Arctic has reached or actually passed a tipping point and that drastic alterations of its climate are now irreversible. Many experts cannot see any way to prevent the disappearance of Arctic species, such as the polar bear, walrus, and seals, once the ecosystem is irremediably altered. Since the Arctic is the "air conditioner" of the global climate, it is feared that lack of sea ice and unstoppable warming of Arctic waters will create dangerously hot NH climate conditions, especially in summer.

PERMAFROST

Permafrost is permanently frozen ground, most of which rims the Arctic. AR4 data from 2005 show that permafrost temperatures in northern Alaska increased 2°–3°C (3.6°–5.4°F) since the 1980s. Warmer air temperature alone cannot account for this increase, so scientists have determined that significantly reduced insulating snow cover is partly responsible for the warming.

In the 1990s, northern Canadian permafrost warmed at a rate of 0.4°C/yr (0.72°F/yr) to a depth of 20–30 meters (66–98 ft.). Permafrost in the Russian Arctic has experienced a temperature rise of 1°C (1.8°F) to depths of 3.2 meters (10.5 ft.) in eastern Siberia and as much as 2.8°C (5°F) in western Siberia. Permafrost on the Tibetan Plateau has warmed about 0.5°C (0.9°F) to depths of 20 meters (66 ft.). Northeastern China saw some of the greatest increases of 1.5°C–2.1°C (2.7°–3.8°F) at depths of two–three meters (6.6–10 ft.) by the late 1990s.[62]

Thawing is shrinking the extent of permafrost. By 2002, the area covered by permafrost on the Tibetan Plateau had retreated upward by 25 meters (82 ft.) since the 1970s, with a 36 percent overall loss of permafrost in this region. In Alaska and Siberia, subsidence due to thawing permafrost is occurring at a rate of 17–24 centimeters/year (7–9 in.), and meltwater lakes are becoming more numerous, with an increase in area of 12 percent in Siberia since the 1970s.[63]

Permafrost's active layer is the part of the soil above the permafrost that thaws and freezes seasonally. Warming air temperatures have deepened the active layer in many permafrost regions by 21 centimeters (8 in.) since the 1970s.[64]

Thawing permafrost could exacerbate global warming as its trapped methane is released into the atmosphere. One 2007 study of ancient (40,000-year-old) methane released by thaw lakes (lakes formed by permafrost ice that has melted and whose water has accumulated on the surface) in Siberia showed that previous studies underestimated by as much as 63 percent the amount of methane in permafrost that could be released into the air. Lakes formed by thawing permafrost are the principal source of methane bubbling (ebullition) into the atmosphere. During the study period, 1974–2000, it was found that ebullition from these Siberian lakes increased 58 percent.[65]

Another study revealed that the more than 1 million square kilometers (more than 386,000 mi.^{2}) of loess permafrost in Alaska and Siberia contain about 500 Gt of methane extending to depths of up to 40 meters (131 ft.).[66] If released into the atmosphere through thawing, this vast amount of methane would have devastating effects on global warming, as it is equivalent to 75 times the world's total fossil fuel emissions.[67] Paleoclimate studies have shown that, based on ancient levels of permafrost thawing and gas emission, about 10 times the amount of methane that is currently in Earth's atmosphere could be emitted by thaw lakes in the future.[68]

Researchers from the National Center for Atmospheric Research (NCAR) used the most advanced computer models to predict that the top three meters (10 ft.) of NH permafrost could be decimated in the next few decades. The scientists found that 50 percent of this upper layer of permafrost could be gone by 2050, and 90 percent could thaw by 2100. The study looked at which permafrost regions would remain frozen at depths below 3.4 meters (11.2 ft.) for different mitigation scenarios. The scientists found that for a high-emissions BAU scenario, permafrost regions could dwindle from 10 million square kilometers (4 million mi.^{2}) to just 2.6 million square kilometers (1 million mi.^{2}) by 2050 and shrink to 1 million square kilometers (400,000 mi.^{2}) by 2100. For an aggressive mitigation low-emissions scenario, permafrost regions could be reduced to 3.9 million square kilometers (1.5 million mi.^{2}) by 2100. The researchers point out that not only would the areas of thawed permafrost increase atmospheric concentrations of methane, they might also release significant amounts of fresh meltwater into the Arctic Ocean, possibly reducing the salinity of the NADW.[69]

GLACIERS

Glaciers and ice caps are ice masses that occur on land and are smaller than ice sheets. Mass balance (MB) describes the amount of ice a glacier contains. MB is calculated by comparing the amount of ice added to the glacier via snowfall and the amount lost from the glacier via melting and outflow. Until about 1970, the MB of most of the world's glaciers was about zero; that is, the amount of ice added was about equal to the amount lost through melting. The 1970 figures underline the role of global warming in the worldwide MB declines since then. MB losses arise from both surface mass loss and greater ice discharge to the sea from more rapidly moving ice. Since the 1990s, the greatest glacier MB loss has been observed in Patagonia (South America), the northwestern United States, Alaska, and Canada. Recent global MB for all glaciers (including those around ice sheets) shows an ice loss of about 230 Gt/yr, resulting in a sea level rise of about 0.63 millimeters/year (0.02 in./yr.).[70]

Higher air temperatures and other factors cause more rapid basal sliding: Meltwater forms at the base of the glacier and acts as a lubricant that accelerates the glacier's downward slide. Warmer air is also shrinking glaciers dramatically. Glacial retreat is measured by the disappearance or retreat upward of a glacier's tongue, the leading or outward edge of the glacier. On average since 1900, North American glacier tongues have retreated more than 1,700 meters (5,577 ft.); South American glacier length has been reduced by about 1,000 meters (3,281 ft.); and Asian glacier tongues retreated more than 1,200 meters (3,937 ft.) up into the mountains.[71]

Even under the most optimistic scenarios, warming temperatures are expected to melt many continental glaciers completely in this century. Experts predict that glaciers and ice caps will lose up to 0.5 meters (1.6 ft.) of ice per year for each 1°C (1.8°F) of climate warming.[72] Today, about 60 percent of the ice melt that contributes to sea level rise comes from glaciers and small ice caps, and this contribution is expected to increase as temperatures rise and glacial melting accelerates. In 2006, meltwater from small glaciers and ice caps contributed about 1.1 millimeters (0.04 in.) to sea level rise; by 2050 that contribution will increase to 81 millimeters (3.1 in.) and to 240 millimeters (9.4 in.) by 2100.[73]

Many of the world's rivers are fed by glacial meltwater or mountain snowpack, also in steep decline. As glaciers shrink, at some point they will lack sufficient water to feed the rivers they create and sustain. Thus, many of these rivers will dry up or run only when filled by rainwater. Some of the world's largest and most vital rivers, in terms of the ecosystems and populations that depend on them, are in danger of petering out as the glaciers at their headwaters melt away. This is particularly true for glaciers on the Tibetan Plateau and in the Himalayas, which feed the Ganges, Brahmaputra, and other Asian rivers, and in the Andes, where glaciers help maintain the Amazon and other South American rivers. For example, the Gangotri glacier, which supplies more than 70 percent of water to the Ganges River, is shrinking at a rate of 36.6 meters/year (120 ft./yr.), twice the rate of two decades ago. Under a BAU scenario, rising temperatures could cause all Himalayan glaciers that feed the Ganges to disappear by 2030. This would have disastrous consequences for the more than 500 million Indians who depend on water from the Ganges.[74] Experts predict that the loss of these major freshwater resources might well create hundreds of millions of environmental refugees who can no longer survive once vital rivers dry up or trigger intra- or international conflicts over water resources.

GREENLAND

If the Greenland ice sheet's 29 million cubic kilometers (6.96 million mi.^{3}) of ice melted completely, sea levels would rise at least 7.3 meters (24 ft.).[75]

AR4 data do not report the dramatic changes observed in Greenland since 2006. To that time, research revealed a total ice mass loss of about 129 Gt/yr. between 2002 and 2005. The velocity of outlet glaciers had also increased substantially, from an ice flow discharge rate of about 51 Gt/yr. in 1996 to 150 Gt/yr. in 2005. Accelerated ice flow losses also expanded poleward from 60 degrees N to 70 degrees N by 2005. The AR4 also describes how basal meltwater lubricating the base of the ice sheet could increase the "sliding velocity" of the ice as it moves toward the sea.[76] Projected surface MB change on the Greenland ice sheet was estimated at about 0.3 millimeters/year (0.01 in./yr.), lifting sea levels between 0.2 and 3.9 millimeters/year (0.008–0.15 in.), depending on the mitigation scenario.[77]

Research conducted since 2006 has worsened the prognosis for Greenland's ice sheet and its response to and effects on global warming. Increasing

GHG concentrations in the air have raised the surface temperature over Greenland by 3.9°C (7°F) since 1991. The warming's destructive effects on the ice were most thoroughly documented in 2007, when the extent of melt on the ice sheet exceeded the previous 2005 record by 10 percent. Researchers also found that melting is starting earlier in the year, lasting longer, and decimating outlet glaciers at an alarming rate. The huge Jakøbshavn glacier in western Greenland is melting twice as fast as a decade ago, rushing toward the sea at 12 kilometers (7.5 mi.) yearly, or 30–40 meters (98–131 ft.) per day. The melting of this one outlet glacier is typical of numerous others, nearly all of which have increased their flow velocity by 50 percent in the past two to three years.[78]

The higher temperatures that are causing melting at the ice sheet's surface have also been found to cause melting far below, at the base. Advanced satellite analysis, reported by NASA in 2008, showed that the entire glacier is highly sensitive to even minor amounts of surface melting. For example, in 2005 rapid subsurface melting started only 15 days after a small degree of surface melting began. As one researcher explained, "This indicates that the meltwater from the surface must be traveling down to the base of the ice sheet—through over a mile of ice—very rapidly, where its presence allows the ice at the base to slide forward, speeding the flow of outlet glaciers that discharge icebergs and water into the surrounding ocean."[79]

The flow of meltwater from the surface to the base of a glacier creates a "moulin," or river of water flowing downward through the ice to the base of the glacier, where it lubricates the glacier-rock interface and significantly accelerates flow velocity. In recent years, thousands of moulins have formed all over the Greenland ice sheet, "like rivers 10 or 15 meters (33–49 ft.) in diameter" (though some are so large they've been compared to Niagara Falls).[80]

Moulins, and the accelerating thaw of the ice sheet, have generated another very troubling phenomenon: earthquakes. Glacial earthquakes were unknown in Greenland until about three years ago. Today, meltwater from moulins is shearing enormous slabs of ice from the bedrock beneath the ice sheet. These blocks of ice, many more than 800 meters (2,625 ft.) deep and 1,500 meters (4,921 ft.) long, contain immense rocks. As the meltwater slides the rock-toting ice blocks over geologic faults in the bedrock, earthquakes are generated. Many climatologists concur that glacial quakes are ominous signs that an unprecedented change is taking place in the increasingly unstable Greenland ice sheet.[81]

Robert Correll, a contributing scientist to AR4, concurs with the recent scientific consensus that there has been "a significant acceleration in the loss of ice mass . . . since the last [2007 IPCC] report." Massive chunks of ice, some several cubic kilometers in size, are also falling off the ice sheet during the more frequent "ice quakes." Correll explains that "These earthquakes are not dangerous in themselves but [they show] . . . that events are happening far faster than we ever anticipated."[82]

Conditions like these make IPCC predictions outdated. Scientists are now seriously considering a large-scale (or possibly even total) collapse of the Greenland ice sheet, with a concomitant rise in sea level of two meters (6.6 ft.) or more—enough to inundate New York, London, New Orleans, a good deal of Florida, and many other low-lying regions. If the entire ice sheet slips into the North Atlantic, such a massive input of freshwater might weaken (or stop) the NADW and the ocean's THC.

The Albedo Flip Feedback

The AR4 Synthesis Report gives a sea level rise range by 2099 of between 0.18 meters (0.6 ft.) (most aggressive mitigation scenario) and 0.59 meters (2 ft.) (BAU scenario). IPCC scientists qualified these predictions by stating that they do not include "the full effects of changes in ice sheet flow . . . Therefore the upper values of the ranges given are not to be considered upper bounds for sea level rise." The report goes on to say that if ice discharge from Greenland and West Antarctica continues to grow *linearly*, sea levels could be expected to rise an additional 0.1–0.2 meters (0.3–0.6 ft.).[83]

However, some leading climatologists are warning that disintegration of ice sheets under current and future BAU conditions will not be gradual and linear, but will occur in an abrupt, nonlinear flip once a crucial tipping point is passed. This tipping point would come from changes in albedo on the ice sheets. An albedo flip would occur when a large enough surface area on the ice sheet is changed from high-albedo ice to low-albedo melt ponds. The darker, wetter melt ponds would absorb more light and heat, which would melt more ice (both on and below the surface), which would absorb even more heat, which would produce so many moulins and so much basal lubrication that ice melting and discharge into the ocean would speed up exponentially, leading to rapid and irreversible ice sheet disintegration.

The loss of buttressing ice shelves, which are particularly vulnerable to warming air and ocean water, would generate a positive feedback, for as they decline and thin, they provide a wider exit route for melting inland glaciers, which further erode the ice shelves, and so on.

Significant and increasing ice shelf loss is being observed in Greenland and along the WAIS. Satellite data show that the rate of ice mass loss on both major ice sheets has doubled in recent years, a possible indication of irreversible acceleration of the disintegration process.

The current 0.74°C (1.3°F) increase in globally averaged temperature has already caused serious and widespread melting on both major ice sheets. Yet an "optimistic" BAU scenario projects a warming of 3°C (5.4°F) by century's end. What effect would that degree of warming have on the ice sheets and on sea level? To answer this question, scientists have compared near-term global warming projections to the somewhat similar mid-Pliocene (ca. 3.5 mya), when surface temperatures were about 2°–3°C (3.6°–5.4°F) warmer than today and atmospheric CO_2 concentrations ranged from 350–450 ppm. During the Pliocene, ice sheet melting was so extensive that sea levels were about 25 meters (82 ft.) higher than today. A sea level rise of this magnitude would inundate nearly all (if not all) of the world's major ports and coastal areas. In short, the world as we know it would no longer exist.[84]

Albedo flip scientists point out that paleoclimate ice sheet computer models, like those cited by the IPCC, did not incorporate the physics of ice streams, basal lubrication, or ice shelf interactions with the oceans. Absent these key processes, the IPCC projections for sea level rise were too optimistic and reassuring, so policy makers and the public failed to grasp the urgency of the problem. These scientists argue that avoiding irreversible destruction of the ice sheets (and Pliocene-like conditions) requires that GHGs be limited to 450 ppm and global warming be kept at or below 1°C (1.8°F). This would require immediate and dramatic action. As James Hansen, chief NASA climate scientist put it, "[T]he world is getting perilously close to climate changes that could run out of control. . . . Civilization developed during a period of unusual climate stability. . . . That period is about to end." Hansen believes we have about 10 years to institute the measures necessary to avoid the "climatic cataclysm" that an albedo flip could cause.[85]

Oceans: Observed and Projected Changes

The oceans are a vital component of Earth's climate and have three principal effects on it. First, they have an enormous heat capacity (ability to absorb heat), about 1,000 times greater than that of the atmosphere. For that reason, a gargantuan amount of heat is needed to warm the oceans only slightly, and the oceans warm far more slowly than the air. Second, ocean circulation is a major distributor of heat around the planet, so ocean circulation and temperature can have large effects on global or regional climate. Third, the oceans are the main contributors of water vapor to the atmosphere and so have a great influence on precipitation and storms.

Nearly everything that is put into the atmosphere is absorbed by the oceans to some extent. Therefore, most GHGs and the additional heat they produce in the atmosphere are absorbed by surface ocean water. Yet because the ocean warms so slowly, it takes many decades before the planet starts to feel the effects of the heat absorbed by the ocean. This phenomenon, called "ocean masking," has so far hidden the full effects of climate change. For example, the oceans have absorbed more than 80 percent of the warming generated by GHGs since 1955.[86] In the near future, however, the global ocean will begin giving off some of the heat it has absorbed, and the true extent of global warming will no longer be masked, but will be felt in full force.

The AR4 reported an approximate 0.1°C (0.18°F) warming of the global oceans to a depth of about 700 meters (2,297 ft.) between 1961 and 2003. During this period, the heat content of the oceans increased to yield a RF of + 0.21 Wm^{-2}, with 20 times as much heat taken up by the oceans as by air, producing a "significant increasing trend in ocean heat content." Data show that over the past decades the oceans have warmed 0.37°C (0.7°F) to a depth of 3,000 meters (9,842 ft.).[87]

As with other projections, future ocean temperatures depend on how quickly and aggressively humanity addresses global warming. With a "committed" response, global ocean temperatures may rise about 1°C (1.8°F) from 2080 to 2099; under a BAU scenario, ocean temperatures could rise 1.5°–3°C (2.7°–5.4°F) through most of the ocean, though Arctic SST could increase by 7.5°C (13.5°F).[88] (The AR4 did not address the likelihood that frozen methane hydrates beneath the seafloor might thaw and be released into the atmosphere.)

Higher SST will put more water vapor into the atmosphere and intensify the hydrological cycle. Therefore, more powerful storms are predicted and global mean precipitation is expected to increase, albeit variably by region. Both precipitation and soil moisture are expected to increase in higher-latitude regions north and south of the hemispheric jet streams. However, precipitation intensity (very heavy downpours) is expected to increase markedly, though precipitation events will punctuate longer periods of dry weather. The AR4 states that it is *likely* that storms will intensify, with higher winds and more rain. Precipitation and soil moisture are predicted to decline in a wide swath of the globe girding the equator.[89]

As might be expected from the ice data, SSTs in the Arctic and Southern Oceans have also risen. SST in the Southern Ocean has risen 0.3°C (0.54°F) in the last 15 years, raising regional sea level by about two centimeters (0.8 in.).[90] Even the extremely dense and cold bottom waters of the Southern Ocean have warmed steadily by about 0.002°C (0.0036°F) per year over the past 30 years. Mid-depth water (about 900 meters [2,953 ft.]) warmed up to 0.4°C (0.72°F) during the same period. The SST near the West Antarctic Peninsula rose by more than 1°C (1.8°F).[91]

The salinity, or salt content, of the oceans is changing. Between 1995 and 1998, subpolar ocean water became diluted with freshwater (from increased precipitation and melting ice sheets and glaciers). Ocean regions getting less precipitation, such as the Pacific and Indian Oceans, saw their salinity rise. However, the North Atlantic is not only becoming less saline, it is also warming to depths 1,000 meters (3,281 ft.) deeper than any other ocean. The warmer water was particularly pronounced under the Gulf Stream and in the region of the NADW. The AR4 notes a "marked freshening" of the waters exiting the Arctic and entering the NADW. Though water transport through the NADW has declined 30 percent since 1957, there is still too little evidence to support a direct effect on the THC/MOC.[92]

The AR4 predicts that during the 21st century it is *very likely* that the THC/MOC will slow down. Studies project a further slowdown of 25 to 50 percent between 2080 and 2099. Though the AR4 states that it is *very unlikely* that the THC/MOC will undergo a large, abrupt transition during the 21st century, the uncertainties surrounding the fate of the Greenland ice sheet have not been factored into this prediction.[93] Scientists stress that though there is great uncertainty regarding the fate of the THC/MOC and that the signs of a collapse may be too subtle to detect easily, this should not be a cause for complacency. They suggest that there might be a substantial delay between the initial triggering of a THC/MOC collapse and the actual collapse.

Global sea levels are rising. Two factors are responsible for this: the addition of water to the ocean from melting ice sheets and glaciers and the thermal expansion of ocean water. As substances heat up, they expand (their molecules become more active and move farther apart). This is as true of ocean water as it is of just about all other substances. The AR4 reported that during the 20th century, average global sea level rose 1.7 millimeters/year (0.07 in.), with 25 percent of that rise coming from thermal expansion. Between 1993 and 2003, the rate of sea level rise had increased to three millimeters/year (0.12 in.), with fully half attributable to thermal expansion of ocean water.[94]

Based on AR4 data, sea levels could rise between 200–500 millimeters (7.8–19.6 in.) by 2100. As much as 75 percent of sea level rise by 2099 is expected to come from thermal expansion.[95] However, the AR4 did not take into account accelerated melting of ice sheets and glaciers. If these ice masses melt, sea levels are expected to rise several meters, far above the levels projected by AR4. Recent paleoclimate research points to a more drastic sea level rise. One study of the last interglacial period (100 kya) showed that sea levels then rose six meters (20 ft.) above current levels and suggests that we will approach similar conditions of warming within 50 to 100 years.[96] Scientists studying the interglacial period before that one came to the same conclusions and predicted a similar rise in sea levels.[97]

Another property of the oceans is probably a familiar one. Most people know that a can of warm soda contains a lot less fizz than a can of ice-cold soda. Soda fizz is CO_2, and cold water holds a lot more of it than warm water. So as ocean water warms it will begin to give back some of the CO_2 it has absorbed. As that CO_2 enters the air it will further enhance climate warming. A 2007 study of a 360,000-year-old Antarctic ice core revealed that greenhouse warming is exacerbated by outgassing of CO_2 from the oceans. Based on the paleoclimate data, the researchers expect global temperatures to increase more than predicted by 2100, with about 2°C (3.6°F) of that additional warming coming primarily from the oceans. Once outgassing from the oceans begins, a positive feedback is created in which climate warming and outgassing of CO_2 reinforce each other.[98]

The amount of CO_2 absorbed by the ocean is related to the amount of CO_2 in the atmosphere. Through the 1990s, the oceans took up about 2.2Gt/yr. of anthropogenic CO_2. Though more than half of this CO_2 has remained in the upper 400 meters (1,312 ft.) of the ocean, some recent studies have detected anthropogenic CO_2 to depths of 1,100 meters (3,609 ft.) in the North Pacific, 1,200 meters (3,937 ft.) in the Indian Ocean, and 1,900 meters (6,234 ft.) in the Southern Ocean.[99]

The depth to which anthropogenic CO_2 has penetrated oceans is troubling because it underscores how much CO_2 people are emitting. However, to some extent it is reassuring to know that the oceans have been doing their job as the world's major carbon sink. Unfortunately, the ocean's ability to absorb and store our atmospheric fizz may be weakening as ocean water reaches its saturation point. The results of a major, four-year study, released in 2007, show that the Southern Ocean, the strongest oceanic carbon sink, has reached its saturation point and is starting to release its store of CO_2 The Southern Ocean's absorption of CO_2 has decreased each decade since 1981, even though human emissions increased 40 percent during this period. It seems that global warming has increased westerly winds over the ocean, and the winds are churning up the water and bringing CO_2 from the depths to the increasingly saturated surface. The more the climate warms, the stronger the winds, the more saturated the ocean surface becomes, and the less CO_2 it absorbs from the air. It is a classic positive feedback cycle. "Oceans ought to be able to absorb CO_2 for hundreds of years into the future before becoming saturated. This was not something that should be happening," one researcher commented.[100]

Overall, oceanic uptake of anthropogenic CO_2 has declined. Between 1750 and 1994, the world's oceans absorbed about 283 GtC, or about 42 percent of total GHG emissions. For the period 1980 to 2005, ocean absorption fell to 143 GtC, or about 37 percent of total GHG emissions.[101]

OCEAN ACIDIFICATION

Perhaps the most worrying and immediate change in the oceans resulting from CO_2 emissions is a significant reduction in the pH of ocean water. The pH scale shows the relative acidity or alkalinity of a substance. A substance such as pure water, which is neither an acid nor a base, has a neutral pH of 7.0. The lower the pH, the more acid a substance is (e.g., sulfuric acid has a pH of about 2); the higher the pH, the more basic, or alkaline, a substance is (e.g., lye has a pH of about 13).

When CO_2 enters ocean water, it becomes part of a series of chemical reactions, one of whose end products is carbonic acid (H_2CO_3). Under normal circumstances (when the ocean is not absorbing huge additional amounts of CO_2), ocean water is able to buffer the CO_2 so it does not form too much acid. Instead, the ocean's carbonate buffer causes hydrogen ions (H^+) to react with the carbonate (CO_3) in ocean water to form bicarbonate (HCO_3), a base. But the more CO_2 the ocean absorbs, the weaker the carbonate buffer becomes. Today, absorption of vast quantities of CO_2 has weakened the buffer so much that, instead of forming bicarbonate, the CO_2 instead breaks down carbonate to form more carbonic acid; thus, the amount of carbonate in ocean water declines as the amount of CO_2 and carbonic acid increase. Globally, the surface ocean has a pH of 8.2 (though this varies somewhat by region). Scientists have already detected a 0.1 reduction in ocean pH below preindustrial levels. The pH scale is logarithmic, so this translates into a 30 percent increase in the acidity of ocean water.[102]

The acidification of the ocean is having profound effects on the marine environment—none of them good. Research has shown that marine organisms that form calcium carbonate ($CaCO_3$) shells are having a much harder time accomplishing this feat because far less carbonate is available to them. Many of these organisms form the base of the marine food chain (e.g., shell-forming plankton, foraminifera). If these species die out due to lack of $CaCO_3$, entire marine food chains could collapse. As marine food chains are disrupted and shortened, scientists expect a few invertebrate species to dominate the marine environment. Jellyfish, particularly, are expected to swarm the oceans, and recent jellyfish population explosions seem to be supporting this prediction.

Higher SSTs have also strengthened the vertical stratification (layering) of ocean water and reduced mixing between layers. This tends to keep most

of the carbonic acid in surface layers, but it also prevents carbonate from sinking to depths where deep-sea organisms live and form their protective shells. So, deep-sea food chains are disrupted as well.

To add insult to injury, greater levels of acid in seawater are beginning to eat away at (erode or dissolve) the $CaCO_3$ shells already protecting shelled organisms. Detailed studies show that the greater concentration of carbonic acid in ocean water is pitting and even cracking the shells of marine organisms.

Some of the most devastating effects of ocean acidification have been observed in coral. Coral animals (polyps) form their cocoons, and thus their reefs, out of a type of $CaCO_3$. An estimated 25 percent of all marine fish species (1.9 million species, many an important human food source) rely on coral reefs for at least some part of their life cycle. Corals, therefore, are not only suffering from coral bleaching (loss of symbiotic algae) and die off due to higher SSTs, they are now facing ruin from a dire lack of carbonate. Worse, many marine organisms that live among coral, such as parrotfish and sponges, nibble on the coral for food or as they seek a protective hideout in the reef. So corals must have a constant supply of $CaCO_3$ not only for growth but just to maintain themselves.

Experts estimate that hundreds of millions of people rely on coral reefs for food; billions of dollars in commercially valuable fish depend on reefs or may be severely harmed by ecosystem collapse due to ocean acidification. The acidification caused by CO_2 emissions may destroy the living ocean as we know it for thousands of years to come. Ocean surface pH has been 8.2 for the last 44 million years, yet a doubling of CO_2 emissions (about 560 ppm) could decrease ocean pH by 0.5 units by 2100, and this rate of change is at least 100 times faster than that found in the paleoclimate record. The last time acidification on this scale occurred (about 65 mya) it took more than 2 million years for corals and other marine organisms to recover; some scientists today believe, optimistically, that it could take tens of thousands of years for the ocean to regain the chemistry it had in preindustrial times.[103]

Many scientists had viewed the oceans as a long-term sink for anthropogenic carbon. They assumed that, as in normal (nonacidic) conditions, once shelled organisms died their carbon-based shells would sink to the seafloor where the carbon would be sequestered for millennia in sediment. This process is called the biological pump that sequesters carbon in deep-sea sediment. If shelled marine organisms can no longer make shells out of our emitted carbon, or if most or all of them become extinct, the oceans can no longer be viewed as a viable carbon sink.

The prospect of an acidified ocean is so grim, one scientist testified before Congress that the only "appropriate [emissions] stabilization target for CO_2 is . . . zero." He stated flatly that unless zero emissions are achieved quickly, ocean pH could fall to 7.7 by 2100—an acidic condition not seen in 300 million years. If we don't drastically cut CO_2 emissions, according to another researcher, there may be "no place in the future oceans for many of the species and ecosystems we know today. . . . [I]n the end we will have the rise of slime . . . the reign of the jellyfish." One scientist urged, "I can't really stress it in words strong enough. It's a do-or-die situation."[104]

ADAPTATION AND MITIGATION

Adaptation

Adaptation refers to those measures that humankind can take to adjust to the changes that global warming will inevitably bring. Even if we cut CO_2 emissions to zero by tomorrow, there is still so much CO_2 in the atmosphere (and oceans) that climate changes currently in the pipeline will affect our lives. If we anticipate these inevitable changes and implement the adaptations needed to address them, their impact can be lessened. These adaptations include strengthening transportation infrastructure and buildings, constructing flood barriers for major coasts and coastal cities, restructuring water supply systems for conservation, overhauling agriculture to conform to new climate conditions, and establishing a nationwide disaster and health-emergency system.

Of course, implementing adaptive measures is expensive. Some skeptics oppose these expenditures because they address predictable but uncertain disasters. We may get lucky and that monster hurricane may swerve away from us. The problem is that though it may not clobber us this year, as climate change intensifies, we will surely be affected by disasters and altered climate conditions sooner or later. Studies have shown that it is far more cost effective to spend money on prevention (adaptation) before disaster strikes than after it. For example, some cities at risk of flooding decided to severely restrict development on floodplains. The cost of creating and maintaining the flood-prevention program was $1.3 million; the amount the cities saved in property damage was estimated at $11 million.[105] Some forms of adaptation, such as preservation of coastal wetlands and forests, cost nothing.

The principal problem the world faces regarding adaptation revolves around its cost and who foots the bill. Developed nations have the money to implement even the most expensive adaptive measures (assuming they choose to do so) to safeguard their land and people. Poor, developing countries, which are expected to suffer the most severe effects of climate change, cannot afford the needed adaptations.

Many experts contend that it is in the interest of rich nations to help poor nations with adaptation. The humanitarian reason is obvious, but self-interest is also a factor, as aiding developing nations is likely to reduce the number of environmental refugees that climate change could create. For example, a recent report on the effects of climate change in the Near East projects a significant decrease in precipitation, crop losses of 20–35 percent, severe water shortages, and around a 2.5 percent reduction in GDP (gross domestic product) in the region. Combined, these factors could create 250–500 million refugees.[106] The European Union (EU) is aware of the refugee problem this could cause, so member nations are formulating plans to aid these and other developing nations with adaptation measures.

Wealthy nations are analyzing the costs and benefits of implementing adaptive measures domestically. Nearly all developed countries are also attempting to determine the extent to which they are willing to help pay for adaptations needed by poor, developing countries. Some monetary commitments have been made, but they are inadequate. Negotiations are ongoing.

Mitigation

Mitigation refers to steps taken to reduce GHG emissions now and in the future to prevent a drastic and irreversible climate shift. Mitigation entails replacing fossil fuels with renewable energy sources (solar thermal and photovoltaics, wind, geothermal, tidal, ocean wave, biomass and alternative liquid fuels, etc.). It also involves making every aspect of our lives more energy efficient so we use less fuel (e.g., superinsulating existing buildings, requiring new buildings to be superinsulated, driving plug-in hybrid or alternative fuel motor vehicles, creating and encouraging the use of mass transit, buying locally grown food, etc.). Mitigation can be undertaken at every level of society, from individuals to communities to nations. However, if it is to halt or reverse climate change, mitigation requires a coordinated, global commitment. Climate experts strongly recommend that GHG emissions be reduced to keep CO_2 concentrations at or below 450 ppm with a 1°C (1.8°F) temperature rise; if that goal is by now unattainable, they insist that emissions be held to 550 ppm with a temperature increase of no more than 2°C (3.6°F). Beyond these limits, so many positive climate feedbacks will likely kick in and so many tipping points may be passed that climate change may well run out of control. Achieving these targets requires developed nations to cut GHG emissions by about 80 percent (or more) by 2030 and requires industrializing nations such as China and India to align their emissions accordingly.

The world runs on fossil fuels, and an 80 percent cut in their use will have dramatic effects on every aspect of life. That's why the concept of mitigation tends to make people nervous: it requires changes in lifestyle and, most likely, in some social values; and it will be very expensive (at least initially). Yet as we work our way toward an 80 percent—or optimally a 100 percent—reduction in GHGs, we can implement technologies that are available today to reduce our GHG emissions to below 1970 levels in just a few years. Two Princeton University scientists created a "stabilization wedge" that shows that currently available technologies and lifestyle changes can significantly reduce GHG emissions. Many of the measures they suggest can be implemented for little or no cost. In fact, some GHG reduction measures actually save money (have net negative cost) and help cancel out the costs of more expensive measures. Effective mitigation must involve every sector of society, but a viable and aggressive national energy policy must underpin the entire enterprise if it is to succeed.

COSTS

There is no doubt that weaning the world off fossil fuels will be very costly. Before governments shell out trillions of dollars on mitigation, policy makers have to know that the cost of mitigation is worth it. So economists apply a cost-benefit analysis to the fate of the planet. They ask, is the cost of mitigation less than the cost of doing nothing? Or, do the benefits of avoiding climate catastrophe outweigh the costs entailed in preventing it? For many, the answer is obvious.

The Stern Review on the Economics of Climate Change, produced by Sir Nicholas Stern, Head of the UK Government Economic Service, is a major study of the economics of mitigation. Most of its calculations are based on a BAU, or near-worst-case scenario, for GHG emissions and climate change with positive feedbacks. According to the report, the disastrous impacts of ignoring mitigation in a BAU scenario would reduce the global per capita welfare of and consumption by each individual by 5–20 percent. The overall cost of doing nothing is estimated to be 5–10 percent of global GDP (due to damage or destruction of infrastructure and its effects on the economy, human health, loss of ecosystem services, etc.). However, policies to curb GHG emissions to 500–550 ppm (CO_2-eq) would involve expenditures that lower GDP only 1 percent per year by 2050. This 1 percent reduction would come from investments in new infrastructure, urban redesign, mass transit, new types of transportation and fuels, energy-efficient buildings (new or retrofitted), renewable energy, energy and water conservation programs, reducing the demand for energy-intensive goods, sharply cutting the energy used by industry to manufacture goods, and other energy efficiency programs in all sectors of society. So called "no regrets" policies, such as avoiding deforestation, indirectly cut emissions and generally have zero cost.[107]

Some economists have criticized *The Stern Review* for being too pessimistic in its climate projections, yet most concur that the costs of doing nothing far outweigh the costs of mitigation. One study projected a cost of 16 percent of global GDP by 2300 if temperatures rise about 10°C (18°F), as compared with a 2 percent of GDP cost for mitigation to avoid the consequences of such drastic climate change. Another study calculates a cost of less than 1 percent of GDP for mitigation that would halve GHG emissions. Further emissions cuts, to 70 percent or more by 2100, would cost about 2.5–3.5 percent of GDP. However, this figure includes neither alternative energies that will take over the role in energy production once held by fossil fuels nor increases in the cost of carbon (e.g., gasoline, heating oil).[108] If alternative energy sources are brought on line and crude oil prices continue to rise (as expected), mitigation causes less of a decline in GDP. The AR4 estimates that stabilizing GHG emissions below 530 ppm (CO_2-eq) would result in a global annual GDP decrease of about 0.12 percent, with about 2.5°C (4.5°F) of warming; keeping emissions at 590–710 ppm (CO_2-eq) would reduce global annual GDP by only 0.06 percent, but raise globally averaged temperatures by 3°–4°C (5.4°–7.2°F).[109]

It is important to note that in some economic analyses the estimates of declining GDP during mitigation are exaggerated because they omit two vital factors: the price of fossil fuels and job creation. The higher the market price for fossil fuels, the more cost effective mitigation becomes. As oil prices skyrocket, money drains out of every sector of society and GDP falters. And in every nation on Earth, workers will be needed to rebuild infrastructure and create new forms of transport; to retrofit and insulate buildings; to design, build, and maintain alternative energy projects; to rebuild and maintain a new, efficient electric grid, and so on. In 2007, the UN and the International Labour Organization (ILO) released a report estimating that tens of millions of "green jobs" would be created through mitigation programs. In the United States alone, 5.3 million well-paying jobs—that cannot be outsourced—would be created. One U.S economist said about the report, "Added together, we are clearly on the edge of something quite exciting and transformational." But he added that the "right government signals" and policies are needed to realize this transformation.[110]

A Sustainable Future

Is it possible for people to live in fossil-fuel-free, zero-carbon societies? The answer is a resounding "yes." Alternative energies, particularly solar and wind, have the potential to power world economies for generations to come. In fact, solar power alone can provide nearly *four times* the amount of energy the world will need by 2030 (including economic growth).

It is true that realizing a zero-carbon lifestyle will entail some changes. Even as our lives are powered increasingly by electricity derived from renewable sources, some things will change. The government must either tax CO_2 or cap emissions by auctioning ever fewer emissions permits in order to make using carbon-based energy less attractive and more expensive. As the cost of carbon increases, the market will seek and use less expensive, alternative energy sources. Government should also provide subsidies, tax breaks, and other incentives to help individuals and businesses make the transition to alternative energy and help finance construction of a new alternative energy infrastructure.

Individuals must be given incentives to encourage them to drive plug-in hybrid cars and drive less, use energy-efficient lightbulbs and appliances, insulate their homes, upgrade to energy-efficient heating systems, and fly less often. People can also reduce emissions by limiting the amount of meat they eat: producing 1 kilogram (2.2 lb.) of meat emits 36.4 kg CO_2-eq, and 4.5 kilograms (10 lbs.) of plants are needed to make 0.45 kilograms (1 lb.) of meat.[111] People can also reinvigorate their communities by buying locally grown food and other local products, thus avoiding the emissions associated with long-distance transport. Finally—and controversially—people should reconsider their role as consumers. Every object a person buys is produced using some amount of fossil fuels, so at least until modern life is powered by renewable energy, individuals should try to consume less and reuse and recycle more. These lifestyle changes are especially important now, while humanity is reducing GHG emissions as much as possible, year by year.

Some people feel that we are living in dangerous and depressing times, burdened by overwhelming challenges. It is true that the challenges climate change poses are enormous. But accepting the challenges and acting to meet and overcome them also means that we are living in very exciting times. Smart and creative people the world over are developing new technologies to tackle global warming. An Indian car company soon expects to mass-produce cars that run on compressed air and cost about $5,000; prototypes are already on the road. An Idaho company's research has shown how roads and highways could be embedded with solar PV (photovoltaic) cells to meet all U.S. electricity demand; strengthening the solar cells to withstand the wear and tear of traffic is still in the works, but it's a great idea that may one day be realized. One solar energy company is perfecting a method of printing solar components onto thin film using an ink-jet printer; eventually, solar

PV may be cheaper than electricity today. The United States could derive all its energy needs from concentrating solar power (CSP) installations in the Southwest alone. Scientists in Europe have shown how large-scale CSP installations in the Sahara could power all of Europe and a more highly developed Africa. The Arabian Desert could do the same for the Near and Middle East. Advances in electricity transmission and storage make these concentrated sites of electricity production viable.

Some new technologies await improvements. For example, the global push to reduce gasoline use by replacing it with plant-based ethanol sounded like a great idea. Now we are finding that mass production of palm oil for ethanol is destroying rain forests; producing corn-based ethanol adds more GHGs to the air than it saves. And planting vast agricultural tracts for ethanol production is leading to food shortages and sharply rising food prices around the world. So, should ethanol and other gas substitutes be abandoned? Not according to researchers who are using bacteria and algae to break down a host of waste materials—including old tires—to make ethanol or similar nonpolluting fuels.

Another promising avenue of research is seeking ways to capture carbon emissions or remove CO_2 from the air. One New York–based firm has devised a means of turning captured CO_2 emissions into plastic. U.S. chemists have created an entirely new class of porous materials, called ZIFs (zeolitic imidazolate frameworks), that can capture and retain large amounts of CO_2. One liter of ZIFs can store 83 liters (22 gal.) of CO_2. These materials may be vital in capturing CO_2 as we phase out coal-burning power plants.

Some economists have worried that climate change may affect globalization, which relies on cheap transportation. The era of cheap transport may be coming to an end as the monetary and environmental costs of fossil fuels rise. Recently, though, innovators have built ships that are fitted with high-tech sails, which greatly reduce the amount of fossil fuel that needs to be burned. Early models sported single sails, but engineers are working on ships wholly powered by a computer-controlled array of sails. One shipbuilding enterprise is building prototype ships that are powered by wave action.

Yet more is needed. At a recent climate change conference, many scientists stated that the most important thing an individual can do to curb climate change is to vote for leaders who understand the challenge of climate change and will take aggressive measures to combat it.

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