CHAPTER 1

Global Climate, 2100 AD

First, I worry about climate change. It's the only thing that I believe has the power to fundamentally end the march of civilization as we know it, and make a lot of the other efforts that we're making irrelevant and impossible.

—President Bill Clinton, World Economic Forum at Davos, Switzerland (January 31, 2006)

This chapter depicts the dangerous and often terrifying ways in which a new and hotter climate will manifest itself, from North America to Africa, Asia, and the islands of Oceania.

Where We're Heading, Once and for All

Prepare yourself for some bad news. I promise I'll try to make it brief. I'm going to take you on a whirlwind tour to see what our world will be like in less than 90 years, if present climate abuse continues and greenhouse gas emissions thus continue their current growth. This scenario not only could really happen; in some respects it has already begun, and we are now in its early stages.

Some may view this forecast as alarmist, because the temperature increases that underlie it are toward the high end of the range of those expected, but as you will learn later in the book (chapters 4 and 6), some temperature projections are even higher, and the climate impacts may well be compounded by rapid global population growth as well as by the human health effects, wars, and other social conflicts discussed in chapter 8.

So your life may still seem normal now, or not, but rapid climate change is already altering the world in ways that are truly alarming. Long before 2100 AD, it will profoundly affect our health, our homes, our businesses, and our farms, as well as our water, power, and transportation systems. Calling attention to the real dangers now is both a moral obligation and an essential part of the struggle to avert these consequences (not to be confused with alarmism).

The impacts of climate channge are not limited to easily recognized extreme weather events, such as floods, hurricanes, tornadoes, or droughts—deadly and expensive as those events are. The impacts also include other dire consequences:

- Heat waves
- Dying forests
- Abnormally large wildfires
- Habitat destruction
- Accelerating rates of extinction
- Altered seasons and disruption of normal seasonal ecological relationships
- Invasive species encroaching deeper into once-intact ecosystems
- Lethal diseases fanning out from the tropics
- Island nations about to be obliterated
- Disappearing sea ice and glaciers
- Rising seas
- Acidifying oceans
- Declining ocean plankton
- Melting permafrost and Arctic wetlands

These phenomena are undeniable, although their causes are still disputed by climate science deniers. During our imaginary "visit to the future," we will glimpse how these dangerous and seemingly isolated climate changes collectively threaten our future welfare and survival. By the time you complete this book, I hope you will understand why and how all these effects are indeed a result of "manmade" climate change.

Current climate change trends reveal that the world is almost certainly going to surpass an average warming of 3.6°F (2°C), probably in about 40 years or so, on its way to *much* higher temperatures. While at first 3.6°F may not sound like much, it is nonetheless about two and a half times the warming that the Earth has already experienced since preindustrial times.[a] For the past two decades, this 3.6°F has been the amount of warming that most scientists and policymakers had regarded as the upper safe boundary between acceptable and dangerous climate change.

In a colossal global policy failure, however, the leading nations of the world over those same 20 years have failed in many rounds of international negotiations to stabilize or bring down global carbon dioxide emissions. Now, however, over the past decade, astonishing and alarming global climate changes have already begun in response to only 1.4°F of average global surface temperature warming. Thus, 3.6°F of warming—rather than a safety threshold—is a nebulous transition zone between highly dangerous and extremely dangerous climate change.[1]

Carbon Dioxide, a Tenacious Gas

To those who are new to climate studies, it may come as a shock that the major climate change that has now begun is largely irreversible with current technology. Contrary to popular belief, we cannot just "overshoot" a safe temperature and then, as if with a magic global thermostat, somehow turn the heat down to normal again. Once we "overshoot," we are in effect stranded at the new equilibrium temperature. The climate would remain overheated because of the long-lived heat-trapping gases with which we have overloaded the atmosphere.

Despite widespread misconceptions, carbon dioxide, the principal long-lived heat-trapping gas, does not disappear within hundreds of years, which would be bad enough. In fact, a substantial portion of the carbon dioxide remains in the atmosphere for thousands of years.[2] Through our emissions from industrial pollution, transportation, agriculture, and deforestation, we have in effect created a new world atmosphere. It will take millennia for Earth's natural carbon-removal processes to fully reabsorb those gases from the atmosphere.

Only if we could extract the extra heat-trapping gas from the air could we restore a semblance of our previous climate. However, we would have to extract a great deal (hundreds of billions of tons), and the climate would

[a] The onset of the modern industrial era is generally viewed as coinciding with the start of the Industrial Revolution in England at about 1760. (It was marked by a shift from the use of wood to greater reliance on coal and by the use of machinery in manufacturing, as well as by improvements in the efficiency of steam engines, and by technological advances in important industries.)

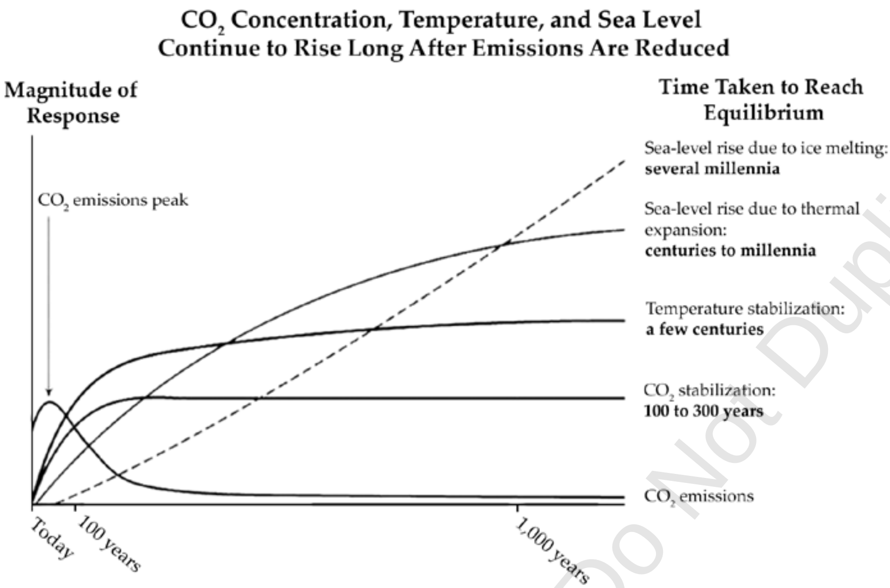

FIGURE 1-1. This diagram illustrates that even after carbon dioxide emissions peak and begin declining, carbon dioxide concentrations, global temperatures, and sea level all continue rising toward new elevated equilibrium conditions over periods ranging from centuries to millennia. Note that although carbon dioxide emissions fall quickly and steeply on the diagram, the excess carbon dioxide humanity added to the atmosphere remains there and thus temperature remains elevated instead of returning to normal preindustrial levels. Source: Taroh Matsunos et al., 2012. © 2012 The Japan Academy.[3]

respond very slowly.[b] But unfortunately, we currently have no quick, affordable way to scrub vast amounts of carbon out of the atmosphere. So the really bad news is that, because of the properties of long-lived global heating gases, whatever peak temperature we reach as a result of having added them to the atmosphere will be Earth's new temperature for a long, long time. That makes it imperative for us to reduce our emissions as much as possible and as quickly as possible. The longer we delay this process, the larger the emission reductions we'll have to make in the future to achieve the same result.

Now you understand the severity and finality of climate change. It has no quick fix. A realistic understanding of the problem is necessary, however, if we are to limit climate damage. Realism is preferable to illusions and false optimism.

The good news is that knowledge about the risks created by our present climate policies, or more properly, by their inadequacy, is spreading rapidly

[b] See www.trillionthton.org for current cumulative human-induced releases of carbon dioxide.

throughout the world. If enough people understand them, there is a chance that we may yet adopt climate policies that bring prompt, deep reductions in emissions.

The technology to constrain emissions is definitely here, and the world definitely has the resources to tackle the challenge. Many cities and states, for example, have already set ambitious carbon dioxide reduction targets, and some regions have set up multistate and international carbon exchanges. The Federal government is tightening energy efficiency standards and fuel efficiency standards for vehicles while moving to regulate carbon pollution from power plants for the first time.[c] To see why we must do far more, however, join me now for an imaginary journey into the future to see the havoc that will be produced by the current laissez-faire global climate policy. In the absence of an enforceable international climate treaty with a commonly agreed-upon global emissions reduction target, each nation will decide for itself how much carbon pollution it wants to release.

2100 AD

Suppose today is August 1, 2100. The world's average temperature has risen more than 10°F.[4] That's an awful lot. Some climate models project that, with business as usual (that is, with no meaningful international effort to curb the rise in global emissions), temperature might be up only 7°F by 2100. But that would be extremely damaging, too.

Because most of the planet is covered by oceans, which on the average are cooler than the land, when the world's average temperature goes up 1°F, the average temperature over land will rise about 1.5°F in the early stages of warming. Toward the interior of continents, it will go up about 2°F.

The tremendous 10°F average planetary temperature increase, or the very large temperature increase of 7°F, would also be magnified two or three times in the Arctic. Temperatures in the high Arctic, including parts of Alaska, Canada, and Greenland, might thus have risen as much as 14 to 20°F. Moreover, these temperatures would not be final but transitional (as will be further explained in chapter 3) on their way to even higher temperatures. Again, that's because of the long-lived atmospheric residence time of carbon dioxide and some other greenhouse gases.

[c] See President Obama's climate change speech at Georgetown University on June 26, 2013, and the Administration's June 2013 Climate Action Plan.

The Great Melting

Let's now consider climate changes that we could see by 2100 if the warming continues to accelerate as forecast in response to continued increases in carbon pollution. The changes may initially seem remote to your daily life if you live in a city in the temperate zone, but as we proceed from considering the remote polar regions of the Earth to the middle latitudes, you will see how these changes will adversely impact us all.

By 2100, the Arctic Ocean is virtually ice-free. That amplifies global warming, because the reflective ice is replaced by darker water, which absorbs more heat. Without the ice, walruses are virtually gone. The huge shoals of shrimp-like krill that swarmed and bred beneath the margins of the ice shelves are gone. The whales that strained tons of krill have starved. So have the krill-eating fish and seals that had eaten the fish—and that needed ice during breeding and pupping season. Polar bears that depended on the seals and that bore their young on ice have become very scarce. A small population remains on land where they interbred with grizzlies.

FIGURE 1-2. Polar bears on a melting ice floe in Canada's Beaufort Sea in August 2004. Credit: Dan Crosbie, Environment Canada.

The Marine Food Web

Floating summer sea ice is coated underneath by a biologically important layer of marine algae. Tiny floating aquatic organisms called zooplankton feed on the algae. But with the ice gone, they have now lost an important food supply. The summer sea ice also shielded the water from the mixing effects of wind. It thus had protected a layer of warmer surface water that had nurtured microscopic floating plants known as phytoplankton.

These unpresumptuous little organisms didn't get much attention back in 2013. But as they formed the base of the ocean's food web, they were essential to the whole marine food chain. When the ice and its coating of marine algae disappeared, the spring phytoplankton bloom was delayed. That led to a scarcity of zooplankton. In turn, that led to a shortage or disappearance of the young krill and other plankton feeders, such as juvenile marine organisms, including baby fish.

Thus, with the collapse of the Arctic sea ice, the Arctic ecosystem went into a tailspin. The seemingly boundless fisheries became a distant memory. Arctic commercial fishing ended. The Inuit and other native subsistence hunters and fishermen had to give up their traditional lifestyles.

On the other end of the world, the planet's warming affected Antarctica. It had not only melted the floating Arctic sea ice, but as sea level rose, it had elevated the Antarctic ice shelves attached to the shore, while warmer ocean currents melted away at their base. The hinge-like connections between the ice shelves and the shore weakened and then . . . but I'm getting ahead of the story.

Back in 2010, the Antarctic Peninsula had already warmed 4.5°F in only 60 years—more than three times the Earth's average warming.[5] Thus it was far from surprising when, with continued warming of the air and undersea currents, much of the great Ross Ice Shelf—an area the size of France—collapsed in the late twenty-first century.

Although loss of the Ross Ice Shelf didn't raise sea level (its weight was already supported by the sea, displacing an equivalent mass of water), the Ross Ice Shelf nonetheless had served as an ice dam. The dam had helped to hold the Antarctic Ice Cap and its glaciers firmly in place on land. Once the ice shelf collapsed, the flow of ice from Antarctica accelerated. This icy new infusion did raise sea level.

The Responsive Ocean

The trend was ominous because Antarctica contains about nine times as much ice as Greenland. The last time that the Earth had warmed by over

3.6°F—during the Eemian interglacial period, which ended 114,000 years ago—enough ice had melted to lift the sea 13 to 20 feet (4 to 6 meters) higher than at present.[6]

The Greenland Ice Sheet, meanwhile, had not been stable between 2000 and 2100.[d] In 2000 AD, Greenland was losing about 180 billion tons of ice a year.[7] The melting was adding nearly three hundredths of an inch a year to sea level by 2013. Over the next 87 years, however, the loss accelerated greatly. Thousands of billions of tons of Greenland ice melted and cascaded into the ocean. Along with contributions from the West Antarctic Peninsula, further buoyed by the expansion of warmed seawater, average sea level had thus risen four feet by 2100.[8] The elevated oceans were now rising very quickly—almost half a foot every ten years.[9,10]

Sea-level rise is not uniform everywhere. By 2100, some coastal land had subsided, due to the effects of the continuous extraction of groundwater for irrigation.[11] The seas along these coasts were thus even higher, relative to the land, than the global average. The overall resulting net average rise in sea level by 2100 had a catastrophic impact on coastal and near-coastal areas around the world. Simultaneously, the infusion of freshwater from melted ice reduced the ocean's salt content and seawater density.

These changes in seawater chemistry were compounded by a major increase in the concentration of dissolved carbon dioxide in the ocean, increasing an acidification of seawater that had begun in the twentieth century. Whereas the population of the ocean's pervasive floating algae (phytoplankton) had fallen by 40 percent in the late twentieth century, it was now experiencing an even more serious crash. (See chapter 11.) No one really knew at what point their population would stabilize, or how their species composition would change across the ocean in response to the new conditions.

Since, as noted earlier, plankton populations form the base of the ocean's food web, their decline and population disturbance directly jeopardized the ocean's productivity. All plankton feeders were thus adversely affected. Simultaneously, the water's increased acidity interfered with the ability of many plankton feeders, such as oysters, clams, mussels, and crustaceans (like lobsters and shrimp), to accumulate enough calcium to form their shells or, in the case of coral, their skeletons. Thus, the Dungeness crab—once hauled by the millions from the Pacific Ocean of North America—the blue crabs of the Chesapeake

[d] For a current report on the extent of the melting of the Greenland Ice Sheet, see http://nsidc.org/greenland-today.

Bay, and the lobsters of Maine all had now vanished or were rare. Restaurants and seafood consumers noticed. About a billion people worldwide depend directly or indirectly on seafood as an important source of protein, and many millions more depend on seafood or products for their livelihoods.

The same salinity and density changes that devastated plankton and the ocean's food chain also slowed the vast system of currents across the oceans known as the oceanic conveyor belt circulation. That slowdown then reduced the northward transport of heat from the equator by the Gulf Stream. So paradoxically, as the world warmed, Western Europe's climate began to more closely resemble Iceland's. Its agriculture suffered. People noticed that, too, but it was too late.

The Great Parching

In the vast permafrost region of Canada in 2100, scrawny trees tilted at crazy angles in the soft earth. The permafrost that used to underlie their relatively shallow root systems had melted. Some of the northern forests were dry. Some had burned many years ago during exceptionally hot wildfires and were now dead. Others looked tired and sickly. In the highest latitudes, however, more rain and snow had fallen as temperatures rose.

At lower latitudes, most of North and South America, including the entire Amazon Basin and Brazil, however, had become much, much drier. Throughout the world, dry areas in general had become drier. In the United States, droughts had become more frequent in the Midwest, Southwest, and heavily populated parts of the East.[12] Heat waves had become more frequent, prolonged, and ferociously hot. Some areas where a heat wave previously meant a temperature of 100 to 102°F now had heat waves in which the mercury hit 114°F or above.

In the southern and blistering southwestern United States, important rivers had simply vanished in the intense summer heat, unable to keep pace with greater evaporation and ever-increasing demands from farms, suburbs, and cities. Backup water supplies over-pumped from the ground had by now failed. Long before the wells went dry, however, groundwater tables had dropped far beneath the root zones for many plants, creating patches of desert within arid landscapes or expanding existing deserts.

Drought, Food, and Hunger

Desperate municipalities, meanwhile, had applied relentless pressure on agricultural water users to give up their scant irrigation water supplies.

Agriculture in early twenty-first-century America had typically consumed about 90 percent of all water used. Agricultural counties in 2100 regretted not having set up groundwater management districts in the early twenty-first century to apportion their scarce water resources in a more rational manner. Instead, the famous "Tragedy of the Commons," described by twentieth-century ecologist Garrett Hardin, had come to pass.[13] Each groundwater user had basically grabbed as much water access as he could. That seemed to maximize each person's share, short-term, but hastened the demise of the unmanaged common groundwater basins. So everyone lost out.

With water so scarce and costly, many farms over the past decades had first fallowed their fields and, when the rains failed, had finally gone out of business. Then food prices had shot up. Farm workers had been thrown out of work. Manufacturers and farm equipment dealers had had to cut back. At the same time, businesses built around commerce in feed, seed, fertilizer, agricultural chemicals, and crops had all withered. Real estate prices had slumped. Many people simply left the region. Farm economies unraveled.

As portions of the South had become too hot or dry for corn and soybeans, the remaining farmers had shifted to crops that could still survive. But pastures and rangeland dried out. A lot of livestock died. The United States was now forced to bid for corn and soybeans on world markets to keep food affordable. But importing food had become difficult. Few nations had crop surpluses. Climate change had made the global climate more variable and thus harder for farmers to anticipate. Moreover, when enough rain fell to produce crops, the heat reduced yields.

China, India, and other ever-hungrier and more desperate nations bid heavily against the United States for food. World grain prices skyrocketed. Malnutrition increased in hard-hit, drought-stricken areas, including southern and central Africa, Southeast Asia, Australia, and southern Europe. Due to the high food prices, water shortages, and widespread poverty, food and water riots were common. Governments now rose or fell in tandem with their ability to keep people fed and quench their thirst. Roughly 30 percent of the world's land area was afflicted with some degree of drought at any given time in 2100. Livestock and chickens that once gorged on cheap corn, sorghum, and soy had become luxuries. The price of milk and baked goods, too, was far beyond the means of many low-income people.

In the United States, drier summers and scarce runoff in the Great Lakes Basin had brought water levels down. Sunken deeply, the Great Lakes were discolored by greenish-yellow algal blooms. Inflow to the St. Lawrence

Seaway had dwindled, making navigation difficult. The twentieth century's ambitious and expensive efforts to restore the Great Lakes had been abandoned years earlier because of droughts and because the nation was coping with even more serious problems.

Urban Defense

Tremendous changes had occurred along the coastlines of Connecticut, Delaware, the District of Columbia, Maryland, New York, New Jersey, Virginia, and Rhode Island. By 2100, massive new seawalls and breakwaters had sprouted around many urban centers in that northeastern corridor. Long convoys of large trucks were still supplying these huge construction sites on a daily basis with many tons of rock and cement. Many less important populated areas had simply been abandoned to the ocean and were now under water.

Superstorm Sandy in 2012 proved to be a foretaste of the large hurricanes that came with increasing frequency in the decades that followed.[e] With average sea level elevated by more than three feet,[f] 3 percent of Boston was below sea level along with 7 percent of both New York City and Jacksonville, Florida.[14] Nine percent of Norfolk, Virginia—subsiding anyway[g]—was now under water.[15] The situation was much worse in Florida where 15 percent of Tampa and 18 percent of Miami were submerged.[16]

Miami's plight was complicated by the fact that the city reposes on porous carbonate rock. As the Atlantic Ocean rose ever-higher, the carbonate filled with seawater below ground like a sponge. The ocean then bubbled up through basements, streets, and parks.[17] It was, of course, impossible and prohibitively expensive to entirely protect all these areas from the ocean.[h] The tip of Florida, for example, was entirely submerged. More than nine-tenths of New Orleans was below sea level.

[e] Hurricane Sandy, in the fall of 2012, took more than a hundred American lives, destroyed homes and businesses, crippled transportation systems, caused tens of billions of dollars in damage, and brought power outages and fuel shortages to millions. The storm was remarkable for its size, extending from the Carolinas to Maine and from New York to Michigan.

[f] Some experts project five feet or more (see reference 12).

[g] It sits on the impact crater that formed Chesapeake Bay 35 million years ago.

[h] To eliminate storm surges, the wall would need to be close to 20 feet high, and it would cut people off from sight of and access to the ocean, something few residents would countenance.

Blemishes on the Big Apple

In 2012, New York was one of the world's wealthiest cities, a showcase of urban luxury and sophistication, an entertainment and media powerhouse, a center of global finance and trade. Thus, the city had a lot to lose from sea-level rise, including two trillion dollars in coastal property.[18] It tried its best to fend off the sea.

For decades, despite considerable seawall construction, parts of lower Manhattan and the financial district were repeatedly subjected to major flooding by a series of twenty-first-century hurricanes and floods. Every two years or so it seemed the city would experience severe flooding from what used to be considered "storms of the century."[19]

It wasn't the storms themselves that caused the most havoc, but the towering storm surges that often accompanied them. During Superstorm Sandy in 2012, a storm surge of 14 feet had hit Staten Island. Roughly a century later, the storms were even more powerful and frequent and were rising above greatly elevated seas.

Tunnels for subways and roads connecting Manhattan with Queens, Brooklyn, and New Jersey had proven very vulnerable to flooding. The subways had suffered more than $5 billion in damages from the millions of gallons of corrosive seawater that flooded the system during Superstorm Sandy. Billions more were required in an effort to keep pace with continuing damage from subsequent storms and to stormproof the system. Additional billions were needed to protect low-lying John F. Kennedy International and LaGuardia airports, parts of which had to be abandoned due to flooding.

When mass transit periodically had had to shut down in New York in the mid-twenty-first century, millions were unable to get to work or find fresh food. Many were not able to reach hospitals. Power shortages had complicated the situation. Certain low-income neighborhoods got more than their share of storm surges and transit cutoffs. They deteriorated.

It was gradual at first. Anyone able to leave the low-income areas did so. Finally, with businesses and residents moving out, the remnant neighborhoods degenerated into squalid, impoverished no-man's lands, plagued with crime, decay, and unemployment, sweltering in humid summer temperatures that rarely dipped beneath 100°F for weeks on end. Heavily armed National Guard units were called out frequently, not just to provide disaster relief but to patrol the streets of blighted neighborhoods.

Unfortunately, not all the East Coast's vulnerable fuel depots, chemical plants, nuclear power plants, toxic waste dumps, and landfills had been successfully protected or moved from the coast. So it was in the New York–New Jersey area. With the US economy struggling, industrial facilities in New Jersey and elsewhere were unable to cope with the multibillion dollar costs of decommissioning and relocating or protecting these facilities. Leaks of toxic chemicals at some of these sites became a chronic problem as the seas rose. Caustic and carcinogenic fumes wafted on the wind, and liquids leaked into floodwaters and seeped into the soil.

Finally, in 2070, New York completed its flood-protection system. Years in planning and vastly over budget, the five-mile-long massive outer harbor barrier had huge movable gates that could permit navigation and tidal action when opened but could be shut against onrushing storm surges. The massive barriers did a lot to moderate large storm surges, but some areas still flooded and ghost factories still dotted the shoreline.

Similar scenarios played out in other coastal cities throughout the nation, exhausting their disaster relief funds and emergency response capabilities. Few urban areas, however, could equal the financial resources that New York had mustered to cope with the ocean. Many low-lying urban regions of the United States in 2100 therefore resembled "Third World" countries. The inhospitable new climate was thus not just a stress on natural systems, like forests and wetlands, but also an enemy of social justice, public order, and human progress. Climate change became the consummate destroyer of human hope for a better future.

Of course, the degradation of New York and other great American cities had heavily burdened the US economy. The nation was beset by climate-related woes and was no longer on the path to greater prosperity. Instead, it had grown preoccupied with warding off a climate-related economic contraction.

The national debt had been contracting in the 2050s but, by the later part of the century, it had swollen to unprecedented levels as the nation reeled from climate-related disasters and the ensuing fiscal strain. Simultaneously, the United States was at last belatedly spending heavily on new energy and transportation infrastructure while also trying to extend economic aid to climate-battered developing nations. These "aid" payments, of course, were not exactly altruistic. They resembled climate ransoms paid to recipient nations in exchange for their cooperation in reducing their carbon pollution of the global atmosphere.

Thus, instead of economic optimism and global prosperity, the economic pundits of 2100 talked endlessly and apprehensively about the world's economic future. Their concerns were understandable. Every day the news brought stories of increasing global strife, hunger, instability, and worsening ecological collapse on an overpopulated planet where billions depended precariously at best on a shrinking natural resource base.

Rural Shores

On the outskirts of a typical small town on Nantucket Sound—which had not been protected from the ocean due to the expense—an old road led straight into the water in 2100. Waves covered what used to be the beach, nearby fields, and small near-shore freshwater ponds.

Skeletal remains of shorefront buildings and walls protruded from the surf. A congealed mass of plastic flotsam and jetsam identified the high-water mark. (With a global population of more than 13 billion still using disposable plastic containers and packaging, ocean pollution had by this time reached crisis proportions. But the world now had more pressing concerns than enforcing recycling regulations.)

Over long stretches of the rural New England and Middle Atlantic coast, new high-water marks attested to savage storm surges that had pounded inland across roads and breakwaters far from what was once the coast. Many coastal roads were now elevated onto a system of dikes to withstand further flooding. Utility and rail lines had also been reconstructed farther inland away from treacherous seas. Power poles and pylons leaned crookedly, the ground beneath them waterlogged by intruding seawater.

Wetlands, Bays, and Barrier Isles

At least half of the nation's coastal wetlands had also been flooded by the rising seas. Normally, when seas rise slowly over long time periods, wetland plants in a natural intertidal habitat simply spread inland onto higher ground as their original habitat is drowned by the sea. But in urban areas, roads, levees, and landfills fence wetlands in and trap them in place. The wetlands therefore had shrunk or disappeared beneath the waves.

The wetland loss in turn had helped devastate the fishing industry. More than half of the commercial fish species use wetlands during their life cycle. Fish populations had plummeted by 2100 because of the wetland loss compounded by overfishing and the climate-driven changes in the ocean's salinity, acidity, temperature, and currents.

In Chesapeake Bay, one of America's most important estuaries, the water in 2100 was warm and murky with sediment and algae. Chesapeake Bay oysters, famous for centuries, had dwindled in number due to the dirty, acidic water, and oyster farms had closed. In towns and farms along the bay shores, freshwater wells had been ruined by rising seas. Urban water intake pipes had been moved farther up the Potomac River. The bay's smallest islands were totally gone; larger ones had shrunk.

Farther south, waves lapped where islands once buffered Virginia from heavy seas. The Outer Banks of North Carolina, including the Cape Hatteras barrier, were virtually gone. Albemarle-Pamlico Sound was exposed to the full force of Atlantic storms that once would have spent their fury on the lost barrier beaches. North Carolina by 2100 had lost more than 1,000 square miles to the sea. Whereas wars historically have broken out when one nation has taken even a few miles of land from another, the United States by the twenty-first century had given up thousands of square miles to the sea without putting up a fight—until it was all too late.

The map of the southeastern United States had been redrawn. Thousands of square miles of once-dry coastal land are under saltwater here by 2100, including the famous multibillion dollar Miami shoreline, the Florida Keys with its crystalline coves, and much of Everglades National Park.

Malaria, yellow fever, and bonebreak (dengue) fever are now prevalent in Florida as pesticide-resistant, disease-carrying mosquito populations thrive in the warmer weather. Mosquitoes that transmit malaria survive only where winter temperatures exceed 61°F. Chillier temperatures had kept them in check during the twentieth century. During the twenty-first century, however, the area of potential infection had expanded with rising temperatures, spreading the disease north and to higher elevations. Tourists and retirees who could afford to leave shunned the infested areas of Florida.

The Delta and Gulf

By 2100, much of the low-lying Mississippi Delta area and parts of Louisiana were also flooded. Many coastal pipelines and much other important infrastructure were underwater. The commercially important spotted sea trout, oyster larvae, and flounder had lost most of their habitat. The commercial fish and shellfish industries not damaged by Gulf oil spills were gone. Few edible fish were left to catch, and many of those contained dangerous toxic chemicals.

Flooding had become a huge problem everywhere in bayou country by 2100. Following an incomplete recovery after Hurricane Katrina in 2005, New Orleans, which was then six and a half feet below sea level, sank another several feet due to subsidence and sea-level rise. With so many localities all begging for help at once, federal flood disaster relief funds were soon overcommitted. Federally subsidized flood insurance was slashed. A strange pervasive numbness—a fatalistic kind of national "compassion fatigue"—seemed to set in on those not directly affected by each new disaster.

On the Gulf Coast of Texas, Galveston spent billions reinforcing its seawall. Sunken pipelines and abandoned oil pumping stations nonetheless remained visible from the air. Here and there, greenish coppery slicks coated the coastal water above leaking submerged landfills. As the seas had risen along the Texas Gulf Coast, much of the wetlands and wetland-dependent birds, fish, and shellfish had disappeared here, too. The state's once economically important brown shrimp catch was devastated. Just as on the Louisiana Coast, most fishing people here lost their livelihoods.

Scorched Earth and Sweltering Valleys

It was sad to contemplate how much the country had changed west of the Mississippi by 2100. Ever since 2030, vast wildfires on drought-stricken land in the Southwest had blackened large swathes of Arizona, New Mexico, and Colorado, destroying thousands of homes and killing unlucky residents and firefighters. And instead of a summer fire season, many parts of California now had a year-round fire season.

On the day that our time traveler entered California in 2100, a couple of large wildfires were still actively burning out of control in brushy hill areas east of the populated southern coast. Thick ash-laden grey smoke from these fires had hung for days in low valleys as the blazes consumed vegetation and homes built along bone-dry canyons. People with asthma or chronic obstructive pulmonary diseases, such as bronchitis and emphysema, were seeking help with their breathing at overcrowded local emergency rooms.

The San Francisco area—not known for high temperatures—on the average had had only 12 days of extreme heat in the early twenty-first century. Most residents had not even owned air conditioners. However, with the 10°F average global increase in temperature that had occurred by 2100, even once-temperate San Francisco was having 70 to 94 days of extreme heat per year.

In hotter areas of the state, temperatures approached 120°F in bad heat waves. Surges in heat-related illnesses and deaths would ensue, particularly among the very young, the elderly, and those suffering from heart disease or other chronic ailments.

Whereas the state had added tens of millions of people during the twenty-first century, it was nonetheless having to make do with a lot less water. Miles of once-productive farmland in California's Imperial and Coachella Valleys lay hot, dry, and fallow. Parched by decades of drought, the Colorado River basin was no longer able to provide the one million acre-feet of water it used to send to California's Metropolitan Water District. Stringent water rationing was now common during the state's very dry summer and fall.

While California's winter runoff had increased by 2100—charged by heavy winter rains—the winter snowpack had greatly diminished and melted earlier each year. Spring and summer runoff therefore had fallen to critically low levels. Although reservoirs in the state had been enlarged in multibillion dollar retrofits, they still weren't able to hold enough of the larger winter flow to make up for the summer shortages. Water was thus scarcest in California when farms needed it most for irrigation. Wild California salmon populations and other cold-water species that needed high spring flows had long since been decimated by the chronic low flows and the warmer temperatures.

Along the Pacific Coast, the medium-density residential developments built over coastal sand dunes right up to the beaches had been destroyed by the rising seas and storm surges. Expensive property near San Francisco Bay was also flooded by rising seas and intense winter storms.

Snowless Mountains and Failing Dikes

The Sacramento-San Joaquin River Delta—the largest freshwater estuary on the West Coast in 2013—had provided drinking water to two-thirds of California.[20] It was thus crucial to the state's water supply system. However, parts of the Delta that were already some 25 feet below sea level behind clay dikes did not fare well with the passage of the twenty-first century.[21]

The Delta's aging, unstable system of fragile dikes, weakened by storm surges and saltwater intrusion, failed after a major earthquake on the San Andreas Fault in 2085. Some of the delta's freshwater marshes turned salty as seawater pressed inexorably inland. Submerged roads and bridges throughout the Delta were still visible in 2100. Much of the freshwater supplies once stored by the Delta were gone.[22] Some of the area's water conveyance structures had also failed in the quake.

In the Pacific Northwest, because the diminished mountain snowpack had melted earlier each year, little water was available in the summer and fall of 2100 to produce hydropower, on which much of the region's economy depended. Stream flows in many waterways also often were too low for fish; as in California, the region's magnificent wild salmon stocks were nearly extinct. On Mount Rainier, where the penstemon, primrose, and white heather used to grow, trees had replaced the splendid alpine wild-flower meadows.

Asia

Across the Pacific, the rapid climate change of the past century had spread disease in many areas. Malaria now threatened 60 percent of the world's residents, many of whom lived in Asia. Hundreds of millions of people were infected each year, and millions were dying. More Asian people were also falling victim to bonebreak fever, river blindness, encephalitis, cholera, yellow fever, and waterborne intestinal illnesses. Rising temperatures, which speed up spoilage, had also caused increases in food poisoning from salmonella in contaminated food.

In the Pacific Ocean, the nations of Kiribati, Tuvalu, and the Marshall Islands had disappeared into the sea. The same thing had happened to other "stepping stones" across the Pacific. Some of the larger Solomon Islands had survived, but were now smaller and partially evacuated.

Most of the world's tropical coral had died or was dying by 2100, due to a combination of higher ocean temperatures, severe storms, freshwater and sediment from heavy downpours, and contamination. The once-spectacular coral reef between the Kyushu and the Ryukyu Islands, with its brilliantly colored fishes and anemone, was now desolate, bleached an unnatural white.

The Yangtze Flood

A colossal flood on the Yangtze River had left 250 million Chinese homeless in 2091. Massive refugee camps stretched as far as the eye could see along the edges of the enormous flood zone. Although some 220 million people returned to the floodplain after the waters receded, 30 million had nothing to go back to. It was as if a mass of people equal to 70 percent of the US population in 2010 had been driven from their homes and then a population larger than that of Texas in 2010 had been left destitute indefinitely. Ironically, despite the flooding, the north of China was at the same time parched by extraordinarily dry weather.

Between 2070 and 2095, several million people were also displaced by sea-level rise and flooding in coastal areas of Myanmar, Thailand, and Vietnam, as well as Indonesia, the Philippines, and Malaysia. During the same interval, two-thirds of Bangladesh went underwater from an extraordinarily severe monsoon that halted its already impoverished economy.

Remembering Africa

In the twentieth century, Africa was not exactly a model of fine resource stewardship. The continent's tropical forests were being rapidly destroyed. Wildlife was being brutally exterminated. Species were going extinct. Water resources were being depleted. Soils were eroding, and grasslands were turning into deserts. The carnage had continued and in some places had intensified during the twenty-first century.

Africa's population in the twenty-first century had continued expanding faster than its economic growth, while its natural resources deteriorated. Even in 2012, tens of millions of Africans had been living in shacks and sheds with few comforts. By 2100, Africans had even fewer natural resources left per capita to support themselves. Wars and lawlessness over large areas had created millions of miserable refugees. Meanwhile, the continent had remained largely dependent on rain-fed agriculture to raise food for domestic consumption and export, while drought had stalked through the countryside. Needless to say, this was not a great business model. Millions of starving farmers were forced to leave their dying herds and drying fields in search of food and water in the cities.

Political instability still plagued Egypt. The situation had worsened when a large part of the Nile Delta was lost to rising seas in the twenty-first century through the combined effects of flooding and erosion. Rising sea levels actually had delivered Egypt a two-fisted blow, reducing economic production while creating a crush of environmental refugees. Meanwhile, food prices had risen sharply.

Large numbers of impoverished Egyptians—no one even knew exactly how many—were suffering from hunger, malnutrition, preventable disease, and, yes, starvation in the twenty-first century. Revenue from tourism, an important part of the twentieth century Egyptian economy, had virtually disappeared in response to the widespread misery and menacing instability.

Along West Africa's coast, few nations had the money to defend themselves against the sea, though many countries had large, low-lying coastal cities. Severe flooding and heavy economic and human losses were the norm in these cities by 2100. And with less rainfall, crop failures and famine were even more frequent than in the twentieth century.

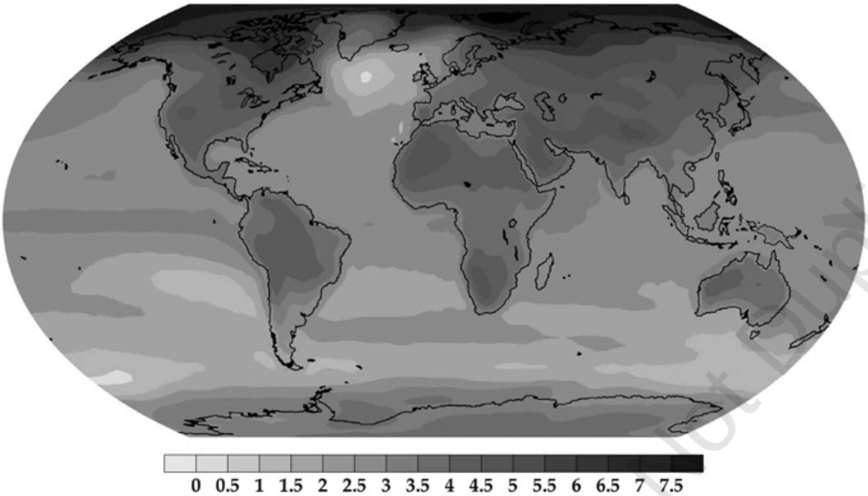

FIGURE 1-3. Projected surface temperature changes in the late twenty-first century (2090–2099) relative to the average surface temperature from 1980–1999, in degrees Celsius (1°C = 1.8°F) over different regions of the globe. Source: IPCC, Summary for Policymakers, *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change, 2013.[23]

The national parks and wildlife refuges on which West Africa's tourism depended had been gravely damaged by poaching, abuse, neglect, and droughts. Tourists no longer arrived at coastal resorts, where the beaches had disappeared and flood dangers had risen. Much of West Africa's economy was thus crippled, along with the Sahelian lands to the south of the Sahara.

Dog Days in Europe

After having endured a severe economic crisis in the early part of the twenty-first century, Spain, Italy, Greece, and parts of Turkey were especially barren and dry in 2100. Chronic water shortages, especially in the more southerly areas, were aggravated by higher temperatures, heat waves, and drought. Many reservoirs and wells dried up.

In Italy's low-lying Po River plain, construction crews were once again trying to elevate already towering flood barriers. In Venice, which was built on a lagoon, whole neighborhoods and world-famous tourist attractions had been abandoned due to the repeated flooding.

In the Alps, the imposing glaciers were gone by 2100, save for a few small pockets of ice in cool, sheltered areas. They seemed almost a mockery of the majestic mountain glaciers that once drew millions of tourists to Austria, Italy, France, and Switzerland. Mountain slopes had now become unstable due to the melting of the glaciers and high-elevation permafrost. Landslides had become common after heavy rains. Some downslope villages had to be abandoned. Average alpine temperatures had shot up as the century had progressed and, as a result, mountain snowpacks had declined across Europe. Water levels in the Rhine had dropped significantly, and runoff declined sharply in places like Hungary.

The extensive interior wetlands of the Netherlands were quite dry in 2100, due to higher temperatures and increased evaporation. All along their shorelines, coastal marshes had shrunk. Long accustomed to battling the sea, the Dutch had had to erect ever more massive flood barriers. Upgraded shoreline defenses had also been built around Hamburg, London, and other wealthy Western cities.

The Uncertain Future

The scenarios in this imaginary round-the-world journey are not absolutely certain. They are merely reasonable projections, rooted in ever-improving climate science and daily evidence of accelerating climate change. Nonetheless, it is always possible to make more optimistic assumptions, as we will see in the next chapter.

CHAPTER 2

Current Climate Impacts

Civilizations collapse when their environments are ruined.
The obliteration of Nature is a dangerous strategy.

—E. O. Wilson

By altering temperature, rainfall, wind, and weather patterns, sea levels, ocean chemistry, and ocean currents, a rapidly changing climate affects all natural resources, all species, all people, everywhere. This chapter provides far-ranging, irrefutable evidence of several major climate changes that are already profoundly affecting the Earth, its ecosystems, and ourselves. The evidence suggests that a climate catastrophe has already begun.

Portents of Disaster

The first decade of the twenty-first century was the hottest on record.[1] The year 2012 now appears to have been the hottest ever recorded in the lower 48 states—three and a half degrees above the long-term average and a degree higher than the previous hottest-record year, 1998.[2]

Climatologists believe that before industrialization, global mean temperature had not varied as much as 1.8°F within the past 10,000 years. But in the past 100 years, the world got 1.4°F hotter[3]—66 times faster. And the Earth is not only warming astonishingly quickly by historical standards, but the sizzling pace is itself steeply accelerating.[a]

[a] The average warming rate over the past 50 years is nearly twice the average for the preceding century. The current decade seems to be almost a fifth of a degree F warmer, in fact, than the 1990s.

Climate change is perhaps most apparent in the increase in extreme weather and in many dramatic physical changes, such as the vanishing of northern polar ice, the melting of the world's glaciers, the disintegration of floating Antarctic ice shelves, and rapidly rising sea levels. Yet we are still in the very early and comparatively mild stages of the first human-induced climate change in history.

Given that the concentration of heat-trapping gases in the atmosphere is the highest in millions of years, the world is in a sense on borrowed time, saved from experiencing the full consequences of this atmospheric carbon only by long time lags built into the climate system and, ironically, by some of the pollution generated by the fossil fuel combustion that's gotten us into this mess. Aerosol pollution, comprised of shiny sulfate particles, reflects some of the sun's heat spaceward, delaying for a time the full effects of the longer-lived, heat-trapping gases that are also released when fossil fuels are burned. (See chapter 5 for more discussion of aerosols.) We are thus now in a race against time to see if we can take our foot off the fossil fuel pedal soon enough to bring emissions down before the climate system moves into a permanently hotter mode for the next several thousand years.

Even if the planet's air, water, and soil were warming gradually instead of very rapidly, the short-term responses of Earth's natural systems to climate disruption would not necessarily be gradual, but more like lurching "step changes." That's because even if local temperature in a particular region might for some reason be changing slowly, plant or animal species or ecosystems at risk there could still fail quite abruptly should that slowly rising temperature eventually exceed the species' or ecosystem's tolerance limit for heat or drought.

Another example of lurching climate change is the ice shelf clinging to the coastal sea floor that suddenly breaks loose when the surrounding water warms by just a fraction of a degree past the point at which the base of the ice remains solidly frozen to the sea floor.

This principle of potentially jerky or sudden step changes in natural systems has broad relevance. In far northern forests, for example, lakes and other surface water are held above ground by perennially frozen ground known as permafrost. When the soil temperature increases above freezing, permafrost melts. That allows surface water to drain below to ground water. Whole regions can then dry out relatively quickly. This process has already begun. Thus, the plants and animals that depend on the millions of lakes and ponds preserved by frozen ground in the planet's northern latitudes will eventually be lost unless the warming in progress can be arrested. Melting permafrost also allows the organic matter frozen within it to thaw and oxidize to greenhouse gases. (See "Melting Permafrost and Frozen Methane," page 33.)

A long and sobering litany of other climate-related disasters is already occurring, and more are expected. One cannot attribute these disasters entirely to climate change; however, climate change in some cases makes these events more likely or more severe, or both.

Huge, Powerful "Superstorms"

Overall, financial losses from weather-related disasters are up sharply, setting global records. Hurricane Katrina in 2005 killed more than 1,800 people, displaced more than a million, and did more than $100 billion of damage. Hurricane Sandy in 2012 destroyed lives, brought vast coastal flooding, and knocked out power for millions. Hundreds of thousands of homes and businesses were destroyed, damaged, or disrupted. Damages in New York and New Jersey exceeded $70 billion dollars.

Tropical ocean surface temperatures cause moist, warm air to rise and help power storms. Sea surface temperatures off the coasts of New York and New Jersey shortly before Sandy struck were some 9°F warmer than normal, which contributed to Sandy's severity.

FIGURE 2-1. Much of Manhattan went dark after a Consolidated Edison power plant on the Lower East Side was flooded by Hurricane Sandy in October, 2012. Some downtown residents were without lights, heat, and power for five days. Most land-based phone service in the area was also out of commission. Photo © Spencer Platt/Getty Images/AFP.

As sea levels rise and storms intensify, many large coastal US cities are increasingly subject to flooding from high tides and storm surges. New York City was hit by an 11-foot-high storm surge in conjunction with Sandy. Even larger storms are likely in the future.

Floods

As a result of global warming, the atmosphere contains 4 percent more moisture now than it did 30 years ago. More moisture is therefore available to storms. Climate change can also produce abnormally heavy rain or snow by displacing normal storm tracks or ocean currents. Wet weather systems that would normally progress over an area stall instead, dumping huge amounts of rain or snow in one area before moving on. In September 2013, a 4,500-square-mile area across Colorado's Front Range was hit by devastating record floods. Exceptionally high (86°F) sea surface temperatures west of Mexico combined with an extratropical weather system and brought a relentless flow of humid air known as an atmospheric river to Colorado. According to Dr. Kevin Trenberth of the National Center for Atmospheric Research, the floods were created by an atypical series of climate events that might have brought a 500-year flood to Colorado even without climate change;

FIGURE 2-2. Heavy rains caused widespread flooding in numerous Colorado towns. These homes in a residential neighborhood in Longmont, Colorado, were among thousands submerged in mid-September 2013. Photo © John Wark, Associated Press.

FIGURE 2-3. A raging waterfall destroyed a bridge along Highway 34 leading to Estes Park, Colorado, as flooding forced thousands of Front Range residents to evacuate their homes in mid-September of 2013. Photo © Dennis Pierce, Associated Press/Colorado Heli-Ops.

FIGURE 2-4. A Longmont, Colorado, homeowner was comforted by a family friend in front of her possessions as they cleaned up after floodwaters ravaged her home during the 2013 mid-September floods. Photo © Chris Schneider, Associated Press.

FIGURE 2-5. A woman and her young daughter took a close look at a flood-damaged bridge in Longmont, Colorado, in mid-September 2013. Photo © Marc Piscotty, Getty Images North America.

with climate change, however, the floods turned into a once-in-a-thousand-year event that killed six people and forced thousands to evacuate. Powerful floodwaters demolished thousands of homes and farms, and many miles of roads were washed away along with bridges. The preceding images show the impacts that big floods have on communities and their residents.

Heat Waves

The European heat wave of 2003 killed 35,000 people and did $15 billion in damage to agriculture alone.[b] The 2010 Russian heat wave killed 55,000 people and produced massive crop damages. Five hundred wildfires raged over the bone-dry land around Moscow.[c] While heat waves like the European disaster were formerly expected only once in 500 years, they may become fairly common in the overheated world we're now creating.

Along with its worst drought in 130 years in 2002, India had a heat wave in May 2002 that killed more than 1,000 people. The temperature reached

[b] Sir Nicholas Stern, The Economics of Climate Change (Cambridge, UK: Cambridge University Press, 2007).

[c] The World Bank and the Potsdam Institute, *4° Turn Down the Heat: Why a 4° Warmer World Must Be Avoided,* A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analysis (Washington, DC: The World Bank, November 2012).

nearly 124°F in one village in state Andhra Pradesh, where a local official reported that birds fell dead out of the trees from the heat.[4]

Tropical Diseases

Lethal, insect-borne and waterborne illnesses formerly restricted to the tropics are now spreading to large regions previously free of them. South Africa, for example, virtually malaria-free in the early 1970s, has nearly 60,000 cases a year.[5] Malaria has also reached highland regions of Kenya and Tanzania, where it was previously unknown.

Drought

Although individual droughts have complex causes, it is well known that higher temperatures associated with climate change increase the intensity, likelihood, and thus the frequency of hot weather extremes. So it should come as no surprise that nearly 1,700 counties in the United States were declared primary natural disaster areas in 2012. A widespread drought that

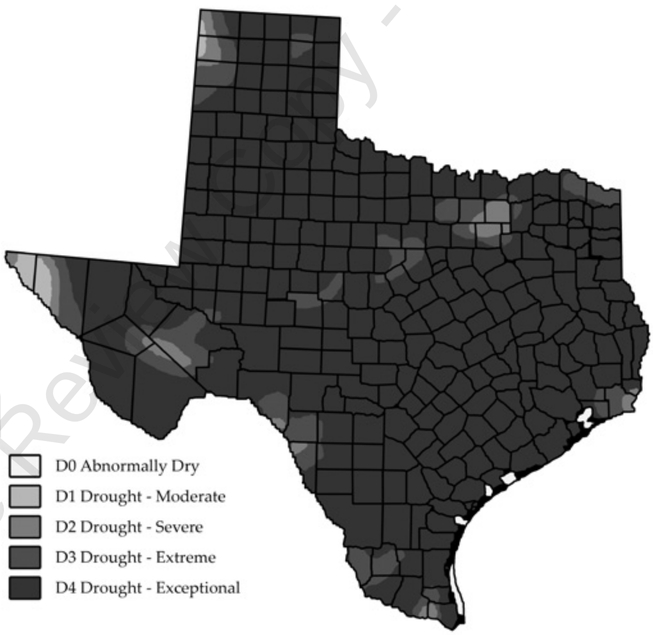

FIGURE 2-6. A historic drought of exceptional intensity afflicted almost the entire state of Texas in 2011. Parts of Texas were still experiencing drought in 2013. Courtesy of the National Drought Mitigation Center.

FIGURE 2-7. Emaciated cattle wait in a Gillespie Livestock Company pen to be sold at auctions during the 2011 drought. Many Texas ranchers could not find hay for their cattle or were unable to afford it. Photo © Jay Janner, *Austin American-Statesman*.

FIGURE 2-8. Two ranchers fold their hands and bow their heads during a 2011 gathering to pray for rain at a downtown park in Fredericksburg, Texas. Photo © Jay Janner, *Austin American-Statesman*.

started in 2010 as a heat wave and drought in the southern United States expanded to engulf more than 80 percent of the nation along with parts of Mexico and eastern and central Canada. The related heat wave took more than 80 Canadian and US lives. Some parts of the country, including Texas, were still in extreme drought in 2013. Severe droughts have also stricken African, Middle Eastern, and other nations in recent years.

Melting Glaciers and Ice Sheets

Vast floating ice shelves along the West Antarctic Ice Sheet have broken up in recent years, with the glaciers behind them flowing more rapidly into the sea. The West Antarctic Ice Sheet is also shrinking and becoming unstable due to loss of its sea ice shelves. These developments are not really that surprising given that the average temperature of the Antarctic Peninsula has gone up by 4.5°F since the mid-1940s, and in some seasons, by 7 to 9°F.

Scientists are observing that the Greenland Ice Cap is melting at an accelerating rate. The rapid loss of the Greenland ice—faster than climate models have predicted—is contributing to sea-level rise and is increasing coastal flooding, including parts of major cities. The melting of the Greenland Ice Cap could eventually lead to massive increases in sea levels and profound disturbances to ocean currents that transfer heat on a global basis.[6]

Glaciers around the world have also been melting rapidly, contributing to sea-level rise. About half the glacial ice in the European Alps has been lost in the past century. More than half the glaciers of Montana's Glacier National Park are gone. Extensive glacier melting has also occurred in Alaska as the images of the Muir Glacier (figures 2-9 and 2-10) illustrate.

Glaciers in the Himalayas, the world's largest mass of ice outside the polar regions, are receding faster than anywhere else in the world. They are the source of many important rivers, including the Indus and Ganges. The loss of high-altitude glaciers and diminishing snowpacks is already starting to bring more frequent droughts and threaten the water supplies of more than two billion people who live in parts of India, Nepal, China, and Pakistan and other regions of water scarcity. The East Asian monsoon has also been unreliable over the past 30 years, reducing rainfall in parts of China.

Sea-Level Rise

Sea level rises on a warming Earth because of ice and snow melt, and due to the expansion of warming seawater. Significant sea-level rise has occurred—about eight inches in the past century—a much faster rate than

FIGURE 2-9. Muir Glacier, Alaska, 1941. Photo by William O. Field, August 13, 1941. *Long-Term Change Photograph Pairs.* National Snow and Ice Data Center/World Data Center for Glaciology, Boulder. *Online Glacier Photograph Database.* US Geological Survey.

FIGURE 2-10. Muir Glacier, Alaska, 2004. Photo by Bruce F. Molnia, August 31, 2004. *Long-Term Change Photograph Pairs.* National Snow and Ice Data Center/World Data Center for Glaciology, Boulder. *Online Glacier Photograph Database.* US Geological Survey.

forecast.[7] As noted in chapter 1, as seas rise, parts of heavily populated, low-lying coastal regions and major cities around the world will be below sea level. Using Google Earth, anyone with a personal computer can now see a simulation of what these cities will look like at various expected sea levels. A recent study published in the journal *Nature Climate Change* has found that damage to coastal cities from sea-level rise will mount to $1 trillion *each year* by 2050 if cities do not make adequate preparations.[8]

Sea Ice Melting

Highly reflective summer sea ice in the Arctic is disappearing. It is being replaced by darker-colored water that absorbs vastly more of the sun's heat and acts as another very strong positive feedback that contributes to global warming and climate change. (For more explanation about climate system feedbacks, see chapter 3.)

Melting Permafrost and Frozen Methane

Permafrost in northern latitudes and frozen methane deposits in the ocean known as clathrates or hydrates together contain trillions of tons of stored carbon. The permafrost and clathrates both have slowly begun to thaw and release methane and carbon dioxide to the atmosphere. The more permafrost and clathrates melt, the hotter the earth becomes, and so the more melting occurs. At some point, the continued melting of these vast stocks of carbon would alter the climate beyond recognition and lead to a "runaway" greenhouse effect, transforming the Earth into an ice-free planet as it was millions of years ago. (Methane is 84 times more powerful a greenhouse gas than carbon dioxide on a per molecule basis over a 20-year period.) According to the geological record, when Earth was ice-free, sea level was about 250 feet higher than at the present.

Extinctions

Plant and animal extinctions are accelerating on land and in the sea. The Amazon tropical rainforest is already beginning to suffer from repeated severe droughts and increased tree mortality. Millions of acres of the forest were devastated in 2010; other severe droughts preceded it in 2007 and 2005.[d] If unchecked, this will destroy the rainforest ecosystem, which stores globally

[d] In the most severely affected areas, one tree in 25 was killed, according to Eli Kintisch, "Widespread Devastation in 2010 Amazon Megadrought," ScienceNOW (American Association for the Advancment of Science), December 7, 2012.

significant amounts of carbon, with disastrous consequences for global climate, wildlife, and humanity.

Harmful Ocean Changes

Vast harmful oceanic changes (temperature increases, acidification, coral reef death, low-oxygen zones) are already occurring. Coral reef bleaching, a sign of severe and potentially fatal stress caused by ocean warming and other factors, is evident in oceans of the world. Half the reefs of the Indian Ocean and around South Asia have already lost most of their living coral. Current trends suggest that 95 percent of the reefs will be dead by 2050 if this continues.[9] Other kinds of marine life are already suffering from oxygen depletion in warming, polluted coastal waters and from the increased acidification of surface waters.

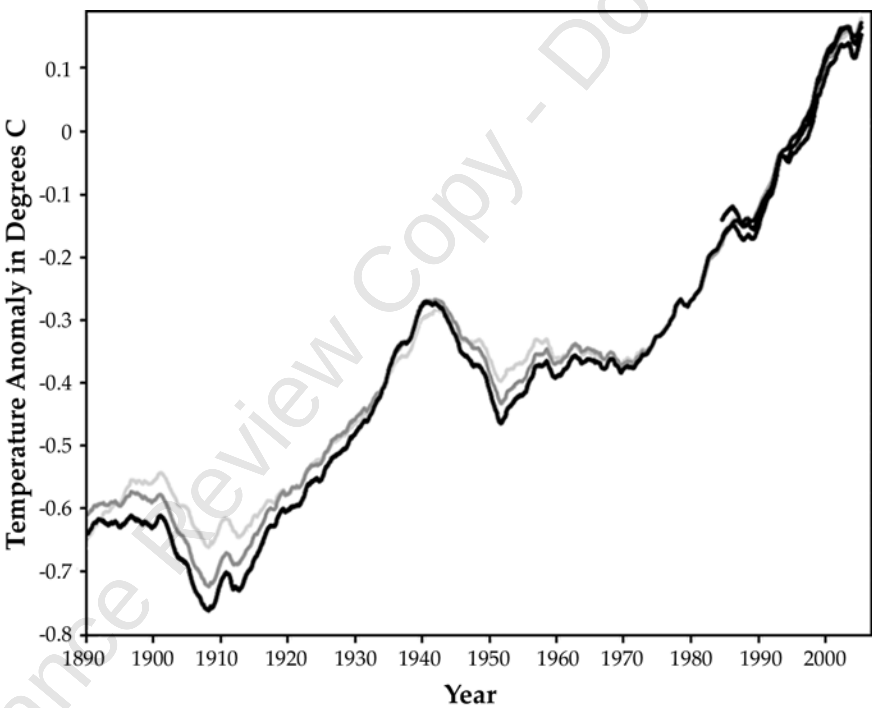

FIGURE 2-11. Using five data sets from several prestigious federally funded research organizations, the graph shows an overall rising temperature trend for most of the last hundred years. Data, compiled by Kelly O'Day and courtesy of Skepticalscience.com, are from the US National Aeronautics and Space Administration's Goddard Institute for Space Studies, the National Oceanic and Atmospheric Administration; satellite data is from Remote Sensing Systems, under contract to NASA.

The drastic climate changes that have already occurred after only 1.4°F—less than 1°C—of warming show the climate system is very sensitive to heat-trapping gases and has already been gravely destabilized. This indicates that greatly amplified additional warming and disastrous consequences are likely should warming continue unabated. The steep, post-1970 rise in global temperature is apparent in figure 2-11.

I will pause now in describing the current effects of climate change to focus in chapter 3 on how the climate system normally operates. This explanation will subsequently be used as a basis to understand the mechanisms by which humans are now dominating climate processes and causing climate change.

CHAPTER 3

Natural Climate Change

Climates found at present on 10–48% of the planet
are projected to disappear within a century,
and climates that contemporary organisms have never experienced
are likely to cover 12–39% of Earth.

—Anthony D. Barnosky et al.[1]

This chapter explains how the climate naturally functions in the absence of interference from the effluents of large-scale industrial and agricultural activities.

To better understand how humans are now affecting the planet's climate machinery—the topic of chapter 4—it is helpful first to know how nature operates on autopilot, without human interference. Then we can clearly infer whether humans are but "innocent bystanders" or the perpetrators of climate change. It turns out that the key to that puzzle is in the sky and is related to subtle changes in "orbital geometry"—the shape of the Earth's orbit around the Sun.

But it was not until the nineteenth century that scientists like the self-taught Scot, James Crowell (1821–1890) begin to suspect the amazing fact that these variations in the Earth's orbit could actually initiate ice ages on Earth. Earth's orbit around the sun is almost circular but is very slightly stretched out to form an ellipse. Over a 100,000-year cycle, the shape of the orbit oscillates from more circular to more elliptical. As the Earth travels around the sun and spins at an angle to its plane of rotation, the angle itself varies on a 41,000-year cycle. Meanwhile, the tilted axis wobbles on yet another regular cycle so that over 23,000 years, the Earth inclines in different directions with respect to fixed stars and more importantly, the sun.[2] All these processes affect the climate, as indeed do volcanic eruptions, large meteor impacts, and even sunspots. (See figure 3-1.)

I will now explain how the relatively slight-to-modest changes which these orbital and other variations induce in the total amount of solar energy absorbed by the Earth can trigger massive climate changes.

Clearly, the Earth's distance from the sun and its inclination toward it affect whether the Earth absorbs more or less of the sun's heat. That much certainly isn't rocket science. However, not only do the orbital and angular changes independently affect the amount of solar energy the Earth absorbs, the interactions of these cycles at times throughout the ages coincide or tend to offset each other. Thus, periodically they reinforce and intensify their independent effects. When this occurs, the enhanced effects set in motion conditions on Earth that gradually amplify the initial reduction in the energy Earth absorbs, and take the planet into an ice age. Similarly, when celestial geometry dictates that orbital and axial cycles combine to increase the peak energy absorbed in the Northern Hemisphere, the ice sheet created during the ice age warms, and thaws.

The warming transpires far more quickly than the freezing process, however. The freezing takes tens of thousands of years, whereas ice sheets have collapsed in a few thousand.[3] The enormous mass of ice sheets causes the land below to subside by as much as a half mile or more. At the lower elevation, temperatures are higher and speed up the melting.

The details of how the Earth's major climate cycles unfold are complicated by the many ways in which the climate system, with all its biology, chemistry, and geology, and the Earth's asymmetrical distribution of continental land masses and oceans respond in myriad ways to the changes in incoming solar heat. But in brief, the Earth's normal long-cycle orbital changes serve to initiate relatively small changes in the amount of solar energy absorbed by the Earth. Over long periods of time, these slight variations in absorbed energy are then powerfully amplified or dampened by terrestrial processes so as to trigger massive climate changes on Earth.

In essence, when less solar heat is absorbed, the area of the Earth covered by snow and ice expands. The whitened landscape then increases the reflection of solar energy to space. This intensifies the cooling begun by the orbital changes.

Planetary cooling or heating triggered by orbital changes also affects the Earth's natural cycling of heat-trapping gases, such as water vapor, carbon dioxide, and methane. These affect the physiology of plants and microorganisms that in turn influence the composition of the atmosphere.[4] The resulting atmospheric changes make the atmosphere more (or less) opaque to the solar heat that Earth constantly receives and then re-radiates to its own atmosphere and to outer space.

Thus, for example, as the Earth's temperature falls, less water evaporates from the land and ocean, so the atmosphere is drier. With less heat-trapping water vapor aloft, the atmosphere is less able to capture heat. In addition, because the planet is cooler, more carbon dioxide dissolves in the ocean, so less remains airborne to heat the Earth. The atmosphere then is more transparent to heat radiated from the Earth, and so more can escape to space, further cooling the Earth.

Climate as Distinct From Weather

Climate is another word for average long-term weather, an ensemble of conditions marked by temperature and moisture, as well as atmospheric motion and transparency. Weather, by contrast, is a relatively short-term phenomenon, even though individual episodes can last for days, weeks, or even months. People sometimes lose sight of these distinctions between climate and weather, however. They mistakenly allow their judgment about climate change—which can be reliably deduced only from the careful analysis of long-term weather trends—to be clouded by their perceptions of weather. A particularly cold or snowy winter is often enough to convince them that the climate is cooling rather than warming. A sudden heat wave or violent storm is then taken as certain evidence of the opposite conclusion.

Weather is notoriously fickle, of course. Sometimes placid, sometimes turbulent, its rapid oscillations can be like noise on an audio channel that makes the main signal—climate change—difficult to hear. Filtering out the noise of weather and random or chaotic climate fluctuations is difficult in the short term. Climate also has normal variation cycles, sometimes getting warmer, sometimes cooler. Moreover, it goes through long-term periods of greater and lesser relative stability. This makes it hard to discern underlying trends through casual observation.

Long-term climate trends are also somewhat obscured by large seasonal climate changes in the same geographic location, where temperatures often differ by tens of degrees. Day and night also bring large temperature swings. All these complications make it very hard for the untrained observer to detect small-to-moderate underlying trends. Without systematic scientific analysis, it is challenging to make accurate observations about global climate, let alone forecast it. But by focusing on long-term trends and by synthesizing millions of temperature observations taken on land, sea, and in the atmosphere, scientists have developed consistent and reliable measures to track the evolution of global average temperature over time. That, then, gives us a reliable indicator of climate change, such as the data in figure 2-11, page 34.

Lessons from Ancient Climates

At first it may seem strange that a few degrees of change in average global temperature could have much significance for the planet. These seemingly small changes do matter enormously, however. First, they are enduring, and they increase the probability of extreme conditions, such as heat waves, floods, and intense storms. Second, average conditions are not uniform over the planet. Thus, as mentioned earlier, average warming is magnified in the interior regions of continents and especially in high latitudes near the polar regions, creating large stresses on ecosystems there. So a relatively small change may be a great deal more significant when doubled or tripled or even raised by half.

Finally, relatively small average temperature changes are themselves highly significant, because the climate system itself is sensitive to them. Physical evidence from past geologic eras shows how powerfully the Earth has responded over time to small shifts in the amount of energy received from the sun that are ultimately reflected in global average temperature. This knowledge has been derived from data embedded in historical climate records stretching back hundreds of thousands of years—captured in ancient sediments from the ocean floor and from ice cores extracted from the Arctic and Antarctic, as well as from glaciers. Sophisticated analytical methods make it possible for scientists to read these records, as clearly as you're reading the pages of this book.

The Sun's Role

The Earth's reaction to long-term variations in absorbed solar radiation is in turn modified by responses from the land, sea, and atmosphere. Climate is thus determined by everything on Earth—plus the sun and the orbital dynamics that affect how much of its energy we absorb. The sun, however, establishes overarching conditions for our climate and sets climate changes in motion.

Vast quantities of solar energy radiate continuously toward the Earth. As the bright side of the Earth receives both visible and invisible solar radiation, the Earth absorbs some of that energy and both re-radiates and reflects some of it back into space. The portion that the Earth normally retains through absorption by the land, sea, and atmosphere keeps the planet's temperature far above freezing, powers the winds, and produces ocean waves. It also provides the energy that lifts water into the air by evaporation, which eventually results in precipitation.

How can a body 93 million miles away have such profound influence upon the Earth and control our climate?

The sun accomplishes this by being almost unimaginably large and rich in energy. With 99.8 percent of all the mass in our solar system, the sun has plenty to spare. Every second, it crushes 700 million tons of hydrogen in its core into helium and energy. The amount of energy it produces is also far, far beyond ordinary comprehension. Phrases like "billions of watts" do not begin to describe it.

As some of this incomprehensibly vast flood of energy first reaches Earth's outer atmosphere, it encounters an obstacle course of gas molecules, dust, and clouds. Most of the sun's incoming radiation is absorbed or scattered back into outer space or toward Earth by the atmosphere and clouds. However, about a quarter of the radiation misses the clouds and dust. This is the direct beam radiation we perceive from the Earth as bright sunlight.

Of the energy that reaches the Earth's surface, some is reflected, and about half is absorbed by surface water, land, and vegetation. As the energy is absorbed, it heats these surface features and is transformed into infrared radiation (heat), which radiates skyward.

The infrared radiation must again pass through a gauntlet of gas molecules, dust, and other tiny particles in order to leave the atmosphere. Among the gases that it encounters is carbon dioxide, the veritable protagonist of this book. Just as clear glass transmits visible light while a black piece of metal absorbs it and heats up, so, too, atmospheric gases vary in how transparent or opaque they are to radiation.

Each gas absorbs, transmits, or reflects radiation differently, according to the gas' characteristics and the wavelength of the radiation hitting it. Although they make up a very small portion of the atmosphere (well under 1 percent of its volume), carbon dioxide and other heat-trapping gases are powerful absorbers of infrared radiation, in contrast to visible light, which they largely transmit. So, contrary to intuition, even tiny percentages of these gases in the atmosphere have very powerful effects on its ability to retain heat. As heat-trapping gases intercept outgoing heat, the energy they absorb then warms the atmosphere.

Some of that energy is radiated Earthward again, so that it ricochets back and forth between the Earth and the atmosphere.[a] The longer the heat remains trapped in the Earth's atmosphere, the warmer it makes the system.

Climate Cycles

The temperature of the Earth is controlled by the balance of the radiation coming from the sun and the radiation sent back to outer space. When the incoming and outgoing radiation are equal, the overall heat loss or gain is zero. In this condition of thermal equilibrium, the Earth emits as much radiation as it receives, so its temperature stays constant. But incoming and outgoing radiation are not always in exact balance, so the Earth's climate is not constant. The degree and sign of the imbalance (whether positive or negative) indicates Earth's future temperature and climate.[5] Prolonged periods of substantial cooling result in ice ages, when parts of the Earth are covered by layers of ice up to five miles thick. During prolonged warming periods, much of the planet's icy cover melts. Ice sheets retreat toward the poles. Vegetation and animal life expand northward and southward.

The Earth is currently in a warm period known as the Holocene Epoch following the last glaciation, which ended about 10,000 years ago. (We are actually in an interglacial stage of the Quaternary Ice Age, one of the Earth's five known major glacial periods, each lasting millions of years.)[6] In the natural course of events—that is, without the powerful influences of humans on the climate—glaciers would advance again thousands of years from now. However, human influence is now so strong that a return to ice age conditions is impossible for the foreseeable future.[7] Indeed, the Earth's rapid warming in what would naturally be a *cooling* period is powerful evidence that humans are responsible for the climate change being observed.[8,b]

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[a] A fundamental principle of physics known as Planck's Law tells us that the amount of radiation emitted by a perfectly absorbing object or mass known as a black body is proportional to its temperature. A portion of the energy blocked and absorbed by a heat-absorbing gas in the atmosphere is ultimately reradiated to space. Because the gases are aloft, primarily in the troposphere (lower atmosphere), they are at a lower temperature than the Earth. By Planck's Law, they are less efficient energy radiators. As a consequence, the Earth-atmosphere system begins to accumulate more energy than it radiates. So to restore its thermal equilibrium between the incoming and outgoing radiation, the Earth and atmosphere must warm up to radiate more energy back to space. In this manner, the Earth's temperature increases, causing climate change.

[b] For additional powerful evidence that the observed climate changes of the late twentieth and early twenty-first century are of human origin, see the definitive work of Benjamin D. Santer, "Human and Natural Influences on the Changing Thermal Structure of the Atmosphere," *Proceedings of the National Academy of Sciences* (early edition), Released from embargo on September 16, 2013, www.pnas.org/cgi/doi/10.1073/pnas.1305332110.

The Milanković Cycles

As a child in grade school, I had a simple image in my mind of the Earth traveling around the sun on a fixed path. Reality, however, is far more complex and interesting. Not only does the shape of the Earth's orbit change, but so does its position in space relative to the sun. Even the plane of the orbit itself changes slowly over time. The gravitational forces exerted by Jupiter and Saturn are responsible for tugging on the Earth's orbit and changing its shape. The time when the Earth is closest to the sun, the perihelion, also varies cyclically. It is slightly earlier each year, altering the Earth's seasonal changes over a 20,000-year cycle.[c]

The seasons themselves are caused by the tilt of the Earth. As the tilt angle—which varies about two and a half degrees over a 41,000 year cycle—gets larger, the seasons become more intense: summers get hotter and winters get colder.[9] The shape of the Earth's orbit not only varies on the well-known 100,000-year cycle, but also on a "beat cycle" of 400,000 years.[10]

The Earth's tilt, wobble, orbital shape changes, and the changes in timing of the perihelion are collectively known as the Milanković cycles for their discoverer, the painstaking and brilliant Serbian mathematician, geophysicist, and engineer Milutin Milanković (1879-1958).[d,11]

The combined effect of the Milanković cycles slightly varies the amount of radiation reaching the Earth over geologic time and—most significantly—alters the distribution of the radiation on the Earth's surface. The northern hemisphere, with more of Earth's land mass, responds more quickly than the southern hemisphere, which has more ocean. The differential hemispheric distribution of land and water influences the manner in which the Milanković cycles intensify characteristics of summer or winter in each hemisphere.

When the Northern Hemisphere is tilted more steeply away from the sun during the winter and the Earth is simultaneously farther from the sun due to orbital changes, winters are at their coldest in the north and warmest in the south. This makes for rainier summers, because the Southern Hemisphere oceans receive more solar heat, causing increased evaporation. As the Earth returns to a more vertical alignment, this shift, along with other Milanković cycles changes, produces relatively cool summers in the Northern Hemisphere and warmer winters. Winter snowfall then increases as evaporation

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[c] US Naval Observatory. http://aa.usno.navy.mil/faq/docs/seasons_orbit.php. Consulted January 23, 2012.

[d] Astronomical Society. http://www.astrosociety.org/education/publications/tnl/45/globe4.html. Consulted January 23, 2012.

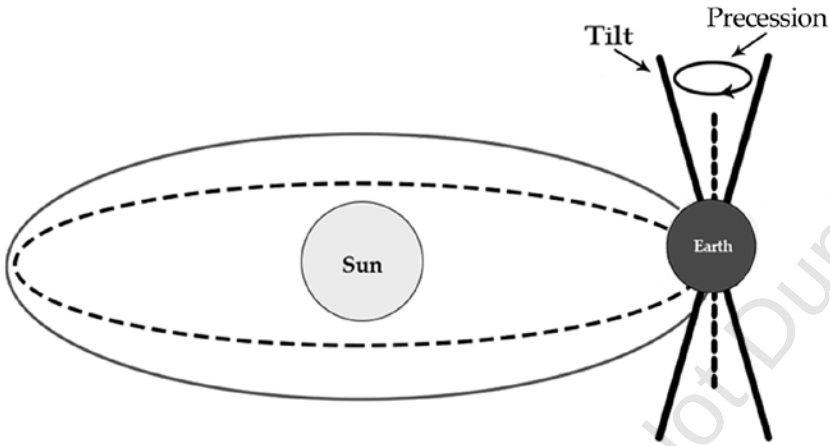

FIGURE 3-1. Ice ages are initiated on Earth by changes in orbital geometry .The diagram illustrates the cyclical changes in the shape of the Earth's orbit and in the tilt of the Earth's axis (T) as it spins on its elliptical path (E) with a slight wobble, its precession (P), which alters the direction in which the axis points. The periodicity of these variations in orbital geometry and in the timing of the perihelion, when the Earth is closest to the Sun, and aphelion, when it is farthest away, constitute the Milanković cycles.

increases. But cooler summer weather permits the winter snow and ice to last longer into the spring and thus to accumulate over larger areas. The increased snow and ice cover increases the reflection of sunlight. This, in turn, reduces the Earth's absorption of heat, further cooling the Earth—an example of what's known as a negative climate feedback. Gradually, summers get cool enough for snow to persist to the following winter over a larger and larger area.[12] As successive layers of snow fall and compress the layers below, snow crystals are transformed into ice. Over millennia the glaciated areas spread and deepen, eventually culminating in ice ages. At the peak of the last glacial period, the ice was up to two and a half miles thick.

Conversely, when the Northern Hemisphere is more strongly tilted toward the sun in summer, ice melts earlier and freezes later in the year, and the total land and sea area covered by ice declines, especially when a steep tilt occurs while the Earth's orbit is closest to the sun during the summer. With the resulting accelerated melting of ice, more and more sea ice is replaced by darker-colored seawater, and bright land ice is replaced by darker-colored soil and vegetation, both of which absorb far more of the sun's heat than does ice. This decrease in Earth's surface reflectivity (its "albedo") is known as a positive feedback effect that increases the Earth's absorption of heat and tends to warm the Earth's climate.

All else being equal—that is, when no massive volcanic eruptions release cooling aerosol particles along with carbon dioxide, and when no movements of the Earth's crust cause a release of large amounts of heat-trapping gases[e]—the overall net effect of the Milanković cycles will then suffice to control the Earth's heat balance by changing the amount of sunlight being absorbed by the Earth.

Earth's Gas "Thermostat"

Milanković today is justly lauded for demonstrating "the interrelatedness of celestial mechanics and Earth Sciences."[13] So how exactly is the variation of climate on Earth coupled to the stuff happening in the sky? Well, we just explained how the Milanković cycles bring on cooling periods. Warming, however, is a different story.

Although slight at first, an initial Milanković warming is sufficient to set in motion natural processes that amplify the warming by raising the concentrations of heat-trapping atmospheric gases here on Earth. Then, in a positive feedback process, those elevated gas concentrations cause a further increase in the Earth's temperature, which results in even higher concentrations of heat-trapping gases. Thus the Earth enters a distinctly warm period, like the one of the past 10,000 years. For these reasons, one can think of the Milanković cycles as triggering climate change. By contrast, the heat-trapping gases in the atmosphere can be thought of like a thermostat that establishes the Earth's temperature once the heat is turned on.

One of the intriguing things about the Earth's climate is that many things are going on at once that affect the concentration of carbon dioxide and other gases in the atmosphere, but all are happening on multiple time scales. Over short time periods of days and seasons, for example, plants remove carbon dioxide through photosynthesis. On the other extreme, some oceanic processes and rock weathering, which alters atmospheric carbon dioxide levels, occur on millennial time scales.[14]

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[e] Enormous volcanic eruptions have occurred in the Earth's past and have dumped vast volumes of carbon dioxide into the atmosphere, causing rapid global warming. At other times, the friction caused by continental plates sliding over methane clathrate–rich areas of the seafloor have warmed those frozen methane deposits and released vast quantities of methane to the atmosphere, which also served to warm the Earth.

Water Vapor

Water vapor is actually the most powerful of the common heat-trapping gases, because it contains hydroxyl ions (OH^-) that strongly absorb heat.[15] Unlike carbon dioxide and the other important heat-trapping gases, however, water vapor only stays in the atmosphere a very short time—just eight to ten days.[16] Natural processes normally keep water vapor in something close to equilibrium. Evaporation from land and water surfaces increases the quantity of water vapor in the atmosphere, whereas condensation decreases it.

Human activity does not directly affect the amount of water vapor in the atmosphere to any appreciable extent globally, although it can increase it locally.[17] But human action has a strong *indirect* effect on water vapor concentration through an intermediary: carbon dioxide. Warm air holds more water vapor than cool air, so water vapor concentration increases as temperature rises. Thus, as carbon dioxide and other heat-trapping gases warm the planet by trapping more of the sun's heat, the Earth's temperature rises, and so the amount of water vapor in the atmosphere also increases, further intensifying the inaccurately named "greenhouse effect" (see box, "Greenhouse Gases and the Greenhouse Effect," page 56).

Notably, the effect of carbon dioxide on global temperature and water vapor is the same whether it originates naturally or whether it arrives in the atmosphere because of human activities, as discussed in the next chapter. Despite the powerful effects of water vapor and other atmospheric gases, proof that the *trigger* for Earth's natural climate change is indeed the orbital and axial changes of the Milanković cycles exists in the Earth's long-term natural climate records.

Antarctic ice core data extending back 800,000 years reveal that past temperature cycles between ice ages and warm periods were not initiated by either water vapor or by changes in atmospheric carbon dioxide concentration.[17] Instead, after each major orbitally induced warming began, carbon dioxide concentrations rose, but only after a time lag of about 800 years. If indeed carbon dioxide and other climate-destabilizing gas levels initially rise only in a delayed response to shifts in the Earth's orbit and axial tilt, does this mean that we shouldn't be concerned about adding carbon dioxide to the air?

That would be like saying that because a spark is needed to fire gunpowder in a cartridge, gunpowder plays no role in powering the bullet. For while carbon dioxide concentrations don't rise of their own accord to provoke Earth's great climate cycles, once they climb in a natural response to warming caused by orbital changes, they soon interfere with the departure of heat from the Earth and thereby raise the Earth's temperature in a positive feedback process. The 800-year delay in the increase in atmospheric carbon dioxide—and hence the climate's delayed response—is caused by a physical process known as thermal inertia. The oceans provide a prime example.

The Oceans and the Climate

Thermal inertia is a measure of a substance's ability to absorb and release heat. The larger and denser a mass, the greater its ability to absorb heat and the greater its thermal inertia.[f] The thermal inertia of the world's oceans is very great because of their enormity and because water has a relatively high specific heat, meaning it requires a lot of energy to raise its temperature. These factors ensure that the ocean warms very slowly. Moreover, because the ocean's surface waters are much warmer than the deep ocean—and because heat naturally rises rather than sinks—the transfer of heat from the warmer surface to the ocean depths is further delayed. Thus there is a long lag of up to a thousand years before heat added to the ocean's surface is well mixed into the ocean as a whole.

For these reasons, the ocean warms very gradually relatively to the atmosphere. Eventually, however, it does warm up. As it does, it absorbs less and less carbon dioxide from the air. (The solubility of carbon dioxide in water declines as temperature rises.) At a certain point, the ocean may even, on balance, begin releasing carbon dioxide *to* the atmosphere rather than removing it *from* the atmosphere. The additional carbon dioxide then further warms the climate. The slowly warming ocean eventually warms the climate in other ways, too.

During El Niño phases and storms, some of the thermal energy in the ocean surface is released to the atmosphere. In addition, over long periods of time, a warming ocean eventually melts frozen methane in the seafloor. Once in the atmosphere it, too, warms the climate. The warming ocean also melts more sea ice. This increases the absorption of solar energy by the sea surface and adds to global warming.

Warmer ocean water will also melt the frozen subsurface anchorages of ice shelves. That will contribute to the breakup of ice shelves. In turn, the loss of these "ice dams" will allow glaciers formerly held behind the ice shelves to flow more quickly into the sea. As the extent of this land ice is thus reduced, the newly ice-free land will absorb more solar energy, and that, too, will further warm the climate.

[f] Thermal inertia is defined in physics as the square root of the product of thermal conductivity, density, and heat capacity.

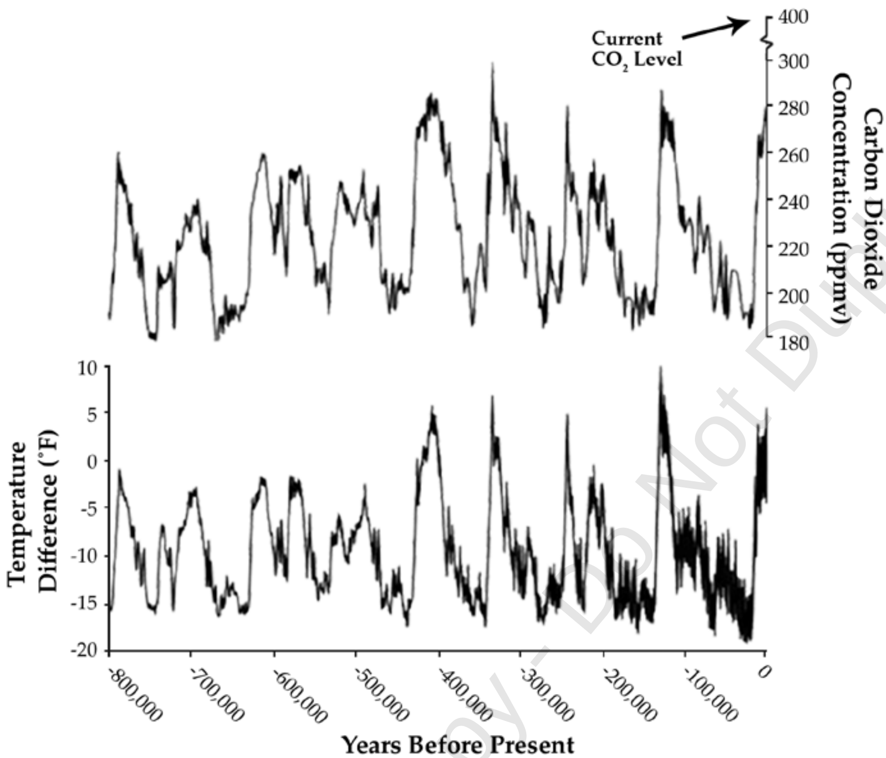

FIGURE 3-2. Estimates of the Earth's changing carbon dioxide concentration (top) and Antarctic temperature (bottom), based on a meticulous analysis of ice core data extending back 800,000 years. The graph highlights the close correlation between carbon dioxide concentrations and global temperature, offset in time by a lag of about 800 years during which the Earth's carbon cycle responds to the warming signal sent by the Milanković cycle changes described in the text. Source: Courtesy of US EPA.

With rising air and ocean temperatures, the rate at which water evaporates from the Earth's land surface and oceans will increase slightly. That will slightly raise the concentration of water vapor in the atmosphere by a couple of percent. This, too, contributes to global warming in yet another example of a positive feedback cycle.[g] (See figure 3-2.)

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[g] The solubility of a gas in liquid diminishes with temperature, all else being equal, so as seawater warms, more carbon dioxide comes out of solution passing across the ocean surface boundary back into the atmosphere. The long turnover time of the ocean—a measure of internal circulation, mixing, and, hence, heat assimilation—limits the speed of this process and therefore delays the response of atmospheric carbon dioxide concentration to natural warming of the Earth-ocean system. This is particularly relevant for long-term climate cycles arising from changes in incoming solar radiation due to changes in the Earth's orbit, tilt, and wobble. (See footnotes a and b.)

Thus, the more the Earth and oceans warms, the more stored carbon dioxide and methane become available to the atmosphere from the oceans and the soil, and the warmer the Earth gets in a continual positive feedback cycle that magnifies the effect of the Earth's initial orbital changes. Although 800 years seems a long time between increases in temperature during Earth's ancient climate history and ensuing increases in airborne carbon dioxide and methane concentrations, these 800-year time lags are very small in relation to the length of ice ages and therefore do not cast doubt on the critical role of carbon dioxide and other heat-trapping gases in bringing the Earth out of ice ages and in "driving" or "forcing" global heating in general.

Now that we have described the basic elements of natural climate change, we are ready for a deeper understanding of the processes by which human activities have dangerously destabilized the climate, which is the subject of chapter 4.