Potential Climate Impacts

CHAPTER 12

Drought and storms and sea level, not just the warming

The Warming Itself

The actual global warming part of "global warming," the change in the average temperature of the Earth, is probably not going to be the most important change in Earth's climate to affect people on the ground. Most of the social impacts will come from secondary effects like droughts and storms, things that are regional in footprint rather than global. Not even the warming itself will be smoothly spread about the Earth's surface, but rather some places and times warm more than others. But the average temperature of the Earth is still a good metric, an indicator of the severity of climate change, even if that particular number, the average temperature of the whole planet, is not the actual number that will affect people the most.

Transient climate runs forced by various Intergovernmental Panel on Climate Change (IPCC) emission scenarios predict temperatures 1° to 6°C warmer by the year 2100 (Figure 12-1). The uncertainty in the forecast for the temperature in the year 2100 derives from two sources, which contribute about equally. One is the temperature response to a given amount of CO_2, and the other is how much CO_2 will actually be released.

A temperature change of 1° to 6°C may not sound like much. The daily cycle of temperature is greater than that, to say nothing of the seasonal cycle. The main impacts of future climate change may come from changes in rainfall rather than temperature; but the temperature change by itself is far more significant to the landscape of the world than you might think.

> Natural temperature changes of a few degrees centigrade in the past changed the landscape of the Earth.

One point of comparison is the temperature difference between now and the last ice age, which is estimated to be about 5° to 6°C. This climate change was huge! If we were looking forward to a glacial maximum in the future, rather than backward into the safe past, we would be in a panic. It would be apocalyptic. Europe was an occasionally habitable tundra. The ice sheet in North America dwarfed what exists today in Greenland. Greenland, in spite of its name, is a pretty fierce place. Of course, Europe and North America were extreme cases because the ice sheets were there, but the landscape elsewhere also changed significantly. Traces of changing snowlines make it clear that it was noticeably colder everywhere. Pollen data show huge changes in vegetation type. The coastlines were barely recognizable. Truly it was a different world.

Another comparison is to the Little Ice Age and Medieval Climate Anomaly periods (Chapter 11). Some reconstructions of the global mean temperature, or northern hemisphere temperature, show temperature changes of perhaps 0.5 to 1°C. These climate intervals were not the end of the world, but they definitely sufficed to rearrange civilizations. In medieval time, European agriculture was a bounty of plenty, in a stable, benign climate. Meanwhile the New

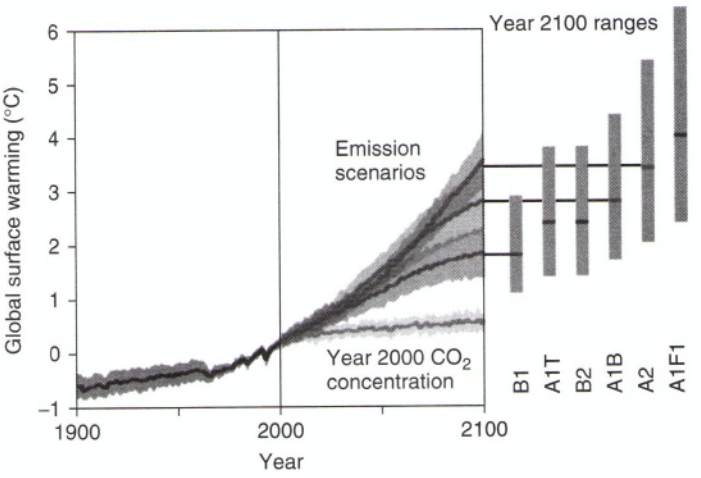

Figure 12-1 Model global temperature predictions for the coming century for several different CO_2 emission scenarios labeled B1, A1T, and so on. These are all business-as-usual scenarios with no effort assumed to slow CO_2 emissions for the climate's sake, but they make different assumptions about future trends, along the lines of the Kaya Identity equation in Chapter 9. The gray-shaded areas show the likely ranges of the responses, based on model results (the bars on the right) plus observational estimates of the climate sensitivity.

World was arid, punctuated by strong, decade-long droughts that coincided with the demise of two organized civilizations in the New World, the Classic Maya and the Anasazi.

The climate was much tippier in the Little Ice Age than it was in medieval times. Temperature or rainfall would change suddenly for a year—or for decades. There were periods of drought, of hot summers, of arctic winters, and mild periods of moderate climate and good harvests. In the years 1690–1730, roughly coincident with the **Maunder Minimum** time of no sunspots, there was sea ice around Britain and northern France and a complete rearrangement of the fisheries in the Atlantic.

My impression is that a warming of 1°C would probably not be a world-shattering change, at least globally, although there is the risk of prolonged or perpetual regional droughts, such as occurred in the American Southwest during the medieval warm time. But by analogy to the intensity of the climate changes that came with the end of glacial time, I would guess that a global mean temperature change of 5°C would be catastrophic.

The distribution of the forecast temperature change is not uniform geographically or in time. Plate 12-1 shows the mean annual temperatures from a climate model described in the Exercises section from Bala et al. (2005). The atmosphere part of the model was developed at the National Center for Atmospheric Research, a government agency in Boulder, Colorado, and the ocean part was developed at the Los Alamos National Laboratory in New Mexico. In general, this particular model has a relatively low climate sensitivity, ΔT_{2x}, of 2° to 3°C for doubling CO_2. The temperatures are plotted as anomalies, differences from the temperatures in year 2000 in Plate 12-2.

Global warming is not globally uniform.

The high latitudes warm more than the low latitudes do, by a factor of 3 or 4, mostly because of the **ice-albedo feedback**. Temperatures in Alaska and western Canada have warmed by 3° to 4°C, compared with a global average of perhaps 0.6°C. Models predict that the tundra ecosystem could disappear almost entirely in a business-as-usual world of 2100.

Much of the high-latitude land surface is **permafrost**, defined as soil that is frozen year round. The surface of the soil may melt in the summer, in which case it is called the **active zone**. As temperatures rise, the active zone gets thicker and the soil column can collapse, leaving houses and trees tilted at crazy angles. Most of the Trans-Alaska oil pipeline has its foundation in permafrost soil. Arctic lakes drain away overnight as melting ice leaves holes in the soil column. Coastlines are collapsing at rates of 40 m/year in some parts of the Canadian Arctic and Siberia.

Warming driven by greenhouse gases is generally more intense in the cold parts of the Earth's surface: in wintertime and at night rather than in the summer and in daylight. This is because greenhouse gases impede the loss of heat to space, so temperatures rise just as quickly in the sun but cool down more slowly by shedding of infrared energy. Air over land tends to warm more than air over water because evaporation can always carry away heat from the water, but the land surface may dry out.

An increase in the average temperature of the Earth's surface translates into many more extreme heat events, such as the European heat wave in August 2003, for example, which killed an estimated 35,000 people. It was thought to be a once-in-a-century event, but it was followed by a similar event in 2006. Greenhouse heat waves tend to remain hot all through the night instead of cooling down and allowing people and foliage some cool nighttime reprieve to recover.

Emergent Effects

The rise in global temperature is like a fever in that most of its impact is not directly due to the warmth itself. Changing the average temperature of the Earth scrambles the climate, rearranging weather patterns and water supply in ways that are not easy to forecast reliably and so not easy to prepare for.

> Global "weirding."

Overall, more rain is expected to fall in a warmer world. On the face of it, this sounds like it might be a good thing in a time when freshwater availability is a problem in many places. However, for the rainfall forecast, the devil is in the distribution, even more than it is for temperature (Plate 12-3).

In the tropics, the weather patterns are governed mostly by an overturning pattern called the **Hadley circulation** (Figure 12-2). Air rises convectively at the equator, where the solar heating is most intense. The rising air cools down because of expansion under lowered pressure, and its water vapor condenses into equatorial rain. Air subsides in the subtropics, bringing

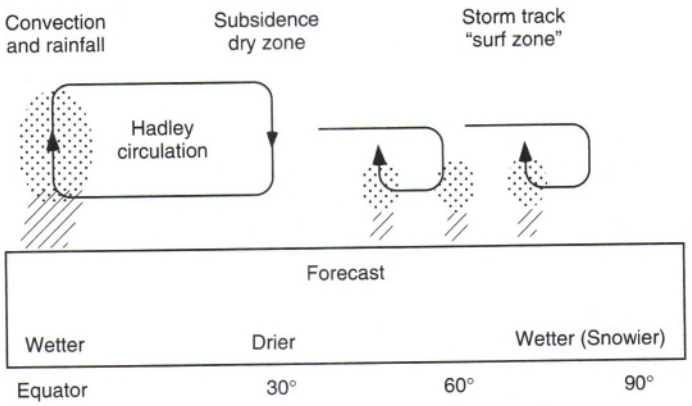

Figure 12-2 The atmospheric circulation and the rainfall forecast.

bone-dry air down to the surface and creating deserts at about 30 degrees latitude north and south. Warming the climate is expected to increase the Hadley circulation pattern, intensifying rainfall at the equator and further drying out the desert regions in the subtropics.

Meanwhile, precipitation in the highest latitudes is expected to increase because of the increase in temperature (because there is more water vapor in warm air). This increase in high-latitude precipitation plays a role in the projections for the large ice sheets (see next section).

Rainfall away from the equator can be divided into two types: storminess and monsoons. Storm-driven precipitation is strongest in particular "storm alleys" on Earth (Figure 12-2). The projection is that the rate of storm-driven rainfall would increase in a warmer world because the warmer air carries more water vapor and because the atmosphere would be in general stormier.

Monsoons are driven by a temperature contrast between the land surface and the ocean. The different temperatures drive the winds to blow in ways that systematically dump water as prodigious rainfall. Monsoon systems are sensitive to changes in the temperature differences that drive them, and their strength tends to vary from year to year even in a natural world. According to climate records derived from cave $CaCO_3$ deposits, monsoons are variable on longer time scales as well, switching on and off abruptly and staying switched for centuries and longer. The projection for the monsoon in southern China and India is to become stronger and stormier. Rainfall in the American Southwest is actually monsoonal in type in that it is driven by Pacific surface temperatures, and it seems to be declining.

Monsoons are particularly vulnerable to climate rearrangement.

Continental interiors are expected to dry out as a result of faster evaporation into warmer air. Even though rainfall globally averaged would increase in a warmer world, areas on Earth that are dry today in general are expected to become drier, increasing the likelihood of drought.

Droughts are driven by changes in the water cycle that vary from one climate model to the next, so forecasts of the impacts in specific regions are not very reliable. This is unfortunate, because drought is probably a more significant danger to agriculture than heat alone. When the results from the climate models from the latest IPCC exercise are combined, however, there is a consistent picture of drying in particular regions, such as the American Southwest, the Mediterranean, and Australia, which are already undergoing drought conditions (Plate 12-4).

Droughts are exacerbated by a feedback from plants. Healthy plants act to capture groundwater, preventing it from running off in a stream but instead evaporating it into the atmosphere, a process called **transpiration**. In this way, plants, and in particular the aggressive plant life of the tropical rain forests, sustain their own existence by recycling rainfall. If the plants die back, rainwater tends to run off, ultimately flowing back into the ocean in rivers rather than re-evaporating into recycled rainfall. The loss of the plants acts to amplify the drought, making the onset of the drought more of a flip-flop than the decline of the rainfall that drove it. The loss of foliage also makes it harder to break out of a drought when rains resume.

Dying vegetation can lock in the drying.

The carrying capacity of the land ultimately depends on water availability. During the Dust Bowl drought in the American Southwest in the 1930s, 85% of the residents of the state of Oklahoma picked up and left. There are proxy records in lake and ocean sediments of droughts in that region in the prehistoric past that were much stronger and more persistent than the Dust Bowl. The Classic Mayan civilization collapsed in several stages that correlated with strong decade-long droughts as documented in lake sediments and cave deposits.

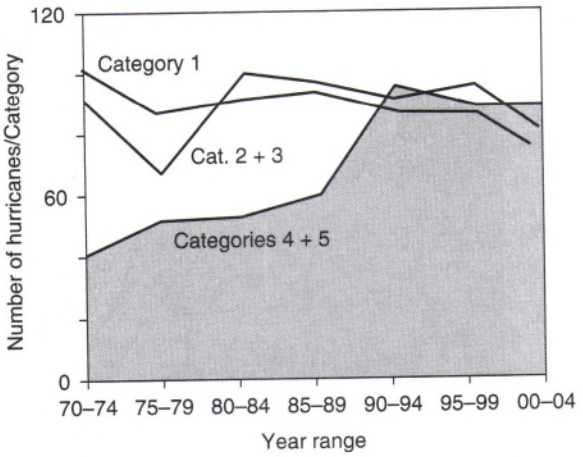

Figure 12-3 The frequency of different intensities of hurricanes through the last decades. From Webster et al., 2005.

Glaciers are expected to melt with warming, and indeed they have already begun doing so (Figure 11-4). This water contributes to a rise in sea level (see next section). Perhaps the most pressing social concern about the loss of glaciers is that they supply water through the summer to a lot of people (see Human Impacts section).

A warmer world would be a stormier world because storms are driven primarily by the heat of water vapor condensing into precipitation. Warmer air carries more water vapor, so there is more energy to be "wrung out" when warmer air rises and cools. Storms and weather are already observed to be getting stronger and more extreme. There have been more hard rains, longer and hotter heat waves, stronger tropical cyclones, and more droughts.

Tropical cyclones, also called typhoons or hurricanes, may get more intense or more prevalent in a warmer world, although there is considerable uncertainty about this. The number of hurricanes per year has been holding steady through the decades, but the frequency of the most powerful hurricanes, Categories 4 and 5 storms, has doubled in the past 30 years (Figure 12-3).

A warmer world would be stormier.

Every year there are about 90 tropical storms, 40 of which become cyclones. These storms grow from particular combinations of winds and pressures that serve as "seeds" for the storms. Whether the seeds grow or dissipate is determined by the structure of winds in the air, whether they blow in the same direction through the entire atmospheric column, or whether they shear the growing storm apart by blowing in different directions at different altitudes.

The hurricane draws its power from the water vapor in the warm air over ocean. Hurricanes do not form if the sea surface temperature is cooler than about 26°C, so their range would expand in a warmer world. Also, everything else being equal, warmer sea surface temperatures would make hurricanes stronger. But the future of hurricanes is difficult to predict reliably because their birth and growth are affected by subtleties in the structure of the atmosphere and ocean, which might change in a warmer world. The strength of a cyclone also depends on the subsurface temperatures of the ocean, because the wind tends to mix cold water up from below, and on the air temperature near the top of the troposphere. The bottom line is, there are good reasons to worry that cyclones might get more intense with rising CO_2, but the connection is not as simple as, say, the link between CO_2 and global mean temperature.

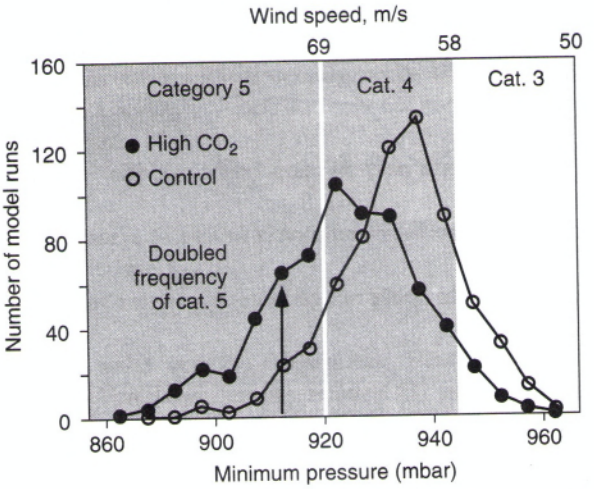

Figure 12-4 The distribution of wind speeds in model hurricanes for a control world (natural climate) and doubled CO_2. From Knutson and Tuleya, 2004.

Model-simulated hurricanes are more intense in a doubled-CO_2 world. Ordinary climate models do not have enough resolution, meaning that their grid points are not close enough together, to simulate hurricanes very well. Hurricanes can be simulated in global models, however, by a technique called **adaptive grid refinement**, essentially inserting grid points into a model when and where they are needed. Alternatively you can think of it as running a second, high-resolution model in the area where a hurricane is, coupled to and exchanging information with a low-resolution global model. The model results in Figure 12-4 predict that there will more category 5 hurricanes in a high-CO_2 world.

A hurricane generates a rise in sea level called a **storm surge**. The low air pressure in the center of the hurricane acts to lift the ocean surface, and the winds tend to blow the water into the center in a pile. The storm surge is the aspect of hurricane Katrina that destroyed parts of New Orleans. If storms get stronger, their higher storm surges will add to the impact of higher sea level, discussed next.

Ice and Sea Level

There are two reasons why sea level would rise in a warming world. One is the **thermal expansion** of the water. Warmer water expands, filling up the ocean basin like mercury rising in a thermometer. Depending on the amount of warming and the circulation and mixing in the ocean, the IPCC forecast calls for about 0.1 to 0.4 m of sea-level rise attributable to thermal expansion alone by the year 2100. This is just the beginning, however, because it takes centures for heat to invade the oceans. Coupled atmosphere-ocean climate models suggest that a long-term CO_2 doubling might eventually, after a thousand years or so, raise sea level by 0.5 to 2.0 m as a result of expansion.

The other component of sea level rise is from **melting ice on land**. There are several functionally different types of ice in the Earth's climate system. **Sea ice** forms from seawater freezing at the surface and may be augmented by snow that lands on the ice. **Glaciers** are formed from compacted snow on a mountaintop and flow down mountains like silent rivers of ice (Figure 11-4). **Ice sheets** are larger than glaciers and are found today in Greenland and Antarctica. **Ice shelves** are pieces of ice sheets that have flowed out onto water, floating but still attached to the ice sheet.

Sea level changes slowly and will continue to rise for centuries.

Floating ice, the sea ice and ice shelves, does not raise sea level when it melts because the ice already displaces its own weight in water. When floating ice melts, its water exactly fills the hole that the ice had previously occupied. This is **Archimedes' principle**.

Ice on land however does increase the sea level when it melts. Of the land ice, the ice sheets in Greenland and Antarctica hold most of the water by far. Together, the two ice sheets could raise sea level by about 70 m if they melted, about the height of, say, a midrise 14-story hotel on Miami Beach. The mountain glaciers hold much less ice, about 0.5 m of sea level, but because they are smaller, they can respond much more quickly to changes in climate. Today, mountain glaciers are contributing more to the rise in sea level than the major ice sheets are, and about as much as from thermal expansion.

The ice sheets in Greenland and Antarctica are the slow giants of the rise in sea level.

The ice in an ice sheet flows, very slowly, from the center, where it accumulates as snow, to the fringes where it melts or runs into the ocean and breaks up into icebergs. The air at the base of the **Greenland ice sheet** is close to the melting temperature, and ice sheet models predict that the Greenland ice sheet would eventually melt if the world were about 2°C warmer than our natural pre-industrial climate (often defined as the climate of the 1950s). Melting Greenland would raise sea level by about 7 m, the height of a two-story building.

The **Antarctic ice sheet** is colder than the Greenland ice sheet, and most of the ice in Antarctica is thought to be relatively stable, not as sensitive to changes in temperature as that in Greenland. The vulnerable part of Antarctica is the **West Antarctic Ice Sheet**, which holds enough water to raise sea level by about 5 m. This ice sheet is unique in that it is sitting on bedrock below sea level (Figure 12-5). When the ice sheet first started forming, the bedrock was above sea level, but the crust gradually sank under the weight of the accumulating ice. The crust sank most deeply in the center, so the ice sheet is setting in a bowl below sea level.

The concern is that a warmer ocean might drive the edges of the ice sheet to melt, allowing it to float free of the bedrock. Floating ice flows much more easily than grounded ice, pulling more ice from the ice sheet. Because the water gets deeper toward the center of the ice sheet, it would become progressively easier for the ice to float free, leading to an accelerating cycle of float, flow, and melt.

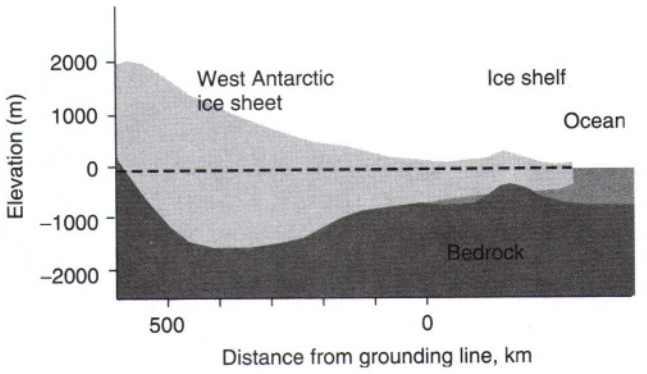

Figure 12-5 A cross-section through the West Antarctic Ice Sheet. Redrawn from Oppenheimer, 1998.

There is geological evidence that the size of the West Antarctic ice sheet may have been smaller during the warmer-than-today Pliocene time, about three to five million years ago. This would suggest that the West Antarctic Ice Sheet might become unstable after 3°C of warming, a slightly higher trigger than for Greenland.

Overall, the IPCC forecast for the rest of the century is for sea level to rise 0.1 to 0.5 m, approximately half attributable to expansion and half to the melting of ice, mostly from small mountain glaciers. Models of Antarctica and Greenland tend to predict that it would take thousands of years for these ice sheets to respond fully and that not much will happen in the coming century. However, recent events, and reconstructions of prehistoric events, give reason to believe that real ice sheets might respond to climate change in ways that the ice sheet models cannot simulate yet. For this reason, the IPCC specifically did not include the possibility of changes in the flow of ice from the sheets into the ocean, what they called "dynamical changes" in the ice, in their latest sea level rise forecast. The forecast comes with a potentially very large asterisk.

Ice on Earth knows a few things about how to melt
that scientists have not figured out yet.

Ice shelves have demonstrated an ability to self-destruct catastrophically. A piece of the **Larsen ice shelf** on the Antarctic peninsula, the size of Rhode Island, collapsed into a sea of icebergs within a few months in 2002 (Figure 12-6). Ice shelves do not themselves affect sea level when they collapse into bergs and melt because they were already floating in the water. However, their presence seems to restrict ice flow from the ice sheet farther inland toward the sea.

Within the ice sheet are rivers of ice called **ice streams**, flowing at speeds of hundreds of meters per year. Upstream of the Larsen B ice shelf on the Antarctic Peninsula, and the collapsing Jakobshavn ice shelf in Greenland, the ice streams accelerated markedly after the ice shelves collapsed. Several of the ice streams draining the West Antarctic ice sheet run into the Ross ice shelf, which is within a few degrees centigrade of the Larsen ice shelf temperature before it exploded.

The significance of iceberg discharge is that it is an extremely efficient method of melting ice. Melting of an ice sheet in place is slow because it takes a long time for the atmosphere to carry that much heat up there. Icebergs move the ice mountain to the sun.

There is also evidence from the prehistoric past of fast collapses of ice sheets. The Laurentide ice sheet, perched on North America during glacial time, purged large amounts of ice into icebergs periodically in what are called **Heinrich events**. The primary evidence is the finding of layers of rocks in open-ocean sediments large enough that they could only have been carried there in floating ice. The sediments tell us that the events lasted a few centuries, and there must

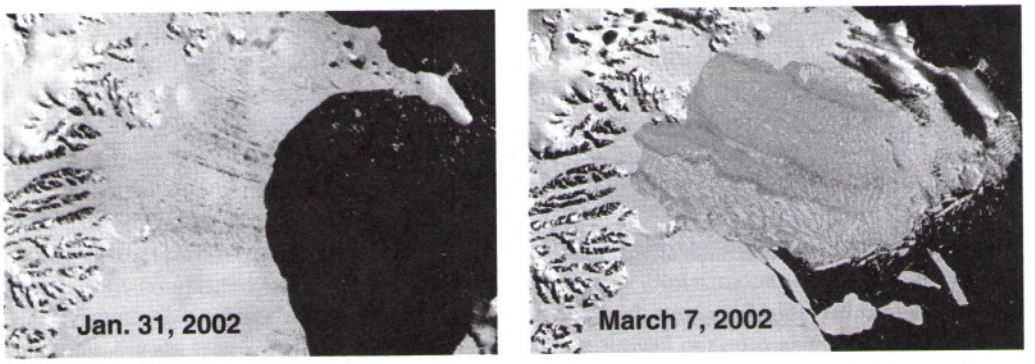

Figure 12-6 Satellite images of the Larsen ice shelf on the Antarctic Peninsula. A huge area of ice shelf exploded into icebergs in just a few weeks.

have been a veritable flood of icebergs, enough to change the circulation of the North Atlantic and alter the climate around the world. The events lasted a few centuries and are estimated to have raised sea level by something like 5 m.

Currently there are no computer models of ice sheets that can reproduce the Heinrich events. There is too much ice-rafted debris spread out over too much of the North Atlantic. Ice sheet models do not collapse that quickly or pick up that much debris. The question is whether the Greenland or West Antarctic ice sheets could also collapse in a similar way. Presumably, if it started, it would be completely unstoppable, running its course over a few centuries. Maybe sea level rise from one collapsing ice sheet could provoke the other to go.

Sea level at any given location on the Earth depends on the total volume of water in the ocean, of course, but also on local geological movement of the ground, up or down. The largest vertical motions on the surface of the Earth today are the result of melting of ice sheets from glacial time. Remove all that weight and the local crust will float higher relative to the surrounding crust. There is also vertical motion in other parts of the world that is comparable to the projected rate of the rise in sea level. Bangladesh is a hard example; the local sinking or subsidence rate of the land there is about 0.5 cm/year, comparable to the projected rate of sea level rise, doubling the inundation that Bangladesh would experience just from the rising ocean.

It might be possible to defend the some of the land against the invasion of the ocean. Much of Holland is located below sea level, and the ocean is kept at bay with dikes and pumps. This could presumably work for cities like Manhattan and New Orleans, but long low-lying agricultural areas such as in Bangladesh and Egypt will be more challenging to save. An increase in sea level of 1 m would inundate about 10% of the farmland in these countries, displacing millions of subsistence farmers. Today the Pacific island of Tuvalu imports food because they can no longer grow their own as a result of salt encroachment in their ground water.

The long-term geologic record tells a much more alarming story about Earth's temperature and sea level than one would infer from the IPCC forecast to the year 2100 (Figure 12-7). During glacial time, Earth's average temperature was about 6°C colder than today and sea level was 120 m lower. The Pliocene, three million years ago, comes before the time of glacial-interglacial cycles, a warmer time with sea level 25 m or so higher than today.

During times of hothouse climate, say 40 million years ago, the temperature of the Earth was perhaps 4° to 5°C warmer than it is today. The sea level 40 million years ago is difficult

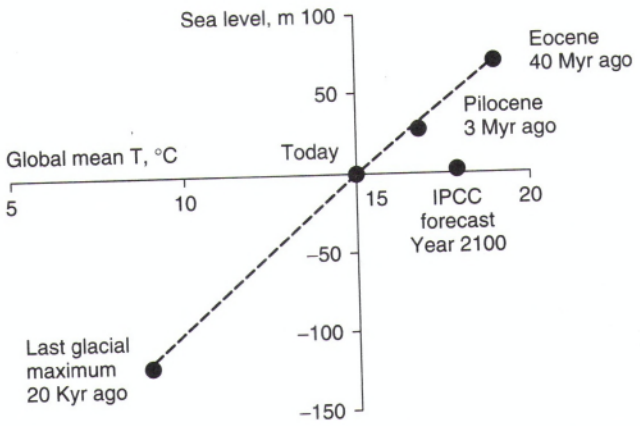

Figure 12-7 The relationship between sea level and temperature on geologic time scales. The Intergovernmental Panel on Climate Change forecast for the year 2100 is for less than 1 m of sea-level rise, whereas the geological reconstructions suggest that if the Earth stayed 3°C warmer for long enough, sea level could rise by around 50 m.

to pin down because on this long time scale, the continental crust bobs up and down, moving the beaches and corals that we find today in ways that have nothing to do with global sea level. However, the hothouse world was a time when there were no ice sheets on Earth, which would raise sea level on Earth today by 70 m if the Earth returned to that climate state.

Eventually sea level could change 100 times more than the forecast for the 2100.

Sea level in the geologic past changed by 10 or 20 m for each 1°C of temperature change. This is about 100 times more change in sea level than the IPCC forecast for the year 2100. The reason for the difference is the presumption that it will take longer than 90 years for the ice sheets to respond to the change in climate.

As explained in Chapter 10 (Figure 10-4), carbon mined from the Earth and emitted as CO_2 to the atmosphere affects climate for tens of thousands of years into the future, plenty of time for the ice sheets to respond. So ultimately, although ice sheets may respond slowly to climate, the carbon cycle is patient and can afford to wait. The target year of 2100 for IPCC forecasting is set by our own lifetimes and the time scale for some kind of conceivable political decision making. But 2100 is not really the appropriate time scale to discuss the phenomenon of the ice sheets responding to CO_2. It is as if we saw someone standing at the edge of a cliff contemplating jumping, and we advise that person that in the first 0.1 seconds after he jumped, nothing bad would happen (because the person had not hit bottom yet). We would be using an inappropriate time scale to describe the situation.

Abrupt Climate Change

An abrupt climate shift would be a surprise, like the ozone hole. Paleoclimate records show sudden flip-flops, where the climate changed in a few years and then remained in its changed state for centuries.

The ice core record from Greenland shows a period of stability called the **Holocene**, the past 10,000 years when civilization and agriculture developed (Figure 12-8). Before this, during the last ice age 20 to 80 thousand years ago, the climate of Greenland was less stable.

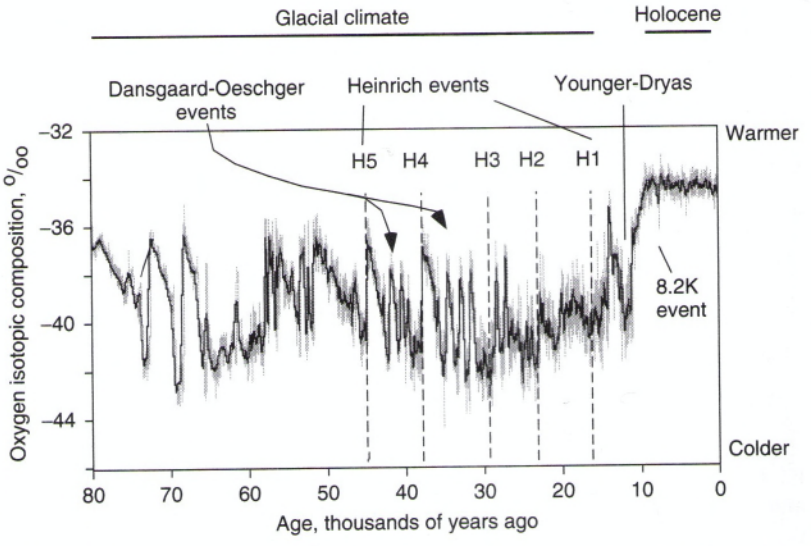

Figure 12-8 Temperature reconstruction from Greenland. From the Greenland Ice Sheet Project (GISP) II ice core.

Temperatures underwent 1,000-year swings called **Dansgaard-Oeschger (D-O) events**, sudden warmings of 10° to 15°C within a few years, followed in general by more gradual coolings. The D-O cycle is punctuated by the Heinrich events, times when the Laurentide ice sheet collapsed into bergs in the ocean. The climate impacts of these abrupt climate changes were most intense in the high northern latitudes but were felt as far away as New Zealand and Antarctica.

> In a way, the IPCC forecasts represent best-case scenarios because they are smooth and there are no surprises.

Scientists are still trying to figure out the reasons for all of the variability in the glacial climate (Figure 12-9). The circulation in the North Atlantic is one player. The Atlantic carries a

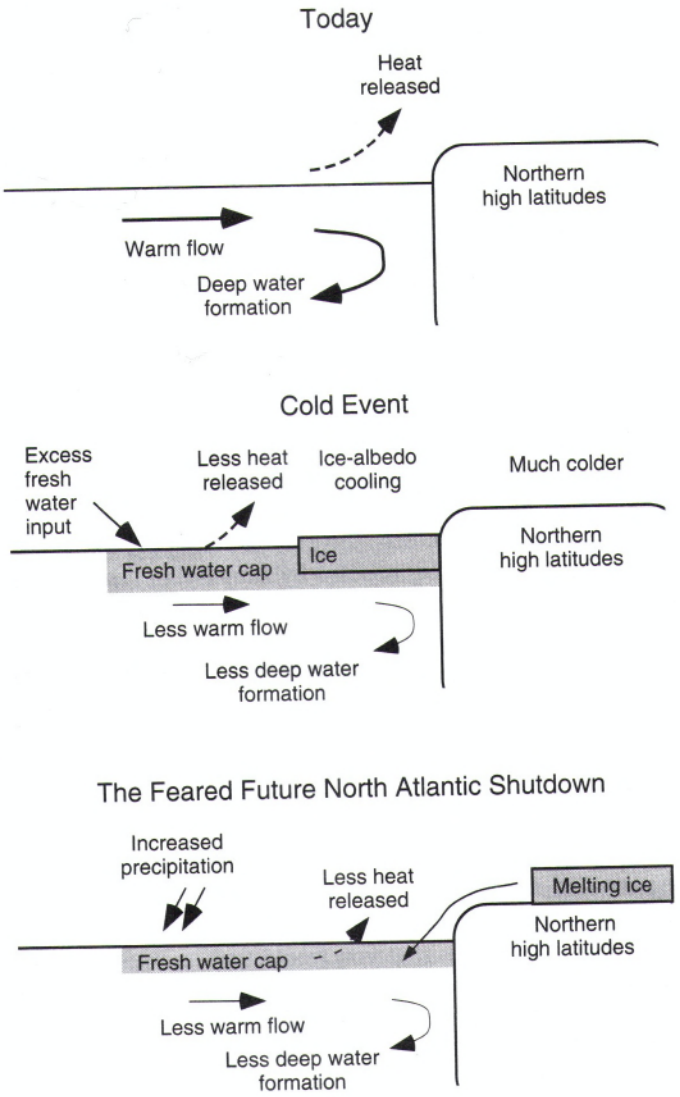

Figure 12-9 How the overturning circulation in the North Atlantic might affect the climate.

considerable amount of heat into the high-latitude northern hemisphere. Warm surface waters in the high latitudes cool and sink, making way for more warm surface flow, bringing in more heat. Tracers for the circulation and chemistry of the ocean, preserved in sediment cores, show that many climate changes in the past, such as the Heinrich events, were correlated with changes in Atlantic circulation.

Another ingredient in the climate shifts was sea ice. Cutting heat transport, perhaps capping the ocean with fresh water that would freeze before it would sink, resulted in an expansion of sea ice cover. Ice reflects sunlight, cooling the area further. Air over sea ice can also get much colder than air over open water can. The climate of Greenland, where ice core records come from, is sensitive to massive sea ice formation because it loses its maritime influence.

The abrupt climate change scenario for the future that people have fretted about is a cousin to the cold configuration of the glacial climate, in which the overturning circulation in the Atlantic slows down, allowing the northern high latitudes to cool. This "Day After Tomorrow" scenario was already mentioned in Chapter 7. The overturning could be impeded by an increase in freshwater input to the North Atlantic surface ocean. The largest potential source of fresh water is the Greenland ice sheet, but it would also rain and snow more in the high latitudes of a warmer world.

Current thinking is that the "Day After Tomorrow" scenario, of a return to an ice age triggered, paradoxically, by global warming, is unlikely because the warming influence of the rising CO_2 will be stronger than the local cooling influence of changing the ocean circulation. My personal intuition is that looking too slavishly at past abrupt climate changes to predict the future is like a general in an army always planning for the last war. My bet is that future abrupt climate changes are going to be surprises.

Biological Impacts

The character of the land surface, whether it is hardwood forest or grassland, is determined to a large extent by the local climate. Temperature is important, of course, although it may be the coldest temperature of the year that really matters, or the warmest, rather than the annual average. Precipitation also plays a role in shaping the natural landscape. And of course the human footprint on the land surface includes agriculture, decorative lawns, and pavement.

The infinite complexity of the real landscape can be modeled by simplifying it into some manageable number of different biome types, such as "tropical deciduous" or "savanna" (Plate 12-5). Biome models are based on the physiologies of plants of various types and keep track of plants, metabolic energy, water stress, nutrient availability, and soil properties. Different biomes have different capabilities and tolerances, and they compete with each other for land surface area.

The equilibrium biome response to a new climate can probably be predicted fairly confidently because the distribution of biomes on Earth today is fairly well correlated with climate. The simplest model for terrestrial biomes could simply be a look-up table of the ranges of conditions inhabited by each biome type.

It is more difficult to forecast transitions between one climate state and another. Some organisms, like insects, move easily, but forests have to move by scattering seeds and a slow process called **ecological succession**. When a forest grows after a clear-cut, the first set of plant and tree species will be different from the species that you would find in an old-growth forest under the same climatic conditions. The process of ecological succession is not trivial to understand in the natural world, which makes it even more difficult to forecast for the future.

The biotic response of a climate model is shown in Plate 12-5. The most striking change in Earth's landscape is in the Arctic. The biome response is strong there because the climate change is intense. The melting permafrost described above also changes the biotic landscape. The model in Plate 12-5 experienced a near total loss of the tundra biome by the year 2300 and the loss of most of it by 2100.

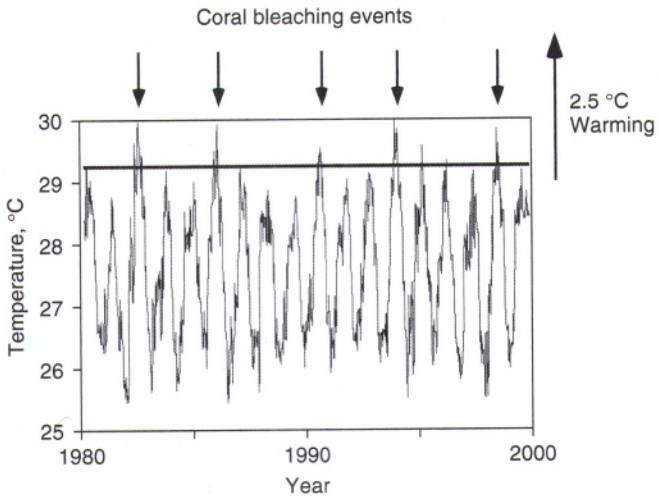

Figure 12-10 Coral bleaching events in Tahiti. Bleaching events occur whenever temperature exceeds a threshold value. A future warming of 2.5°C would be very large compared with the coral stress level. From Hoegh-Guldberg, 2005.

Polar bears are vulnerable to melting sea ice. Polar bears eat only in the winter by fishing for seals through holes in the ice. In summer, when the ice near the coast melts, the polar bears have to live on their accumulated fat. The polar bear as a species may find refuge in a remnant area of sea ice north of Greenland, but where the ice is gone the polar bears will go locally extinct.

In the ocean, coral reefs appear to be vulnerable. Reefs are built by sedentary animals called corals. The corals house symbiotic algae, plants that can perform photosynthesis to aid the nutrition of the corals. Corals almost everywhere in the world are under attack from runoff pollution, clouding the water and cutting their algae off from sunlight. Overfishing threatens corals, as do diseases, invasive species, and acidification of seawater by invasion of fossil fuel CO_2 (Chapter 10). In addition to all these struggles, corals are vulnerable to increases in temperature.

When corals are stressed, they respond by expelling their symbiotic algae. This is called **coral bleaching** because of their loss of color. Bleaching may be a mechanism for the coral to try to find new symbiotic algae that are more suited to the conditions they find themselves in, but it is a measure of desperation. Bleaching is often followed by the death of the coral. Figure 12-10 shows a record of temperatures in Tahiti, with arrows indicating times of coral bleaching events. The correlation between heat spikes and bleaching is very clear. Sediment cores in Caribbean reefs indicate that the degradation of reef communities is more widespread than has been seen in centuries. Corals are also challenged by the acidification of the surface waters from rising CO_2.

In general, the diversity of life (number of species) on Earth is already decreasing because the natural world is restricted and fragmented by human land use. Climate change can only amplify this extinction trend by demanding that natural ecosystems get up and move, just when they are restricted by human land use and therefore least able to do so.

Human Impacts

The strongest direct effect of a warming climate on human welfare will probably be due to changes in water availability. The world is drier today than the more natural world of 1950 and would continue drying in a warmer world. A drought of a few years' duration, or a decade,

can be endured, but rearrangements of the climate system in a warmer world could persist for centuries. Adding to the problem would be melting mountain glaciers and snow pack, which today serve as a source of summertime fresh water in many parts of the world, such as along the Himalayas in India, Pakistan, and Uzbekistan; along the Andes in Lima, La Pas, and Quito; and in the North American Pacific Northwest.

Other aspects of climate changes may also affect crop yields. Corn is sensitive to heat spikes, and just a few can impact the bottom line for the entire season. On the other hand, increasing CO_2 concentration in the air is expected to boost agricultural production by the CO_2 fertilization effect (Chapter 10). Higher CO_2 levels help plants deal with water stress by allowing them to get the CO_2 they need for photosynthesis without opening their stomata as much. Another important factor in the forecast is adaptation. If corn no longer grows in a region because of frequent heat waves, the farmer will plant some other crop that is more heat tolerant.

The story of agriculture in the past century has been explosive, with production growing even faster than population and at ever diminishing costs. The great success of the agricultural revolution seems to argue against worrying about a collapse in global food production.

On the other hand, agricultural yields and the number of people that the Earth can support are products of the infrastructure of our civilization: fertilizers, transportation, and processing of the food. If that infrastructure broke down, it could lead to a collapse of the human population. It has happened before, to the classic Mayans, for example. Sustained regional drought or coastal flooding from a storm surge with rising sea level could lead to distressed migration of millions of people, which would stress the ability of civilized governance to cope. How many of us would survive if there were no food delivered to the grocery stores?

There is a concern that rising temperatures will widen the area where tropical diseases such as malaria and dengue fever will spread. Both have a significant impact on public health, and both appear to be spreading with an increase in the tropical zone of the Earth. In my opinion, the spread of tropical diseases is a serious threat, but it is not the first and most important reason to combat global warming.

In general, the impacts of a changing climate are expected to become stronger and more clearly negative as climate warms more intensely. The impacts would be stronger in the tropics and in the developing world, where there is less wealth to buffer setbacks from the weather and less infrastructure to deal with the aftermath.

TAKE-HOME POINTS

- Climate models that simulate the past predict huge climate changes in the future, relative to what civilized humanity has ever seen before.
- Drought is one of the most dangerous aspects of climate change, as continental interiors warm and dry out, despite a global increase in the amount of rainfall overall.
- Extreme weather events are already getting stronger and this trend is expected to continue.
- Sea level will continue to rise for centuries, from thermal expansion and melting land ice.

STUDY QUESTIONS

1. How can the forecast call for increased rainfall globally and also increased drought?
2. What is the role of vegetation in a drought?
3. Why would storminess increase in a warming world? What kinds of storms could be affected?
4. What are the factors that would increase the risk of storm-surge flooding associated with tropical storms?
5. Why do some kinds of ice on Earth change the sea level when they melt and other kinds do not?
6. Why does sea level take so long to respond to climate?
7. How do reconstructions of sea level changes in the geologic past compare with the forecast for the year 2100? Why?

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