1 FAST FORWARD

We live with familiar weather—ski areas are snowy, deserts are parched, rain forests drip. But what if our climate jumped to something totally unexpected? What if you went to bed in slushy Chicago, but woke up with Atlanta's mild weather? Or worse, what if your weather jumped back and forth between that of Chicago and Atlanta: a few years cold, a few years hot? Such crazy climates would not doom humanity, but they could pose the most momentous physical challenge we have ever faced, with widespread crop failures and social disruption.

Large, rapid, and widespread climate changes were common on Earth for most of the time for which we have good records, but were absent during the few critical millennia when humans developed agriculture and industry. While our ancestors were spearing woolly mammoths and painting cave walls, the climate was wobbling wildly. A few centuries of warm, wet, calm climate alternated with a few centuries of cold, dry, windy weather. The climate jumped between cold and warm not over centuries, but in as little as a single year. Often, conditions "flickered" back and forth between cold and warm for a few decades before settling down.

The history of this climatic craziness is written in cave formations, ocean and lake sediments, and other places. But the record is probably clearest and most convincing in the ice of Greenland. This incomparable, 110,000-year archive provides year-by-year records of how cold and snowy Greenland was, how strong the storms were that blew dust from Asia and salt from the ocean, and even how extensive the wetlands of the world were.

These records show clearly that Earth's climate normally involves larger, faster, more widespread climate changes than any experienced by industrial or agricultural humans. The 110,000 years of history in Greenland ice cores tell of a 90,000-year slide from a warm time much like ours into the cold, dry, windy conditions of a global ice age, a 10,000-year climb back to warmth, and the 10,000 years of the modern warm period. But the ice cores also show that the ice age came and went in a drunken stagger, punctuated by dozens of abrupt warmings and coolings. The best known of the abrupt climate changes, the Younger Dryas event, nearly returned Earth to ice-age conditions after the cold seemed to be in full retreat. The Younger Dryas ended about 11,500 years ago, when Greenland warmed about 15°F in a decade or less. A little more, slower warming then led to our current 10,000 years of climate stability, agriculture, and industry.

But smaller and slower climate changes during recent millennia have affected human civilizations in many ways—and these small climate changes seem to have been getting bigger. The "Little Ice Age" cooling that changed settlement patterns in Europe a few centuries ago was tiny compared to the Younger Dryas or the global ice age, but seems to have been the biggest change for thousands of years.

Records from many places beyond Greenland provide a longer, if fuzzier, view of climate history. Over the last million years, the pattern recorded in cores of Greenland ice has occurred over and over: a long stagger into an ice age, a faster stagger out of the ice age, a few millennia of stability, repeat. The current stable interval is among the longest in the record. Nature is thus likely to end our friendly climate, perhaps quite soon; the Little Ice Age may have been the first unsteady step down that path.

In our climate, great ocean currents sweep north along the surface of the Atlantic, are warmed by the tropical sun, and release that heat into the winters of northern Europe, allowing Europeans to grow roses farther north than Canadians meet polar bears. The ocean waters that cool in the north Atlantic then sink into the deep ocean and flow south on the first stage of a globe-girdling journey before returning. This "conveyor belt" circulation is delicately balanced—add a little too much fresh water to the north Atlantic from rain or melting icebergs, and the wintertime ocean surface will freeze to produce floating sea ice rather than sinking to make room for more hot water. Much evidence shows that the abrupt coolings and warmings occurred when the conveyor circulation suddenly shut off or turned on again, triggering other changes that spread across Earth.

Human-induced greenhouse warming appears capable of triggering a conveyor shutdown, by increasing precipitation in the far north and by melting some of the remaining ice sheet on Greenland. Strange as it seems, "global warming" may actually freeze some regions! But, if we slow down the warming, it is just possible that we can avoid an abrupt change and even help stabilize the climate.

This book is a progress report on abrupt climate changes. We will discuss what has been learned, how this knowledge was gained, and what it might mean to us. The existence of abrupt climate changes casts a very different light on the debate about global warming, so we will examine the greenhouse arguments under this new light. We won't find all of the answers—many are not known yet—but we will frame the questions, and we may gain some clues to our future.

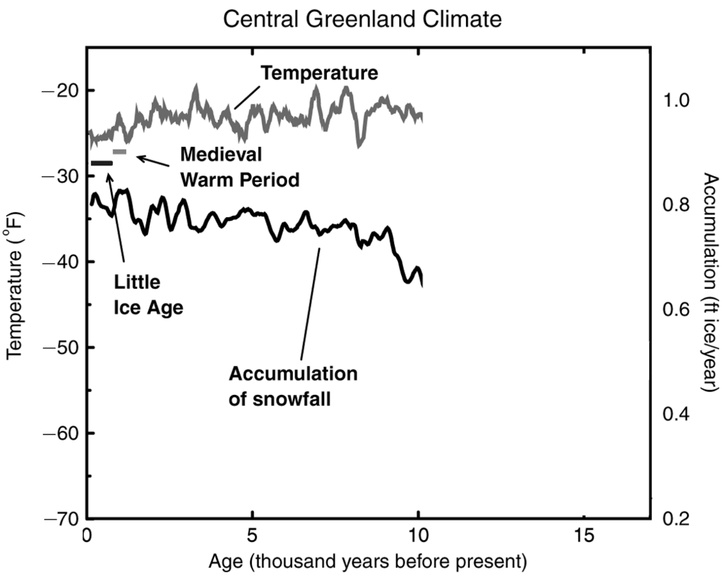
Climate Matters

Climate matters. It mattered to the Vikings, who settled Iceland, explored the New World, and were lured north to Greenland during a period of unusually warm weather a millennium ago. But the warmth did not last, and Viking settlements on Greenland slowly contracted as the climate cooled into the Little Ice Age (see Figure 1.1). The settlers brought farm animals into their houses during the cold winters. Eventually, the settlers ate their farm animals, then their dogs, then disappeared themselves. Climate mattered to Oklahoma farmers during the Dust Bowl years of the 1930s, when many people headed west as much of their soil headed east on withering winds. Today, with floods and drought, feast and famine, climate matters to many of us much of the time.

To be fair, climate is not everything. The victims of the Dust Bowl and of the cooling in Greenland may have contributed to their own plights through farming practices that pro-

FIGURE 1.1

The history of temperature and the rate at which snow accumulated in central Greenland over the last ten thousand years, reconstructed using techniques we will discuss soon. The horizontal bars indicate the mild, wet Medieval Warm Period, when the Vikings settled Greenland, and the colder, drier Little Ice Age, which helped drive the Vikings from Greenland. These records have been "smoothed" by averaging over a century or so, making a short cold time about 8200 years ago appear smaller than it was. The 1 to 2-degree shifts shown here are the kinds of climate change that most experts worry about. The data are from the 1997 paper by Cuffey and Clow cited in the Sources and Related Information.



moted soil erosion, and the Oklahomans were fleeing a great economic depression as well as a change in the weather. While the Vikings froze out of Greenland, their "Eskimo" neighbors, the Thule Inuit, readily survived the cooling.

Still, the Assyrians, the Maya, the Anasazi, and other ancient civilizations seem to have risen to glory while nature watered their crops, and to have fallen when those crops dried out. Climate certainly mattered to them, and it certainly will matter to us.

One of the important debates of our time centers on global warming. On one side are those who argue that human-caused changes in climate will make our lives so difficult that millions of us may die, and the fabric of our civilization may be changed forever. On the other side are those who warn that efforts to avoid such a hypothetical fate may cause us to commit economic suicide and trigger the decay that we fear. To resolve this important debate, thousands of people and millions of dollars are currently devoted to the development of an "Operator's Manual" for planet Earth. Land and water, air and ice, soils and plants—if we can figure out how they work, how they are wired together and depend on each other, maybe we can then make wise decisions about global warming, ozone depletion, and other globe-girdling questions.

This effort is called Earth system science. It is mostly about observing Earth here and now, understanding modern processes, and building models of those processes to use in making predictions. But history also plays a role, in two ways. Just as the records of past peoples help us understand human society, the records of past climates help us learn how the Earth system works. And just as modern political scientists can test their ideas against the history of humans, Earth system scientists can test their models against past climate changes.

The climate models these scientists test are highly altered, computerized weather forecasting tools. If you decide to learn to forecast the weather, every day offers a new problem, and the next day provides the answer in the back of the book. A weather forecaster in training can practice predicting tomorrow's weather more than a thousand times during a college career.

Forecasting the climate is not so easy. Consider a hypothetical modeler who informs a U.S. congressional committee that disaster will arrive in a century unless we change our ways. The chair of the congressional committee is unlikely to subscribe to the doctrine of scientific infallibility, and may harrumph that economic policy should not be based on untested computer output. The real winners and losers of such a debate will be the great-grandchildren of the disputants, because modeler and congressperson alike will have been recycled themselves before the forecast can be tested.

It would be better if the scientist could also tell the congressional committee, "The model that predicts future problems has been tested by simulating many climates of the past, that were wetter and drier, warmer and colder, with greenhouse gases higher and lower than today, and the model successfully reproduced the observations. The model has been used to run simulations that started in the previous warm period and went through the most recent ice age to today, and successfully matched the changes that brought us here." The congressional committee would have a much harder time dismissing such a scientist as a crackpot. But to test our models against the history of climate, we must know that history.

These questions are far from academic. The Medieval Warm Period that opened Iceland, Greenland, and North America to the Vikings, and the Little Ice Age cooling that helped drive the Vikings from Greenland, caused glaciers to advance across farms in Norway, and allowed Hans Brinker to skate on the canals of Holland, were dwarfed by the Younger Dryas and other dramatic climate jumps that ended the last ice age, as shown in Figure 1.2. Some climate models suggest that such jumps could return, and that human activities may cause—or prevent—such a return. Many of us believe that it would be prudent to understand the large climate jumps of the past. This book is an attempt to advance that understanding in some small way.

In the next chapter, you will find a brief introduction to climate history, including the central role played by ice cores. I have been fortunate to help in reading ice-core records during three trips to Antarctica, five trips to Greenland, and countless hours in frozen laboratories. Most of us who study ice cores started out by trying to learn how the ice actually records climate, and Part II of this book provides an introduction to the many methods we use. These methods have taught us amazing things about the climate, which are described in Part III. Those results have forced us to learn about oceanic and atmospheric processes far beyond the ice sheets, as described in Part IV. Finally, all this effort gives us some insight to the future, as described in Part V.

FIGURE 1.2

The history of temperature and the rate at which snow accumulated in central Greenland over the last 17,000 years. The prominent Younger Dryas cold event, and the warmings and coolings before it, dwarf the climate changes that helped chase the Vikings around. The scales on this figure are identical to those on Figure 1.1, and the data are from the same source.