

FROZEN EARTH

THE ONCE AND
FUTURE STORY OF

ICE AGES

DOUG MACDOUGALL

WITH A NEW PREFACE

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*For Grace and Lorn Macdougall,
who always encouraged exploration*

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PREFACE TO THE 2013 EDITION

Ice ages are global episodes of extreme climate change. For that reason, understanding them—why they occur, how they impact our planet, what brings them to an end—provides crucial information for anticipating how climate will change in the future and what the effects may be. Since this book was first published, scientists have made great strides toward untangling the complex interplay of factors that affect the Earth's climate. Much of this progress has come through careful study of ice ages, especially the most recent—the Pleistocene Ice Age.

What are some of the advances climate scientists have made? They include a clearer understanding of various forcing factors (parameters with the potential to change climate, for example the greenhouse gas content of the atmosphere), improvements in computer modeling of future climate change, and the identification of previously unrecognized processes that may have a profound impact on climate. A key ingredient has been the availability of better physical records of climate—for example, ice cores from the Antarctic that reach further back into the past than those previously available, sediment cores from a Siberian lake that provide a high-resolution record of northern climates over nearly the entire duration of the Pleistocene Ice Age, and cave speleothems (such as stalactites) that accumulate slowly, drip by drip, over long periods. These materials give us a window into the changing ice age environment through the climate proxies they contain: chemical and isotopic properties that reflect past temperatures or other environmental characteristics, biological tracers such as pollen grains that reveal the local climate, and other properties that can give clues to precipitation, windiness, seasonality, and other environmental parameters.

This short preface cannot do justice to the immense amount of research on ice age- and climate-related issues that has been carried out over the past few years. But I'd like to focus on a few specific studies that give a taste of the kind of work being done. The first of these deals with the how and why of our planet's warming up from the frigid peak of its most recent cold period a little more than twenty thousand years ago, a time that scientists refer to as the Last Glacial Maximum, usually abbreviated as *LGM*, when thick glacial ice blanketed parts of the United Kingdom and Russia, much of Scandinavia, and large portions of North America, pushing down far south of the Great Lakes.

The Pleistocene Ice Age, which has gripped the Earth over approximately the past two and a half million years, has not been monotonously cold. Instead

climate has cycled between long icy intervals and relatively short warm periods like now, which geologists call interglacials. Analyses of gas bubbles trapped in ice cores from Greenland and the Antarctic—tiny samples of air from the past—show unequivocally that the atmosphere had high concentrations of greenhouse gases during the interglacial warm periods and low concentrations during the cold intervals. The ice cores provide information from times long before humans began to influence the atmosphere, so the greenhouse gas variations they record were entirely natural. The question is, were natural increases in carbon dioxide and other greenhouse gases the cause of warm interglacial periods, or were they somehow a result of the higher temperatures? Clearly this is an important question for understanding how the Earth's climate will respond to greenhouse gas increases caused by humans.

Until recently, the answer to this question seemed to be that the high concentrations during the interglacials were an effect of the increasing temperatures, not the cause. This conclusion was drawn from detailed studies of Antarctic ice cores, which showed that as the Earth warmed into the interglacial, rising temperatures (measured via isotopic proxies in the ice) slightly preceded the greenhouse gas increases (measured directly in gas bubbles from the same ice cores). The time difference was small, and the results were crucially dependent on accurate dating of the ice cores. But the data seemed robust and the conclusion inescapable. Although higher carbon dioxide levels would have enhanced the warming, something else must have been the primary forcing factor.

However, recent work by an international group of climatologists, published in the journal *Nature*, has challenged that conclusion ("Global Warming Preceded by Increasing Carbon Dioxide Concentrations during the Last Deglaciation," by Jeremy D. Shakun and colleagues, *Nature* 484, 5 April 2012). These scientists realized that temperature data from the Antarctic ice cores reflect only local temperatures, whereas greenhouse gas results from the same cores provide information for the Earth as a whole because gases in the atmosphere are well-mixed globally. The researchers wanted to find out what the story would be if they compared the greenhouse gas results with temperature data that were also averaged globally.

In their study Shakun and his colleagues examined temperature information from a globally distributed set of eighty different natural records, mostly ice and sediment cores, through the period from the onset of the most recent deglaciation to the point when the Earth's climate reached approximately its present state (roughly the interval between twenty thousand and eleven thousand years ago). The data show that throughout most of that interval, increasing global average temperatures lagged increasing carbon dioxide concentrations by several hundred years. Surface temperatures averaged for the Earth as a whole evidently changed on a different timescale from those at the sites of the Antarctic ice cores. The authors concluded that greenhouse gases, particularly carbon dioxide, were the primary cause of the global warming and melting of the glaciers.

However, there is a twist in the tale. Or rather, two twists. The first is that the

pattern (although not the total degree) of warming differs between the Northern and Southern Hemispheres. The second is that for a short interval at the very beginning of the deglaciation—in contrast to the rest of the period—the Earth's average temperature rose by a small amount, about 0.3°C (less than 1°F), *before* carbon dioxide began to rise. What do these findings imply? Taking the second observation first, it appears that the initiation of deglaciation—the very beginnings of ice sheet melting—occurred not because of increased greenhouse gases in the atmosphere after all but through minor solar heating of the Northern Hemisphere. Because of regular variations in the Earth's orbit (described in chapter 5), insolation (the amount of solar energy that the Earth's surface receives) was increasing rapidly at high northern latitudes at this time. The temperature rise this caused was small but still sufficient to initiate the melting of Northern Hemisphere glaciers. In a kind of domino effect, this slight warming set off other processes, including the rise of greenhouse gases, that amplified the initial temperature increase many times over and drove the large-scale interglacial warming.

One of these feedback processes was a reduction in reflectivity, or albedo, as the area covered by ice decreased. With less snow and ice, the Earth retained more of the sun's energy instead of reflecting it back into space, raising temperatures further. This is happening today in the Arctic, which is warming more rapidly than other parts of the Earth as the extent of sea ice diminishes. But even more important during the last deglaciation were changes in ocean circulation.

How does ocean circulation affect climate? To understand this it's necessary to remember that because of their huge volume, the oceans hold a tremendous amount of heat. Circulating ocean waters carry this heat from one place on the globe to another. Also—and especially important in terms of the warming and cooling cycles of ice ages—the oceans contain a very large amount of carbon. Some of this is present as dissolved carbon dioxide, and much of the rest can easily be transformed into carbon dioxide. In total, the oceans contain about fifty times as much carbon as the atmosphere. The rapid increase in carbon dioxide during the most recent deglaciation apparently happened when changes in ocean circulation released some of that carbon into the atmosphere.

Ocean circulation is strongly influenced by the geographical distribution of the continents. In the present-day configuration it is largely driven by warm tropical water flowing northward in the Atlantic Ocean, cooling and becoming saltier due to evaporation as it goes. Both these processes make the surface water denser, and in the North Atlantic it sinks, drawing even more tropical water northward to replace it, thus maintaining the circulation pattern (the dense, cold water descends to the deep ocean and flows south toward the Antarctic and eventually into the Indian and Pacific Oceans). Shakun and his colleagues suggest that at the beginning of the most recent deglaciation, the slight warming of northern polar regions caused by increasing insolation slowed or even stopped this pattern of circulation. How did this happen? Fresh water (which is considerably less dense than salty seawater) from the melting glaciers flowed into the North Atlantic

decreasing the density of the surface water to the point where it could no longer sink. This shut down the northward transfer of warm water from the tropics, leading to warming of the Southern Hemisphere and modest cooling, or at a minimum slower warming of, northern polar regions. Climatologists refer to such ocean-driven temperature alternations between hemispheres as the bipolar seesaw. As the southern oceans warmed, Antarctic sea ice cover decreased, and changes in southern ocean circulation released carbon dioxide into the atmosphere, enhancing warming globally.

If you're not already familiar with some of these processes, following the scenario just described may set your head spinning. It involves a complex series of interrelated events driven by multiple climate-forcing mechanisms, amplified by feedbacks such as changes in albedo or ocean circulation patterns. But then, as natural systems are complex, and the bottom line from the work of Shakun and his colleagues is that the greenhouse gas carbon dioxide was the primary forcing mechanism for global warming during the most recent deglaciation. Currently, this research is the most extensive and thorough examination of what caused temperatures to rise globally from the LGM to the present. It is always possible that future work will change some of the details, but for the moment this is one of our best guides for understanding how climate may react to future changes.

An interesting aspect of this work is its conclusion that the ultimate trigger for deglaciation was increasing insolation at high northern latitudes, even though—once the ice age glaciers had begun to melt—carbon dioxide was the primary forcing mechanism for the bulk of the warming. One of the earliest workers who attempted to explain glacial cycles, James Croll, recognized the importance of changes in northern insolation more than 150 years ago; later (early in the twentieth century) Milutin Milankovitch expanded on this idea (see chapters 6 and 7). What these perceptive scientists didn't understand, though, was that the key role of northern summer insolation in Pleistocene Ice Age cycles was at least partly due to the present-day configuration of the continents.

Why is this? Think about the current situation: the South Pole lies within the Antarctic continent, the bulk of which is south of 70° latitude. When global temperatures are low, snow and ice can build up quickly to form a continent-scale ice sheet. But exceptional cold is required to maintain year-round sea ice beyond the continent, so such ice does not extend significantly farther north today. In contrast, the North Pole falls in the Arctic Ocean, a small ocean surrounded by continents on which glaciers build up and retreat in response to relatively small temperature changes caused by variations in Northern Hemisphere insolation. Feedback mechanisms then amplify these changes and affect temperature globally. About twenty-two thousand years ago, during the LGM, such processes allowed glaciers to reach as far south as 40° north latitude in North America. Ice ages in the Earth's distant past (see chapter 8) occurred at times when the arrangement of continents was radically different from today's. Undoubtedly, insolation changes were important for these too, but likely in quite different ways.

The work of Shakun and his colleagues examined only the most recent deglaciation, spanning approximately the past twenty thousand years. But the

Pleistocene Ice Age is characterized by multiple cycles of warming and cooling, ice retreats and advances, stretching back two and a half million years or more. Detailed, high-resolution records through all of these cycles are rare. For example, Greenland ice cores, a primary source of information about past Northern Hemisphere climate changes, extend to only 130,000 years ago, covering little more than one complete cycle. However, during the winter of 2008–9, a group of scientists and engineers operating under the aegis of the International Continental Scientific Drilling Program retrieved sediment cores that record the local climate in northeastern Siberia through nearly all of the Pleistocene Ice Age cycles. The cores were drilled from a lake (with a tongue-twisting name: Lake El'gygytyn) that occupies a 3.6-million-year-old meteorite crater about one hundred kilometers (sixty-seven miles) north of the Arctic Circle. The availability of a continuous record of local Arctic environmental change through the Pleistocene Ice Age is tremendously important because it permits climatologists to compare the real climate variability, as recorded in the sediment cores, with that predicted by climate simulations run with different forcing factors. This is especially valuable for the Arctic because both climate models and observations (including temperature records from the past few decades) indicate that northern polar regions are considerably more sensitive to global warming than other parts of the Earth.

The scientists who examined the Lake El'gygytyn sediment cores recently summarized their work in the journal *Science* ("2.8 Million Years of Arctic Climate Change from Lake El'gygytyn, NE Russia," by Martin Melles and colleagues, *Science* 337, 20 July 2012). What did they learn? Two observations stand out. The first is that in northern Siberia, many "super interglacials," short intervals when local summer temperatures reached levels considerably higher than those of today, punctuated the long Pleistocene Ice Age. The second is that these periods of high temperatures in Siberia correspond closely in time with episodes of ice sheet meltback in the Antarctic that are known from ocean sediment cores.

Melles and his colleagues looked in detail at several especially warm super interglacials, with summer temperatures 4°C to 5°C (7°F to 9°F) higher than those of today, and investigated possible forcing factors that could have produced such temperatures. What they discovered is surprising. Climate simulations that included the effects of both local summer insolation and greenhouse gas forcing (the latter probably more important) could not reproduce the observed high temperatures and instead predicted temperatures that were no higher than those of non-super interglacials. And because the super interglacials at Lake El'gygytyn correspond to periods of sharp deglaciation in Antarctica, it is clear that these high-temperature intervals were not simply the result of localized extreme warmth. The super interglacials were global.

Why didn't the climate models reproduce the high super interglacial temperatures experienced at the Siberian lake? Clearly, still-unrecognized processes or forcing factors must have been involved. Melles and his colleagues speculate that ocean circulation—that great mover of heat around the globe—might be part of the answer, but they can't be sure exactly how. These results are

another reminder of just how complex the climate system is, and how difficult it is to construct simulations or models to predict accurately how temperature, rainfall, and the like will change in the future. More often than not questions answered spawn new questions, and climatologists—indeed, all scientists—always seem to face more work to get to the bottom of things.

Studies such as those described in the past few pages are remarkable achievements; they have detailed how surface temperatures, precipitation, vegetation, ocean circulation, and other aspects of the environment changed during the Pleistocene Ice Age. Even though questions remain, they have gone a long way toward elucidating the mechanisms behind glacial-interglacial cycles. But what about the ultimate question: what initiated the Pleistocene Ice Age in the first place?

In chapter 12, I describe one possible answer, an idea that was suggested not long before the initial publication of this book in 2004: that chemical weathering of the evolving Himalayan Mountains “drew down” carbon dioxide in the atmosphere, reduced the greenhouse effect, and cooled the planet. This may seem a bit confusing because the Pleistocene Ice Age began only about two and a half million years ago, when large-scale glaciers began to form in northern polar regions, yet the Himalayas are much older (they began to form about fifty million years ago when plate tectonic forces caused India to crash into Asia). However, temperature proxies in deep-sea sediment cores show that global temperatures declined steadily from approximately the time of the India-Asia collision (when they were much higher than they are today) until the start of the Pleistocene Ice Age. By about thirty-five million years ago, global temperatures were low enough for ice to begin to cover the Antarctic (which had previously been unglaciated) and climate feedbacks related to this ice cover further cooled the Earth until, eventually, Northern Hemisphere glaciation began. So the question of what initiated the Pleistocene Ice Age rests on what caused the long-term cooling that began around fifty million years ago.

It is well known that carbon dioxide from ordinary air, when dissolved in rainwater, is the primary agent of rock weathering and that extensive weathering depletes its abundance in the atmosphere. That young, rising mountain ranges are sites of intense chemical weathering is also well known. The coincidence in timing between the rise of the Himalayas and a global temperature decrease suggests that weathering of this young mountain range could have been responsible for the lower temperatures, through its effect on atmospheric carbon dioxide. But recently a new candidate has joined carbon dioxide drawdown as a possible cause of the global cooling: sulfur. What, you may ask, does sulfur have to do with climate? Potentially quite a lot. Sulfur is plentiful; in the form of sulfate (SO_4^{2-}), it is the fourth-most-abundant ion in seawater. Because of this, the oceans are a major source of sulfur-bearing aerosols in the atmosphere—suspended microscopic droplets that reflect incoming solar radiation. When the concentration increases, they reflect more solar radiation and the Earth cools. This effect was illustrated clearly in 1991, when a large eruption of Mt. Pinatubo

in the Philippines injected sulfur-bearing aerosols into the atmosphere, lowering global average temperatures by about 1°F for more than a year.

In a recent paper in the journal *Science* ("Rapid Variability of Seawater Chemistry over the Past 130 Million Years," *Science* 337, 20 July 2012), Ulrich Wortmann and Adina Paytan note that the record of past seawater sulfur content shows large and quite rapid changes, and they conclude that deposition and dissolution of vast quantities of the sulfur-rich mineral gypsum almost certainly caused at least some of this variability. Gypsum is abundant in so-called evaporite deposits, which are assemblages of minerals that form in hot, arid regions where salty seawater trapped in restricted basins evaporates. Large-scale evaporite deposits have formed many times during our planet's long history, as evidenced by the numerous salt mines found around the globe (in addition to being important sources of sulfur, evaporites provide us with table salt and potassium for fertilizer). But evaporite minerals are not very stable at the Earth's surface when exposed to ordinary precipitation, they dissolve readily.

Wortmann and Paytan's analysis indicates that the sulfur content of the oceans started to increase rapidly (geologically speaking) approximately fifty million years ago—near the time when uplift associated with Himalayan mountain building began. The authors conclude that this uplift exposed large-scale evaporite deposits to erosion. (Undissolved remnants of these deposits still exist stretching from Oman to Afghanistan, Pakistan, and India.) Large amounts of gypsum in the uplifted deposits dissolved, substantially raising seawater sulfur content and thereby increasing the concentration of sulfur-bearing aerosols in the atmosphere, which ultimately resulted in global cooling. Plate tectonics—in this case the collision of India and Eurasia—thus played a major role in the cooling that led to the Pleistocene Ice Age, through both the drawdown of carbon dioxide and the supply of sulfur to the oceans. These observations illustrate how deeply interconnected even seemingly disparate Earth processes are.

Did plate tectonics and the movement of continents play a role in the Earth's earlier ice ages? We don't know for sure, because as scientists probe further and further back into our planet's history the evidence becomes increasingly fragmentary. The question of timing is crucial: for example, was the onset of an ancient ice age coincident with a continent-to-continent collision like the one that raised up the Himalayas, or not? Dating events accurately enough to answer such questions is more easily said than done. But one thing is clear from recent research: greenhouse gases, particularly carbon dioxide, played a major part in the initiation and the cessation of past ice ages, just as they have for the Pleistocene Ice Age.

Take, for example, the "Snowball Earth" theory, described in chapter 8. Over the past several years evidence has continued to accumulate that several glaciations, with permanent glaciers on the continents and ice covering even tropical seas, occurred during several discrete ice ages between about 600 and 750 million years ago. One of the problems many scientists initially had with the concept of a completely frozen Earth was that it would have been very difficult to melt: an ice-covered planet would reflect so much of the sun's energy that

would stay frozen. However, under such conditions it is likely that enough carbon dioxide (from volcanic eruptions) would eventually accumulate in the atmosphere to produce a “super greenhouse” world, leading to collapse of the ice sheet. Ending Snowball Earth-like glaciations may not have been as difficult as once thought. But what initiated these extreme events?

Since the first publication of this book, computer models of global climate have become ever more sophisticated, capable of incorporating more, and more varied, factors that influence climate. Several groups of scientists have used these models to investigate the probable forcing factors most important for initiating Snowball Earth-like conditions.

At the time of Snowball Earth glaciation, the planet was a very different place than it is today. For starters, the surface received about 6 percent less solar radiation (this is well known from studies of how stars like our sun evolve). Furthermore, all the evidence points to low-latitude locations for most of the existing continents, with none at the poles. Both of these boundary conditions are important for understanding the Snowball Earth glaciations.

The computer models don't tell us exactly what happened, and different versions give slightly different results. But all of the simulations point to the importance of two primary climate forcings: the reflectivity (albedo) of sea ice and the amount of carbon dioxide in the atmosphere. Even with solar radiation only 94 percent as strong as it is today, very low greenhouse gas concentrations are crucial for initiating Snowball Earth episodes in all climate models because—without continents in polar regions—extremely low temperatures are necessary to initiate freezing of the high-latitude seas and maintain year-round ice cover. As cooling proceeds under low greenhouse gas conditions and ice cover expands, however, albedo becomes the dominant factor and eventually results in runaway cooling. Exactly how much of the planet must be covered with ice and snow for this to happen varies depending on the model used. But the point at which runaway cooling begins can't be reached at all without very low greenhouse gas concentrations.

What lessons do the climate models have for the Anthropocene (an informal but very useful label for the time in our planet's history when human activity has overtaken natural processes as a primary driver of atmospheric chemistry and other aspects of our environment)? One startling conclusion from the best and most recent models is that even after anthropogenic carbon dioxide emissions slow down or stop, their effects will persist for much longer than is generally realized: tens of thousands of years. As the science journalist Mason Inman put it, “carbon is forever” (and he wasn't referring to diamonds, which are pure carbon).

Why do the effects of greenhouse gas emissions last so long? Won't the Earth start to cool down when humans stop putting greenhouse gases into the atmosphere? The simple answer to the first of these questions is that the climate system is complex and takes a long time to approach a new equilibrium state; the answer to the second is yes, but slowly and only (for thousands or perhaps even tens of thousands of years) to temperatures well above those of the period before

the emissions began.

Throughout the glacial-interglacial cycles of the Pleistocene Ice Age, carbon dioxide in the atmosphere has fluctuated between a low near 170 parts per million during the coldest intervals to about 300 ppm during the warmest. Today it stands near 395 ppm, the high value mainly due to the burning of fossil fuels. Even taking into account pledged emission reductions, the concentration is expected to continue rising and will likely exceed 850 ppm by the end of the twenty-first century. If carbon emissions were to miraculously fall to zero then, which appears less and less likely with each passing year, climate models indicate that atmospheric carbon dioxide would still be close to 500 ppm a thousand years later. Global average temperatures would still be several degrees Celsius (more than 5°F) higher than those of today. If we end up burning all of the Earth's fossil fuel reserves, atmospheric carbon dioxide will rise even higher over the next few centuries, to levels approaching 2,000 ppm, and recovery to conditions resembling those of today will take correspondingly longer—hundreds of thousands of years. Although about half of the anthropogenic carbon dioxide will eventually dissolve in the ocean, and chemical weathering of surface rocks will gradually consume most of the rest, these are slow processes. The atmospheric content—and the Earth's surface temperatures—will remain high for a very long time.

In the absence of human activity, the cycles of glacial and interglacial periods that characterize the Pleistocene Ice Age would continue, paced by Northern Hemisphere insolation changes. The next severe glaciation would occur some fifty thousand years from now, when the Earth's orbital parameters will result in low summer insolation at high northern latitudes. Once again ice would advance over large swaths of North America, northern Europe, and Asia. But if human activity releases so much carbon dioxide into the atmosphere that greenhouse warming overwhelms the cooling effect of decreased insolation, there will be no Northern Hemisphere glacial advance in fifty thousand years. The next glacial period will not occur for at least another half a million years, by which time most anthropogenic carbon dioxide will be gone. It is astonishing to realize that human activity over just a few centuries could have such a profound effect on our planet stretching tens to hundreds of thousands of years into the future.

To put things in perspective, I should point out that the Earth has experienced periods in the past—even very long periods—with atmospheric carbon dioxide at several thousand ppm, high global average temperatures, and no permanent glaciers except perhaps for a few small high-altitude ice fields. However, that was long before humans arrived on the scene and existing life had adapted to conditions we would consider extreme. The greenhouse gas content of the atmosphere is now rising at a rate unprecedented in the Earth's long history, entirely because of human activity. Most of the consequent environmental changes will occur over the next few centuries. Unless geoengineering solutions can be found—large-scale projects designed to slow or stop global warming by a variety of methods, including extracting carbon dioxide from the atmosphere and storing it permanently—humankind will have to adapt very nimbly in order to

avoid the partial or wholesale collapse of nations and societies. The environmental changes, including higher global temperatures, higher sea level, and potential drastic changes in biological diversity and species distribution, will affect agriculture, human health, and all populations living close to sea level. Who would have thought that studies of ice ages could give us such insight?

Doug Macdougall
October 2012

CHAPTER ONE

Ice, Ice Ages, and Our Planet's Climate History

The American author and historical popularizer Will Durant once wrote, “Civilization exists by geological consent, subject to change without notice.” That is not a new idea, even if Durant phrased it especially well, but nowadays many historians scoff at the notion of environmental determinism, the possibility that climate or geology may have seriously affected the course of human history. And yet there are still many places on this planet where Durant’s observation rings true, especially places with extremes of climate. One such is the arctic region, particularly Greenland. Ninety-five percent of that island country is covered by ice. Towns and villages cling to the coastline; at their backs loom glaciers thousands of meters thick: gleaming, white, blue, clear, transparent ice. The ice weighs on the land like a lead brick on a floating plank, pressing it down below the level of the surrounding sea. If the ice were suddenly removed, the waters of the ocean would rush in to take its place. The glaciers seem fixed and static, but in reality they are dynamic, in constant slow movement outward from their thick centers. New snowfall adds to their mass every year, but at the margins they calve off apartment-block-sized chunks of themselves and send flotillas of weirdly shaped icebergs sizzling and crackling and sometimes eerily and silently floating down the fjords to the sea. The icebergs carry pieces of Greenland with them: sand, pebbles, and boulders gouged and scraped from the land, later to be dropped far out at sea as the ice melts. The Inuit of Greenland have lived with the ice of glaciers for thousands of years. They are truly people of the ice age. Most of the rest of us have been affected by the ice age too, but in less obvious ways.

Permanent icefields—that is, large glaciers—are not common in mainland North America. In the mountainous west, in Alaska and in the Yukon, there are small high-altitude glaciers, but in the overall scheme of things, they are fairly minor features of the landscape. However, as a boy, like many others both in North America and northern Europe, I grew up surrounded by the work of ice. Like most others, I was, at the time, completely unaware of that fact. I am not referring to the ice of a skating rink or of a January puddle. Rather, this was ice just like that of Greenland today, or of Antarctica, ice of vast extent and kilometers thick that blanketed huge swathes of the Northern Hemisphere thousands of years ago. It reached down from centers in Canada and Scandinavia and covered the sites of cities such as Boston, Detroit, and Hamburg. Its legacy is everywhere even today, from the geography of our waterways to the distribution of native peoples in the New World. It ground up solid rock to make the sand of countless

beaches and the soil of midwestern farms in the United States. It sculpted rolling hills and long valleys across the landscape. It scraped up soil and rocks as it flowed, and dumped the debris as terminal moraines in places like Cape Cod and Long Island, New York, far from its original home. It even picked up diamonds from still-undiscovered deposits in Canada and transported them to the United States, twenty thousand years before NAFTA was conceived.

The present-day ice sheets of Greenland, and the glaciers in Alaska and arctic Canada, are residual from that once much more extensive ice covering of the Northern Hemisphere. But it was only in the nineteenth century that the existence of those great ice sheets of the past began to be recognized. Although some of our distant ancestors lived cheek by jowl with the gigantic ice caps, the small glaciers that still survived in high mountain regions by the dawn of modern civilization gave few clues to the earlier extent of ice. The massive ice sheets of Greenland and the Antarctic were far from the consciousness of most of the world's population and remained largely unexplored until the late nineteenth and early twentieth centuries. Except for a few small mountain glaciers in Switzerland, there were no glaciers close to the centers of learning that could serve as examples. The story of the ice ages had to be worked out from other, much more tenuous, evidence. Like most other scientific advances, the realization that the Earth has periodically been gripped in ice ages didn't come in a single Eureka! moment. Rather, it developed over a period of time and through the efforts of many naturalists and other close observers of the natural landscape. It came at a time when the science of geology was still young, when the concept that the Earth had an almost inconceivably long history was still controversial, and when the practice of making careful and systematic observations of the natural world was still relatively novel. The ice age had left its marks abundantly on the lands of the Northern Hemisphere. The signs were familiar to farmers and travelers, but for the most part their origins were obscure. It took keen observation, insight, and imagination to recognize in these marks the events that they actually record. And in spite of the fact that by the early part of the nineteenth century many scientists had discarded the notion that nearly all features of the landscape resulted from the biblical Flood, such ideas died hard. Some theologians and others prominent in society thundered "blasphemy" at the idea of an ice age. Even if they didn't have strictly theological objections, when the idea that northern Europe had once been buried beneath a huge glacier was first proposed, many contemporary scientists summarily dismissed it. There was no analog. They could not conceive of such a drastic transformation of the countryside where they now saw only farmland, forests, and rural villages. From the perspective of a single human lifespan, or even on the timescale of a few generations, the Earth appeared to be quite an unchanging place.

In hindsight, it is easy to say that the geological evidence for ice ages was overwhelming and to wonder why such periods in the Earth's past were not recognized earlier. And to be fair, even in the eighteenth century, nearly a hundred years before the term "ice age" was coined, there were already a few bold scientists who had begun to recognize the significance of the evidence. The

and others who studied the Earth by careful observation were gradually eroding the influence of theologians who tried to shoehorn virtually every observation of the natural world into a literal biblical framework. Still, widespread debate about the reality of ice ages only began in earnest in the 1830s. The very first use of the term, as far as is known, was in a short, humorous poem written by a German botanist named Karl Schimper, who read and distributed copies of his little literary contribution to friends and colleagues at a scientific gathering in Switzerland in February 1837. Schimper was a brilliant but delusional scientist who was eventually committed to an asylum, where he died in 1867. He never became a formal participant in the debate about ice ages, nor did he produce any published works on the subject, but he was a close friend and colleague of the forceful and charismatic Swiss naturalist Louis Agassiz, who today is the person most closely associated with the formulation of ideas about a global ice age. Significantly, Agassiz was brought up literally in the shadows of the Alps, and glaciers—small mountain glaciers to be sure, but glaciers nevertheless—were part of the natural landscape of his childhood. By all accounts, Agassiz, a biologist whose first love was fossil fish, was a vigorous, highly intelligent, and very observant scientist. Like most of his contemporaries, he was initially skeptical about the claim that Alpine glaciers had been much more extensive in the past. But his conversion was rapid when he realized that many of the same landscape features that he observed being produced by contemporaneous mountain glaciers were also present far afield, in the ice-free valleys of his native country and even far beyond. Rural folk who encountered such features in their daily lives had reached a similar conclusion much earlier than Agassiz. The only way they could explain the large and exotic boulders they sometimes found plopped down in the fields was that they had been carried there by ice. That meant that in the past the glaciers must have extended far beyond their current boundaries.

As I hope will become apparent in this book, there is much that can be learned about the Earth, especially its climate, through careful study of the ice ages of the past. The story of how ideas about ice ages have developed, from the work of Agassiz in the 1830s to that of modern laboratories in the twenty-first century, is also a wonderful illustration of how science progresses: not on a smooth trajectory, but in fits and starts and sometimes even with “backward” steps, with long periods of accumulation of evidence and gestation of ideas, a certain amount of serendipity, occasional brilliant flashes of insight, and, especially in more recent times, technological advances. Perhaps because of the scale of the phenomena associated with ice ages, the subject has attracted its share of brilliant, charismatic, and eccentric characters, beginning with Louis Agassiz himself. A few are discussed in some detail later in this book: a self-educated Scot who made the connection between the Earth’s orbit around the sun and ice ages; a Serbian mathematician who worked out—by hand, long before the advent of computers—a mathematical framework for determining temperature changes through time at any latitude on Earth; and an iconoclastic American schoolteacher-turned-academic who proved that parts of the northwestern United States had been ravaged by floods beyond imagining as ice age glaciers melted back into Canada.

Louis Agassiz began discussing his ideas about an ice age at scientific gatherings in 1837, and within a few years, in 1840, he had published his observations and theory in a book. What was truly radical about his treatment was his proposal that ice had covered most of Europe during the ice age, even perhaps, most of the land on Earth. As is often the case with new concepts, the one did not initially win many adherents. However, the debate about the reality of ice ages quickly became one of the most fiercely argued controversies of nineteenth-century science. It continued, unabated, for decades.

And the eventual acceptance of the ice age theory was far from the end of the story. Since that time, literally hundreds, perhaps even thousands, of scientists have pursued research into the causes and effects of the ice ages, and many thousands of scientific papers have been written on the subject. In the course of that work, Agassiz's contributions have been remembered in small ways and large. When researchers discovered evidence of a vast ice-dammed lake that had formed along the margins of the melting ice age glaciers in the central part of North America, they named it Lake Agassiz. In Winnipeg, Canada, which lies within the area that had been covered by the waters of glacial Lake Agassiz, there is even an Agassiz microbrewery. Agassiz, who complained when he came to the United States about the American practice of drinking iced tea with lunch instead of wine, undoubtedly would have been pleased.

In principle, the idea of an ice age is a simple one—in the past, it was colder, glaciers were much more extensive than they are today, and huge ice sheets covered large sections of the continents that are now free of ice. However, understanding the phenomenon and determining how an ice age occurs, and what the ramifications are for the Earth and all its inhabitants, is far from simple. Today, it is difficult for anyone to be an expert in every aspect of ice age studies; the intellectual challenge presented by the geological evidence, with its multiple puzzles, has attracted the efforts of geologists, chemists, physicists, mathematicians, biologists, and climatologists. The work has taken on additional urgency in recent years because of mounting concern about the future of the Earth's climate system. While at first thought this might seem odd—the dominant problem today is global warming, not cooling—it has become clear that our planet has experienced huge climate shifts during the current ice age (as we shall see, the Earth today is still in the grip of an ice age). Understanding how these changes in the global climate occurred in the past, and what their effects were, is a key step toward predicting future changes. But in spite of the great advances that have been made in working out the details of what actually happened during the ice age, there is still much uncertainty about how, and especially why, an ice age actually begins. To be sure, there are hypotheses, but none have yet attained the status of an accepted scientific theory. Much remains to be done.

Louis Agassiz built his ice age theory within the framework of the then-popular catastrophist view of Earth history: the idea that rapid, large-scale events were responsible for many geological observations. He didn't really concern himself with a mechanism; he just assumed that temperatures had plummeted suddenly and the Earth "froze." He envisioned glaciers extending as far south as the

Mediterranean Sea in Europe, and deep into North America. However, later research has shown that Agassiz's ice age was neither as rapid in onset as he proposed nor just a single cold period. We now know that the Earth's most recent ice age comprises a long succession of ice incursions deep into Europe (although not as far as the Mediterranean) and North America, separated by much warmer periods.

It is often not appreciated that today's climate is just a geologically short warm spell in this continuing ice age. But in addition to the ice sheets of Greenland and Antarctica, mountainous regions today sustain permanent ice fields even in the tropics. The brilliant white cap on Mt. Kilimanjaro described by Hemingway in *The Snows of Kilimanjaro* is actually a permanent glacier, in spite of the fact that Kilimanjaro is only 300 km (roughly two hundred miles) from the equator. The Andes too host equatorial glaciers. If you were an astronaut circling the Earth at the end of a northern winter, you would observe that nearly half the land area and more than a quarter of the oceans were white with snow and ice. Only a fraction of this is permanent glaciers, but still, about 75 percent of all the fresh water on our "blue" planet is frozen in glaciers. Even so, in comparison with the average of the past few million years, the present-day interglacial climate is benign. The last time the Earth was as warm as it is today was about 120,000 years ago; for most of the time since then it has been much, much colder.

All of the evidence we have about past climates suggests that the Earth has been progressively cooling for the past 50 or 60 million years. Before then, most of the world had experienced warm temperatures—the fossil remains of tropical and subtropical plants and animals from those times are found even north of the Arctic Circle. Sometime near 35 million years ago, there was an especially sharp drop in global temperatures—this is when, most researchers believe, glaciers began to form in Antarctica. However, although temperatures continued to fall as the Antarctic icecap grew, it was not until about 3 million years ago that permanent glaciers appeared in abundance in the Northern Hemisphere, again accompanied by an abrupt temperature decrease. This is generally agreed to be the start of the current ice age, and since that time, most climate changes around the globe have been associated with the waxing and waning of ice sheets in the Northern Hemisphere. Fortunately for us, the glaciers have withdrawn to high altitudes and latitudes during the present warm period. But on average, for the past few million years, the Earth has been considerably colder than over most of its four and a half billion years of existence. During much of Earth history, except for short, rare, intervals, glaciers such as the one on Kilimanjaro have been absent. In contrast, within the current ice age, warm periods with moderate climates similar to the present have been short by geological standards, generally lasting only ten to twenty thousand years. We are already about ten thousand years into the current warm episode. If history is any guide, and if human activities don't warm the Earth too severely, the ice will return, and quite soon on a geological timescale. The sites of cities such as Montreal and Edinburgh and Stockholm, and perhaps even New York and Chicago, will be buried deep in glacial ice, as they were in the past.

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