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 reaso understanding them—why they occur, how they impact our planet, what bring them to an end—provides crucial information for anticipating how climate wi change in the future and what the effects may be. Since this book was firs published, scientists have made great strides toward untangling the comple interplay of factors that affect the Earth's climate. Much of this progress has com through careful study of ice ages, especially the most recent—the Pleistocene Ic Age.

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

This short preface cannot do justice to the immense amount of research on ic age– and climate-related issues that has been carried out over the past few year But I'd like to focus on a few specific studies that give a taste of the kind of wor being done. The first of these deals with the how and why of our planet's warmin up from the frigid peak of its most recent cold period a little more than twent 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 Unite 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 th past two and a half million years, has not been monotonously cold. Insteac climate has cycled between long icy intervals and relatively short warm period like now, which geologists call interglacials. Analyses of gas bubbles trapped in ic cores from Greenland and the Antarctic—tiny samples of air from the past—sho unequivocally that the atmosphere had high concentrations of greenhouse gase during the interglacial warm periods and low concentrations during the col intervals. The ice cores provide information from times long before humans bega to influence the atmosphere, so the greenhouse gas variations they record wer entirely natural. The question is, were natural increases in carbon dioxide an other greenhouse gases the cause of warm interglacial periods, or were the somehow a result of the higher temperatures? Clearly this is an importar question for understanding how the Earth's climate will respond to greenhous gas increases caused by humans.

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

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

In their study Shakun and his colleagues examined temperature informatio from a globally distributed set of eighty different natural records, mostly ice an sediment cores, through the period from the onset of the most recent deglaciatio to the point when the Earth's climate reached approximately its present stat (roughly the interval between twenty thousand and eleven thousand years ago The data show that throughout most of that interval, increasing global averag temperatures lagged increasing carbon dioxide concentrations by severa hundred years. Surface temperatures averaged for the Earth as a whole evident changed on a different timescale from those at the sites of the Antarctic ice core The authors concluded that greenhouse gases, particularly carbon dioxide, wer 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 th pattern (although not the total degree) of warming differs between the Norther and Southern Hemispheres. The second is that for a short interval at the ver beginning of the deglaciation—in contrast to the rest of the period—the Earth average temperature rose by a small amount, about 0.3°C (less than 1°F), *befor* carbon dioxide began to rise. What do these findings imply? Taking the secon observation first, it appears that the initiation of deglaciation—the ver beginnings of ice sheet melting—occurred not because of increased greenhous gases in the atmosphere after all but through minor solar heating of the Norther Hemisphere. Because of regular variations in the Earth's orbit (described i chapter 5), insolation (the amount of solar energy that the Earth's surfac receives) was increasing rapidly at high northern latitudes at this time. Th temperature rise this caused was small but still sufficient to initiate the melting o Northern Hemisphere glaciers. In a kind of domino effect, this slight warming se off other processes, including the rise of greenhouse gases, that amplified th initial temperature increase many times over and drove the large-scal interglacial warming.

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

How does ocean circulation affect climate? To understand this it's necessary t remember that because of their huge volume, the oceans hold a tremendou amount of heat. Circulating ocean waters carry this heat from one place on th globe to another. Also—and especially important in terms of the warming an 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 ca easily be transformed into carbon dioxide. In total, the oceans contain about fift times as much carbon as the atmosphere. The rapid increase in carbon dioxid during the most recent deglaciation apparently happened when changes in ocea circulation released some of that carbon into the atmosphere.

Ocean circulation is strongly influenced by the geographical distribution of th continents. In the present-day configuration it is largely driven by warm tropica water flowing northward in the Atlantic Ocean, cooling and becoming saltier du to evaporation as it goes. Both these processes make the surface water dense and in the North Atlantic it sinks, drawing even more tropical water northward t replace it, thus maintaining the circulation pattern (the dense, cold wate descends to the deep ocean and flows south toward the Antarctic and eventual into the Indian and Pacific Oceans). Shakun and his colleagues suggest that at th beginning of the most recent deglaciation, the slight warming of northern pola regions caused by increasing insolation slowed or even stopped this pattern o circulation. How did this happen? Fresh water (which is considerably less dens than salty seawater) from the melting glaciers flowed into the North Atlanti decreasing the density of the surface water to the point where it could no longe sink. This shut down the northward transfer of warm water from the tropic leading to warming of the Southern Hemisphere and modest cooling, or at minimum slower warming of, northern polar regions. Climatologists refer to suc ocean-driven temperature alternations between hemispheres as the bipola seesaw. As the southern oceans warmed, Antarctic sea ice cover decreased, an changes in southern ocean circulation released carbon dioxide into th atmosphere, enhancing warming globally.

If you’re not already familiar with some of these processes, following th scenario just described may set your head spinning. It involves a complex series interrelated events driven by multiple climate-forcing mechanisms, amplified b feedbacks such as changes in albedo or ocean circulation patterns. But then, a natural systems are complex, and the bottom line from the work of Shakun an his colleagues is that the greenhouse gas carbon dioxide was the primary forcin mechanism for global warming during the most recent deglaciation. Currentl this research is the most extensive and thorough examination of what cause temperatures to rise globally from the LGM to the present. It is always possib that future work will change some of the details, but for the moment this is one 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 fo deglaciation was increasing insolation at high northern latitudes, even though— once the ice age glaciers had begun to melt—carbon dioxide was the primar forcing mechanism for the bulk of the warming. One of the earliest workers wh attempted to explain glacial cycles, James Croll, recognized the importance changes in northern insolation more than 150 years ago; later (early in th twentieth century) Mulutin Milankovitch expanded on this idea (see chapters and 7). What these perceptive scientists didn’t understand, though, was that th key role of northern summer insolation in Pleistocene Ice Age cycles was at leas partly due to the present-day configuration of the continents.

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

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

Pleistocene Ice Age is characterized by multiple cycles of warming and cooling, c 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. Fo example, Greenland ice cores, a primary source of information about pas Northern Hemisphere climate changes, extend to only 130,000 years ago covering little more than one complete cycle. However, during the winter o 2008–9, a group of scientists and engineers operating under the aegis of th International Continental Scientific Drilling Program retrieved sediment core that record the local climate in northeastern Siberia through nearly all of th Pleistocene Ice Age cycles. The cores were drilled from a lake (with a tongue twisting name: Lake El’gygytgyn) that occupies a 3.6-million-year-old meteorit crater about one hundred kilometers (sixty-seven miles) north of the Arctic Circle The availability of a continuous record of local Arctic environmental chang through the Pleistocene Ice Age is tremendously important because it permi climatologists to compare the real climate variability, as recorded in the sedimen cores, with that predicted by climate simulations run with different forcin factors. This is especially valuable for the Arctic because both climate models an observations (including temperature records from the past few decades) indicat that northern polar regions are considerably more sensitive to global warmin than other parts of the Earth.

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

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

Why didn’t the climate models reproduce the high super interglacia temperatures experienced at the Siberian lake? Clearly, still-unrecognize processes or forcing factors must have been involved. Melles and his colleague 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 ar another reminder of just how complex the climate system is, and how difficult it to construct simulations or models to predict accurately how temperature rainfall, and the like will change in the future. More often than not questior answered spawn new questions, and climatologists—indeed, all scientists—alway seem to face more work to get to the bottom of things.

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

In chapter 12, I describe one possible answer, an idea that was suggested no long before the initial publication of this book in 2004: that chemical weatherin of the evolving Himalayan Mountains “drew down” carbon dioxide in th atmosphere, reduced the greenhouse effect, and cooled the planet. This ma seem a bit confusing because the Pleistocene Ice Age began only about two and half million years ago, when large-scale glaciers began to form in northern pola regions, yet the Himalayas are much older (they began to form about fifty millio years ago when plate tectonic forces caused India to crash into Asia). Howeve temperature proxies in deep-sea sediment cores show that global temperature declined steadily from approximately the time of the India-Asia collision (whe they were much higher than they are today) until the start of the Pleistocene Ic Age. By about thirty-five million years ago, global temperatures were low enoug 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 unti eventually, Northern Hemisphere glaciation began. So the question of wha initiated the Pleistocene Ice Age rests on what caused the long-term cooling tha began around fifty million years ago.

It is well known that carbon dioxide from ordinary air, when dissolved i rainwater, is the primary agent of rock weathering and that extensive weatherin depletes its abundance in the atmosphere. That young, rising mountain range are sites of intense chemical weathering is also well known. The coincidence i timing between the rise of the Himalayas and a global temperature decreas suggests that weathering of this young mountain range could have bee responsible for the lower temperatures, through its effect on atmospheric carbo dioxide. But recently a new candidate has joined carbon dioxide drawdown as possible cause of the global cooling: sulfur. What, you may ask, does sulfur have t do with climate? Potentially quite a lot. Sulfur is plentiful; in the form of sulfat ($SO^{2-}{}_4$), it is the fourth-most-abundant ion in seawater. Because of this, the ocean are a major source of sulfur-bearing aerosols in the atmosphere—suspende microscopic droplets that reflect incoming solar radiation. When the concentration increases, they reflect more solar radiation and the Earth cool This effect was illustrated clearly in 1991, when a large eruption of Mt. Pinatub 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 sulfurrich 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 severe glaciation, 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 it would stay frozen. However, under such conditions it is likely that enough carbo dioxide (from volcanic eruptions) would eventually accumulate in the atmospher 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 onc thought. But what initiated these extreme events?

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

At the time of Snowball Earth glaciation, the planet was a very different plac than it is today. For starters, the surface received about 6 percent less sola 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 th existing continents, with none at the poles. Both of these boundary conditions ar important for understanding the Snowball Earth glaciations.

The computer models don’t tell us exactly what happened, and differen versions give slightly different results. But all of the simulations point to th importance of two primary climate forcings: the reflectivity (albedo) of sea ic and the amount of carbon dioxide in the atmosphere. Even with solar radiatio only 94 percent as strong as it is today, very low greenhouse gas concentration are crucial for initiating Snowball Earth episodes in all climate models because- with no continents in polar regions—extremely low temperatures are necessary t initiate freezing of the high-latitude seas and maintain year-round ice cover. A cooling proceeds under low greenhouse gas conditions and ice cover expand however, albedo becomes the dominant factor and eventually results in runawa cooling. Exactly how much of the planet must be covered with ice and snow fo this to happen varies depending on the model used. But the point at whic runaway cooling begins can’t be reached at all without very low greenhouse ga concentrations.

What lessons do the climate models have for the Anthropocene (an inform but very useful label for the time in our planet’s history when human activity ha overtaken natural processes as a primary driver of atmospheric chemistry an other aspects of our environment)? One startling conclusion from the best an most recent models is that even after anthropogenic carbon dioxide emissio slow down or stop, their effects will persist for much longer than is general realized: tens of thousands of years. As the science journalist Mason Inman put i “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 Eart start to cool down when humans stop putting greenhouse gases into th atmosphere? The simple answer to the first of these questions is that the clima system is complex and takes a long time to approach a new equilibrium state; th answer to the second is yes, but slowly and only (for thousands or perhaps eve tens of thousands of years) to temperatures well above those of the period befor the emissions began.

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

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

To put things in perspective, I should point out that the Earth has experience periods in the past—even very long periods—with atmospheric carbon dioxide o several thousand ppm, high global average temperatures, and no permaner glaciers except perhaps for a few small high-altitude ice fields. However, that wa long before humans arrived on the scene and existing life had adapted t conditions we would consider extreme. The greenhouse gas content of th atmosphere is now rising at a rate unprecedented in the Earth's long histor entirely because of human activity. Most of the consequent environmenta changes will occur over the next few centuries. Unless geoengineering solution can be found—large-scale projects designed to slow or stop global warming by variety of methods, including extracting carbon dioxide from the atmosphere an storing it permanently—humankind will have to adapt very nimbly in order t avoid the partial or wholesale collapse of nations and societies. The environmenta changes, including higher global temperatures, higher sea level, and potential drastic changes in biological diversity and species distribution, will affe agriculture, human health, and all populations living close to sea level. Who woul have thought that studies of ice ages could give us such insight?

Doug Macdouga
October 2012

CHAPTER ONE

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

The American author and historical popularizer Will Durant once wrot “Civilization exists by geological consent, subject to change without notice.” Tha is not a new idea, even if Durant phrased it especially well, but nowadays mar historians scoff at the notion of environmental determinism, the possibility tha climate or geology may have seriously affected the course of human history. An yet there are still many places on this planet where Durant’s observation rin true, especially places with extremes of climate. One such is the arctic region particularly Greenland. Ninety-five percent of that island country is covered b ice. Towns and villages cling to the coastline; at their backs loom glaciers thousand meters thick: gleaming, white, blue, clear, transparent ice. The iceca weighs on the land like a lead brick on a floating plank, pressing it down belo the level of the surrounding sea. If the ice were suddenly removed, the waters the ocean would rush in to take its place. The glaciers seem fixed and static, but i reality they are dynamic, in constant slow movement outward from their thic centers. New snowfall adds to their mass every year, but at the margins the calve off apartment-block-sized chunks of themselves and send flotillas of weird shaped icebergs sizzling and crackling and sometimes eerily and silently floatin down the fjords to the sea. The icebergs carry pieces of Greenland with them to sand, pebbles, and boulders gouged and scraped from the land, later to b dropped far out at sea as the ice melts. The Inuit of Greenland have lived with th ice of glaciers for thousands of years. They are truly people of the ice age. Most 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 mainlan North America. In the mountainous west, in Alaska and in the Yukon, there ar small high-altitude glaciers, but in the overall scheme of things, they are fair minor features of the landscape. However, as a boy, like many others both i North America and northern Europe, I grew up surrounded by the work of ic Like most others, I was, at the time, completely unaware of that fact. I am n referring to the ice of a skating rink or of a January puddle. Rather, this was ic just like that of Greenland today, or of Antarctica, ice of vast extent and kilometer thick that blanketed huge swathes of the Northern Hemisphere thousands years ago. It reached down from centers in Canada and Scandinavia and covere the sites of cities such as Boston, Detroit, and Hamburg. Its legacy is everywher even today, from the geography of our waterways to the distribution of nativ peoples in the New World. It ground up solid rock to make the sand of countles beaches and the soil of midwestern farms in the United States. It sculpted rollin ~~hills and long valleys across the landscape. It scraped up soil and rocks~~ as flowed, and dumped the debris as terminal moraines in places like Cape Cod an Long Island, New York, far from its original home. It even picked up diamond from still-undiscovered deposits in Canada and transported them to the Unite States, twenty thousand years before NAFTA was conceived.

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

In hindsight, it is easy to say that the geological evidence for ice ages wa overwhelming and to wonder why such periods in the Earth's past were no 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 fe bold scientists who had begun to recognize the significance of the evidence. The and others who studied the Earth by careful observation were gradually erodin the influence of theologians who tried to shoehorn virtually every observation o the natural world into a literal biblical framework. Still, widespread debate abou the reality of ice ages only began in earnest in the 1830s. The very first use of th term, as far as is known, was in a short, humorous poem written by a Germa botanist named Karl Schimper, who read and distributed copies of his littl literary contribution to friends and colleagues at a scientific gathering i Switzerland in February 1837. Schimper was a brilliant but delusional scientis who was eventually committed to an asylum, where he died in 1867. He neve became a formal participant in the debate about ice ages, nor did he produce an published works on the subject, but he was a close friend and colleague of th forceful and charismatic Swiss naturalist Louis Agassiz, who today is the perso most closely associated with the formulation of ideas about a global ice ag Significantly, Agassiz was brought up literally in the shadows of the Alps, an glaciers—small mountain glaciers to be sure, but glaciers nevertheless—were pa of the natural landscape of his childhood. By all accounts, Agassiz, a biologi whose first love was fossil fish, was a vigorous, highly intelligent, and ver observant scientist. Like most of his contemporaries, he was initially skeptic about the claim that Alpine glaciers had been much more extensive in the pas But his conversion was rapid when he realized that many of the same landscap features that he observed being produced by contemporaneous mountain glacie were also present far afield, in the ice-free valleys of his native country and eve far beyond. Rural folk who encountered such features in their daily lives ha reached a similar conclusion much earlier than Agassiz. The only way they coul 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 th glaciers must have extended far beyond their current boundaries.

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

Louis Agassiz began discussing his ideas about an ice age at scientif gatherings in 1837, and within a few years, in 1840, he had published h observations and theory in a book. What was truly radical about his treatment wa 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, th one did not initially win many adherents. However, the debate about the reality o ice ages quickly became one of the most fiercely argued controversies o nineteenth-century science. It continued, unabated, for decades.

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

In principle, the idea of an ice age is a simple one—in the past, it was colde glaciers were much more extensive than they are today, and huge ice sheet covered large sections of the continents that are now free of ice. Howeve understanding the phenomenon and determining how an ice age occurs, an what the ramifications are for the Earth and all its inhabitants, is far from simpl 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 multipl puzzles, has attracted the efforts of geologists, chemists, physicist mathematicians, biologists, and climatologists. The work has taken on additiona urgency in recent years because of mounting concern about the future of th Earth's climate system. While at first thought this might seem odd—the dominan problem today is global warming, not cooling—it has become clear that our plane has experienced huge climate shifts during the current ice age (as we shall se the Earth today is still in the grip of an ice age). Understanding how thes changes in the global climate occurred in the past, and what their effects were, a key step toward predicting future changes. But in spite of the great advance that have been made in working out the details of what actually happened durin the ice age, there is still much uncertainty about how, and especially why, an ic age actually begins. To be sure, there are hypotheses, but none have yet attaine 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-popula catastrophist view of Earth history: the idea that rapid, large-scale events wer responsible for many geological observations. He didn't really concern himse with a mechanism; he just assumed that temperatures had plummeted sudden and the Earth "froze." He envisioned glaciers extending as far south as th

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

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

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