DEEP FUTURE

The Next 100,000 Years of Life on Earth

CURT STAGER

"A probing exploration of the impact of climate change over geological time. . . . Essential reading." —*Kirkus Reviews* (starred review)

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FUTURE

**THE NEXT 100,000 YEARS
OF LIFE ON EARTH**

CURT STAGER

HarperCollins e-books

For Kary

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Prologue

Out of the earth has come a creature that has changed … the face of continents, that has harnessed the forces of the earth and turned them against themselves.

—*John Burroughs,* Accepting the Universe

Welcome to the Age of Humans, a new chapter of Earth's history whose name has already entered the lexicon of mainstream science.

Welcome to the end of the natural world as a realm that is somehow meaningfully distinct from humanity, thanks in large part to the worldwide carbon pollution that you and I have unwittingly helped to create and that will affect our descendants for many thousands of years, far longer than most of us yet realize.

And welcome to this peek beyond the curtain of 2100 AD, which currently marks the outer temporal limits of most thought and debate about modern climate change. As you'll soon see, the environmental consequences of our actions today are so large, powerful, and long-lived that they cannot be fully understood from a mere century-scale point of view.

My aim in these pages is to introduce you to a broader perspective on global warming than the one most readers are familiar with, the one that considers "long-term" climate change to be a trend that merely stretches over several years or decades. People like Bill McKibben and Al Gore have brought the planetary scope of CO_2 pollution to the attention of millions, but for most of us, the element of time has yet to be fully explored. David Archer, a farsighted climate modeler whose work I will introduce later in the book, has described the situation thus: "The idea that anthropogenic CO_2 release may affect the climate … for hundreds of thousands of years has not yet reached general public awareness." The time has come to move on from unproductive, politicized arguments over global warming to the next stage of inquiry, where it is no longer a question of *if* it is happening but of when, how much, and for how long.

At first, it might seem strange that an environmental historian, or paleoecologist, like myself should be writing about future events like this. I read the stories of ecosystems that lie stacked in archives not of paper but of mud. My specialty is collecting layered core samples from the bottoms of lakes and bogs in the Adirondacks, Peru, and much of Africa, picking out the remains of microscopic organisms that once lived and died there and reconstructing past climates from the patterns of change they reveal. A layer of salt-loving algae tells me that the local climate was once dry enough to lower the lake level and turn the water brackish. A slug of pollen in another layer attests to wetter conditions that favored forests over deserts.

What a paleoecologist contributes most naturally to this prediction business is a sense of time. Much of what lies ahead of us has already happened before, and those of us with a long-term view of environmental history can often recognize familiar age-old processes in action today as well as likely consequences that may come as a result. We who combine the biological and geological sciences in our historical research also become used to thinking in broad terms that include both the living and nonliving worlds. But more to the point, we also think "deep." For us, a century or millennium may be just an appetizer on the menu, and the duration of a single human lifetime is, statistically speaking, insignificant.

That's not always a popular position, of course. A long view is not necessarily welcome to those who are preoccupied with events in the here and now, but it nonetheless offers potentially useful compass bearings for navigation in a complex and changing world. As a guide on this tour of the future, I'll look beyond the present moment to focus both forward and backward in time, bringing into view the nature of things to come as well as things that have long since been.

The relatively few scientists who have looked deeply into our future like this see the lingering climatic and ecological effects of fossil fuel carbon stretching well beyond the end of the twenty-first century. In order to follow their lines of sight through these pages, we will need to train the mind's eye to take in tremendous sweeps of Earth history, both past and future. Much of what we learn here will come from geoscientists who speak of eras and epochs as the rest of us speak of seasons, people who share with the superrich a close working familiarity with the significance of terms like "million" and "billion." To these professional time specialists, the Eocene and Pleistocene epochs are as real as World War II or the turbulent 1960s are to the rest of society, and they see in those long-gone ages some important lessons that can guide us as we struggle to understand what is happening around us today.

Before we go further in this quest, though, I would like to introduce you to a newly minted technical term that's currently striking resonant chords in the scientific community. At the moment, it still sounds foreign to most ears, but for those who are familiar with it the word represents an almost thrilling acknowledgment of our place in the grand arc of geologic time. It's modeled in the form of other major subdivisions of the fossil record that include what some call the Age of Fishes or the Age of Dinosaurs. Now that human influence has touched almost every cranny of the Earth, a new age has dawned, and it needs a formal name.

In the arcane lexicon of geological nomenclature, this age best qualifies as the latest in a string of episodes known as "epochs" that began 65 million years ago with the demise of the dinosaurs. You might have heard of them before, if you've spent much time learning about fossils. The post-dinosaur years began with the warm Paleocene, whose prefix *paleo* (Greek for "ancient") refers to its great age relative to others that came later. Next came the even warmer Eocene, which saw the early-morning stages of modern mammal evolution. After skipping through three more epochs (Oligocene, Miocene, and Pliocene), each with a distinctive story of evolving life to tell, we find the Earth cooling down during the Pleistocene, and come, at last, to the climatically mild Holocene ("recent whole"), which began 11,700 years ago and traditionally includes the ever-advancing present.

But keep on the alert for a new epochal name that was recently bestowed upon this Age of Humans. No, it's not the "Plasticene," though blogger Matt Dowling has indeed proposed that label with tongue planted firmly in cheek. Partial credit for promoting the new name goes to atmospheric chemist and Nobel laureate Paul Crutzen, but it actually originated with aquatic ecologist Eugene Stoermer. Now an emeritus scholar at the University of Michigan, Stoermer recently told me that his catchy term spread informally through the scientific grapevine before appearing in print several years ago under the joint authorship of Crutzen and himself.

"I can't remember exactly how it first came to mind," he recalled, chuckling like a pleased but somewhat surprised parent whose kid has grown up to become a celebrity. "I used it in conferences here and there, and it eventually caught people's attention." That's not surprising, though, because Stoermer's term neatly defines these and near-future times as indelibly marked by anthropogenic, or human-generated impacts, and it's seeping more and more comfortably into the writings and speech of scientists and lay folk around the world.

So here's your chance to impress your friends, if you're the type who likes to show off by using the latest technical jargon that describes not only recent human history but also the next hundreds of thousands of years of it that are yet to come. Tell them, in the course of casual conversation, "Welcome to the Anthropocene." (Stoermer pronounces it ANthropocene, but anTHROPocene also works.)

By most definitions, the Anthropocene began during the 1700s when our greenhouse gas emissions started to change the atmosphere significantly. But our influences actually extend far beyond climate alone. The formerly dark portion of Earth that faces away from the sun now glows with electric light, as if it were illuminated by billions of fireflies. According to Crutzen, our fishing industries remove more than a third of the primary productivity of temperate coastal areas every year. Farmers sprinkle, spray, and spade more nitrogen fertilizer than is naturally deposited on all the world's forest floors, savanna turf, and bird rookeries combined. And species extinctions today are beginning to outpace any in the history of life.

A small but active corps of visionary scientists is now sketching the broad outlines of what the Anthropocene holds in store for us. But before looking further into the surprising details of what is to come, it's worth noting that we are not the only living things to have changed the atmosphere so much. From a biologist's emotionally detached perspective, there is nothing particularly unusual about the human tendency to pollute our environment; every organism produces waste, and the more organisms that exist in a given habitat the more unwanted by-products they produce. It's just that we humans have now become so numerous, so widespread, and so adept at consuming natural resources that our wastes are polluting the entire planet, even to the point of changing its climate. In that sense, we're becoming victims of our own success as a species.

The first such global pollution crisis was actually the work of marine bacteria, and it struck just over 2 billion years ago at a time when all life on Earth was single-celled. The pressures of mutation and natural selection drove some pioneering microbes to overuse a new way of harnessing the energy of sunlight—what we now call photosynthesis. Unfortunately for most of the other diminutive life-forms of the time, that primordial biotechnology also released a dangerous waste gas into the surroundings. That waste gas was free oxygen.

Excess oxygen steadily polluted the oceans as they grew greener and greener with the tint of chlorophyll and the atmosphere grew more and more corrosive as a result. Formerly gray or black rocks crumbled into reddened remnants of their former selves as the iron particles within them rusted. Any species that could not repair the ravages of oxidation in their cells perished or lived imprisoned in protective aquatic muds. Descendants of those microbial refugees still cower in the fetid muck of marshes and in the oxygen starved depths of certain lakes and seas. We unwittingly harbor legions of benign oxygen haters in the dark recesses of our digestive tracts, and some legumes such as soybeans pack their root nodules with blood-colored, oxygen-binding compounds that shield their resident bacteria, thereby earning paybacks in the form of microbial nitrogen fertilizer.

If language had existed back then in that purely microbial world, headlines would have heralded the advent of a global oxygen catastrophe. Perhaps bacterial alarmists who warned of that first pollution disaster would have described us humans as monstrous, two-legged versions of the "cockroaches that will take over the world after it's been poisoned." In fact, both our distant ancestors and those of modern cockroaches did indeed populate the world only after photosynthetic oxygen made it habitable for animal life.

High above the early oceans, the novel molecules spawned new by-products just as the chemical stew of modern smog does today. Oxygen in the upper reaches of the atmosphere clumped into heavy, tripled clusters and accumulated as a layer of invisible ozone that blocked much of the sun's dangerous ultraviolet radiation. Meanwhile, down below, some of the primitive single-celled survivors of the oxygen pollution crisis were developing ways to use the poisonous gas as a source of energy in its own right. Eventually, Earth's first wriggly protozoans learned to harness oxygen's destructive power to convert the bodies of their smaller neighbors into useful food, and the rest is predatory history.

Today, the waste gas of photosynthesis contaminates a fifth of the air in our lungs and we, the descendants of those first polluters, can't live without it. When the world changes so dramatically, there must always be winners and losers. In this case, we have clearly been among the winners.

About a billion and a half years after the oxygen crisis, early plants that inherited the solar technology of photosynthesis were turning it to new uses of their own. Where the power of sunlight once supported only singular, free-living cells, increasingly large and abundant land plants used it to coax CO_2 molecules from the air, dissect them, and bind their carbon atom components into the fabrics of branches, trunks, leaves, seeds, and spores.

Growing atom by atom, like living crystals, primeval swamp forests hoarded precious carbon. Photosynthetic life plucked CO_2 from a thin gaseous soup in which the target element, carbon, was outnumbered more than ninety-nine to one by oxygen and nitrogen. At death, they took the concentrated carbon troves to their watery graves and were buried, layer upon layer, in mausoleum vaults of mud.

Hundreds of millions of years later, the first hints of Stoermer and Crutzen's Anthropocene began with another biogenic pollution event. Our industrial ancestors unearthed some of those black fossil deposits, called them coal, and set fire to them. Heated in the presence of oxygen, the purified carbons disintegrated back into diffuse swarms of CO_2 molecules, unleashing the hot solar energy of countless Paleozoic summers as their ancient chemical bonds snapped and cast them skyward.

Though at first indistinguishable from the other CO_2 molecules circulating among plants, animals, waters, and winds today, these fossil fumes are different. Most of the CO_2 that enters the air from breath, forest fires, oceanic upwellings, and rot is quickly recycled; about as much carbon is absorbed by photosynthetic bacteria, algae, and plants each year as is released by respiration, and roughly as much of it dissolves into the ocean surface as is naturally degassed from it. At the global level, only a small fraction is lost to sediment burial over the course of a year and only relatively modest amounts hiss from volcanic vents, so the total amount in circulation normally varies little.

Fossil fuel carbons, in contrast, are outsiders. Though some manage to rejoin the ebb and flow of modern life, most join the ranks of the footloose unemployed, swelling the pool of airborne CO_2 faster than other processes can reduce it. Just before the dawning of the Anthropocene, a random sample of a million air molecules would have netted you about 280 carbon dioxides. As I write this I could land 387 or so, many of which emerged from smokestacks and tailpipes within the last 250 years.

Why does this modern pollution spree deserve a new, formal geological name? Even though it represents less than I percent of the gases in the atmosphere, the growing surplus of CO_2 is now making the world hotter than it would otherwise be. Likewise, geologists designated the last two epochs largely on the basis of their climatic conditions; the Pleistocene was dominated by numerous glacial coolings and the Holocene was the latest of several shorter interglacial warm spells, the one during which the first complex human civilizations were born.

As I'll explain later, the greenhouse gas pollution of the Anthropocene will hang around long enough to cancel the next ice age, and the result is that this human-driven epoch may last an order of magnitude longer than the Holocene did. Incredibly, it is we —specifically those of us who live in the twenty-first century—who will do the most to determine its duration. The epochal name is well chosen; this Age of Humans is the product, the environmental backdrop, and the geological trademark of our species.

To some, the Anthropocene marks the end of nature as an entity separate from the apelike *Homo sapiens* species that it spawned in Africa long ago. Much of this conception of humans as privileged occupiers of some lofty plane above other species dates back to

Aristotle's *Scala Naturae,* which is often translated as "The Great Chain of Being." It pictures a ladder or interlocking chain of existence that positions more complex animals above simpler ones and a heavenly creator above all. Because humans in this view combine both physical and metaphysical traits, they form a unique link that joins the celestial and earthly realms. Vestigial traces of the concept still linger in biological nomenclature that classifies complex-looking orchids as "higher plants" and simple-looking mosses as "lower plants." In society at large, it crops up in such terms as "the missing link," the theoretical hairy ape-human that would forge a lowly, anchoring ring in the great chain between us and other primates.

To most biologists today, however, the idea that humans are meaningfully separate from nature is rather old school. Our very ability to change climate on a global scale, simply by emitting our daily wastes, attests to our intimate connection with our physical surroundings. One could even argue that this kind of self-centered and shortsighted conceit, the idea that we are somehow exempt from the ancient laws of the physical world, is what got us into so much trouble in the first place.

This brings us back to an aspect of the Anthropocene revolution that is still under debate in the scientific community. When did the new epoch actually begin? Crutzen and others like him who focus on industrial emissions typically choose the mid-to late 1700s as that starting point. Some tie it specifically to James Watt's development of the modern steam engine in the 1760s.

Others, like climate historian Bill Ruddiman, put it thousands of years earlier. Ruddiman's idea helps to explain a mysterious anomaly in the record of ancient greenhouse gases that is preserved in air bubbles trapped in deep glacial ice. Ice cores, from Greenland and Antarctica, represent hundreds of thousands of years of climate history, and they reveal an intimate connection between past climates and greenhouse gases. These polar ice records show that while climates have seesawed violently between frosty ice ages and warm interglacials in the past, equally dramatic shifts in carbon dioxide and methane concentrations have also occurred, most of which, as we'll see in later chapters, had nothing to do with human activity.

Through most of that history, atmospheric concentrations of these two greenhouse gases fluctuated in near lockstep with each other, but something odd happened during the warm Holocene epoch, which began with an abrupt end to the last major cold episode 11,700 years ago. After an early thermal peak, temperatures began to slide back down into a long-term cooling trend. However, about 8,000 years ago, the CO_2 content of the air began to rise again instead of falling, as it had normally done during cool-offs of the distant past. Several millennia later, methane lifted off independently, too. Ruddiman proposes that the unusual CO_2 rise reflected widespread forest burning and land clearance for agriculture, and that methane later rose in response to the spread of Asian rice production in artificial, gas-bubbling wetlands. In that case, human impacts on world climate might have begun as early as 8,000 years ago.

Still others argue that climatic effects should not be the only criteria for tracking the history of human impacts on Earth. Most biohistorians believe that Stone Age hunters exterminated mastodonts and giant ground sloths along with many other large mammals roughly 10,000 to 15,000 years ago, and their disappearance fundamentally and artificially altered ecosystems all over the planet. In North America alone, more than half of all mammal species weighing more than 70 pounds (32 kg) vanished, and those weighing more than a ton (900 kg) were completely wiped out. One could therefore make a logical case for omitting the Holocene epoch from the geologic time scale altogether and simply folding it into the Anthropocene.

But most of us are less interested in when the Anthropocene began than in what it's going to be like from here on out. Just as fossils and ice cores give us glimpses into the world as it once was, the new science of long-term climate prediction sketches a compelling outline of things to come. In that expansive view, the basic shape of the future already exists, and we can use it to tell the full story of carbon pollution from start to finish rather than settling for the relatively short portion that now dominates our collective thinking. The pacing of most of these coming events will be sluggish on the scale of daily human experience, but their eventual cumulative effects on ecosystems and societies will be enormous and incredibly long-lasting.

And just what is it going to be like from here on out? We'll have to wait for time itself to reveal the details of future political systems, technologies, social interactions, and lifestyles; one never really knows what *Homo sapiens* will do next. But many features of the physical world are far more predictable. This book offers an introduction to those aspects of long-term climatic and environmental change that stand most clearly before us on the horizon. Here is a sampler of what is to come.

We face a simple choice in the coming century or so; either we'll switch to nonfossil fuels as soon as possible, or we'll burn through our remaining reserves and then be forced to switch later on. In either case, greenhouse gas concentrations will probably peak some time before 2400 ad and then level off as our emissions decrease, either through purposely reduced consumption or fossil fuel shortages. The passing of the CO_2 pollution peak will trigger a slow climate "whiplash" in which the global warming trend will top out and then flip to a long-term cooling recovery that eventually returns temperatures to those of the preindustrial eighteenth century. But that process will last for *tens or even hundreds of thousands of years.* The more fossil fuel that we end up burning, the higher the temperatures will rise and the longer the recovery will take.

There's much more to CO_2 pollution than climate change, though. Carbon dioxide will gradually acidify much or all of the oceans as they absorb tons of fossil fuel emissions from the air. That chemical disturbance threatens to weaken or even dissolve the shells of countless corals, mollusks, crustaceans, and many microorganisms, and their loss, in turn, will threaten other life-forms that interact with them. In some ways, this situation resembles the contamination of the primordial atmosphere by microbial marine oxygen, only in reverse; we are responding 2 billion years later with a corrosive gas of our own that is moving from the air back into the sea. Eventually, the neutralizing capacity of Earth's rocks and soils will return the oceans to normal chemical conditions, but the acid-driven loss of marine biodiversity will be among the most unpredictable, potentially destructive, and irreversible effects of Anthropocene carbon pollution.

Before the end of this century, the Arctic Ocean will lose its sea ice in summer, and the open-water polar fisheries that develop in its absence will last for thousands of years, radically changing the face of the far north as well as the dynamics of international trade. But when CO_2 concentrations eventually fall enough, the Arctic will freeze over again, destroying what will by then have become "normal" ice-free ecosystems, cultures, and economies.

Much or all of Greenland and Antarctica's ice sheets will melt away over the course of many centuries, with the final extent of shrinkage dependent upon how much greenhouse gas we emit in the near future. As the edges of today's icy coverings draw back from the coasts, newly exposed landscapes and waterways will open up for settlement, agriculture, fishery exploitation, and mining.

Sea level will continue to rise long after the CO_2 and temperature peaks pass. The change will be too slow for people to observe directly, but over time it will progressively inundate thickly settled coastal regions. Then a long, gradual global cooling recovery will begin to haul the waters back from the land. But that initial retreat will be incomplete, because so much land-based ice will have melted and drained into the oceans. At some time in the deep future, the sea surface will come to rest as much as 230 feet (70 m) above today's level, having been trapped at a new set point that reflects the intensity and duration of the melting. Only after many additional millennia of cooling and glacial reconstruction will the oceans reposition themselves close to where they lie now.

We have prevented the next ice age. The ebb and flow of natural climatic cycles suggests that we should be due for another glaciation in about 50,000 years. Or rather, we used to be. Thanks to the longevity of our greenhouse gas pollution, the next major freeze-up won't arrive until our lingering carbon vapors thin out enough, perhaps 130,000 years from now, and possibly much later. The sustained influence of our actions today on the immensely distant future adds an important new component to the ethics of carbon pollution. If we consider only the next few centuries in isolation, then human-driven climate change may be mostly negative. But what if we look ahead to the rest of the story? On the scales of environmental justice, how do several centuries of imminent and decidedly unwelcome change stack up against many future millennia that could be rescued from ice age devastation?

These are the sorts of extraordinary things that you'll encounter in this book, but rest assured that it's not just a litany of gloom. I hope instead to leave you with a well-founded sense of hope and a wake-up call. You and I are living in a pivotal moment of history, what some have called a "carbon crisis"—a crucial and decisive turning point in which our thoughts and actions are of unusually great importance for the long-term future of the world. But all is not yet lost, and climate change is not on the list of deadly dangers to most humans; as I will explain later, *Homo sapiens* will almost certainly be here to experience the environmental effects of the Anthropocene from start to finish. And that's only fitting, seeing as we're the ones who launched this new epoch in the first place.

But why, then, should we care enough about the distant future even to finish reading about it on these pages? The reason is simple. Although humans will survive as a species, we are faced today with the responsibility of determining the climatic future that our descendants will live in. It may well be a struggle to hold our carbon pollution to a minimum, but failing to take the heroic path and control our collective behavior is likely to drag us and our descendants into a realm of extreme warming, sea-level rise, and ocean acidification the likes of which haven't been seen on Earth for millions of years. And the outlook for most nonhumans is far more worrisome than it is for our own kind. Severe environmental changes have happened before, even without our influence in the mix, but the situation that we and our fellow species now face is unique in the history of this ancient planet.

So welcome to this glimpse of our deep future. Welcome to the Anthropocene.

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Stopping the Ice

One can only hope that the expected extremes of the Anthropocene will not lead to conditions that cross the threshold to glaciation.

—Frank Sirocko, paleoclimatologist

Shockingly long-term climatic changes await us as a result of modern human activity, but examining our effects on the deep future also raises a related question that is well worth considering: what would global climates have been like if we had left our fossil fuels in the ground rather than burning them?

In that alternative reality our descendants would still fret about climate, sea levels, and ice caps but the news would read quite differently from that of today. "There's a massive, destructive climatic change coming, but scientists say that we can stop it if we take appropriate action now. If we go about business as usual, coastal settlements will be destroyed by sea-level shifts and entire nations will be covered with water. Frozen water. But there's still hope. If we simply burn enough fossil fuels, we'll warm the atmosphere enough to delay that icy disaster for thousands of years."

I'm talking about the next ice age. When a paleoecologist like myself thinks about global climate change the exercise is as likely to involve visions of ice-sheet invasions as it is to include greenhouse warming. We still don't know exactly why continent-sized glaciations come and go as they do, but they clearly have a rhythmic quality to them. Natural cyclic pulses take the long line of temperature history and snap it like a whip, looping it into a series of steep coolings and warmings. When viewed from a long-term perspective, major warmings of the past 2 to 3 million years can seem like brief thermal respites when the world came up for air between long icy dives; that's why we call them "interglacials" rather than something that sounds more normal or permanent. The cyclic pattern also suggests that more ice ages await us in the future, so strongly in fact that climate scientists routinely refer to our own postglacial warm phase that we live in today as "the present interglacial." Because of this admittedly unusual perspective, many of the paleoecologists I know balance their concerns about modern climate change with "yes, but it could also be a lot worse."

Although such views are rare outside of narrow academic circles, I believe that they belong in the mainstream. Time perspectives long enough to include ice age prevention are not just the stuff of mind games but potentially important aspects of rational planning for our climatic future. In order to appreciate why this is so, however, it helps to look more deeply than usual into the nature of ice ages.

The last one began about 117,000 years ago and ended 11,700 years ago. During that long and terrible reign of cold, roughly a fifth of the world's land surface resembled the icy interiors of Greenland and Antarctica today, especially in the higher northern latitudes. Most of what is now Canada and northern Europe was smothered under immense sheets of slowly creeping ice up to 2 miles (3 km) thick. The sites of today's Chicago, Boston, and New York were obliterated, and what we now call Long Island is a plowed-up bow wave of detritus that marks the southern limit of the last major ice advance. Entire landscapes sagged under that tremendous weight, pressing down hundreds or even thousands of feet into the planet's softer innards, and the gritty underbelly of the ice gouged deep scratches and grooves into solid bedrock that still scar the formerly glaciated regions of the world.

When you see glacial deposits and ice-scoured rock formations along a northerly roadside or trail, it's easy to let your imagination strip away the towns and trees and crush your surroundings under great, grinding slabs of ice. I envision it quite often near my home in the Adirondack Mountains of upstate New York. Recently I was reminded of the frozen past when I stepped off a woodland path near Saint Regis Mountain to take a closer look at one of the largest glacial erratic boulders I've ever seen.

The massive chunk of gray anorthosite was broader and taller than my house, and the prying fingers of winter frost had plucked garage-sized flakes away from its lichen-crusted flanks. They lay in low heaps around the central body of rock like cast-off clothing. The base of the giant perched just high enough above the ground to leave shadowed crawl spaces below that made me think of of crouching hermits and cave bears. Peering into one of them I scanned its dusky floor for signs of residents but saw only earth-colored gravel. Clean, well-sorted, smoothly rounded gravel, just like the stuff in the shallow streambed nearby. Gravel that was never buried under forest soils or leaf litter and that still looked as fresh as it did when melting ice dropped this gigantic sheltering rock on top of it.

That primeval scene drew my imagination back to when these mountains were still emerging from their long, lightless imprisonment. The rustling beech, maples, and birches before me faded away, along with the duff and dirt beneath them, exposing a desolate brown wasteland of wet sand and pebbles that glistened under a cold clear sky. Not a tree in sight, not a shrub or flower, not even many lichens on the virgin boulders yet. Cloudy silt-laden streams and molten blue pools sparkled in the low spots, and remnant hill-sized blocks of decomposing ice hunkered down in the deeper hollows, sloughing off layers of dusty surface debris like old dogs shedding winter fur. Far off on the northern horizon lay an unfamiliar range of white, mile-high hills, the sun-scored southern face of the melting ice sheet. The vision lasted only a few moments, but a strong feeling of connection to long-ago times when Big Ice ruled this landscape stayed with me through the rest of my hike that day.

The author examining a glacial boulder near Saint Regis Mountain in the Adirondack Park, upstate New York. *Kary Johnson*

Let's continue with this imagination game. What if it happened again?

Here and now in the Adirondacks we worry, with good reason, about the effects of acid rain, invasive species, and global warming on our local ecosystems. But those problems won't exterminate every last Adirondack fish and fowl, and even the most extreme case of Anthropocene heating would still leave the land covered with some sort of greenery, if not all the kinds we're currently used to.

A full glacial advance, on the other hand, is a total wipeout. Every lake is bulldozed or smothered under a thick blanket of cobbles, sand, and gravel. Every sugar maple, every golden-tinted trout lily, every tuft of moss heaves up in bow waves of dirt and stones and is crushed to pulp. Every animal with legs or wings flees southward. The Adirondack peaks vanish under a heavy white tide, the iconic ski jumps at Lake Placid topple and are ground to splinters, and every settlement from Saranac Lake to Old Forge is obliterated.

Meanwhile, farther north, most of Canada disappears. That includes Quebec City, Montreal, Ottawa, Toronto, Winnipeg, Calgary, and Vancouver, not to mention every wild area from Hudson Bay to Banff. From a human perspective, there's no place called Canada for tens of thousands of years except in the same sense that a gigantic frosty slab called Antarctica now squats on the South Pole. And out across the Atlantic, advancing walls of white demolish Dublin, Liverpool, Oslo, Stockholm, Copenhagen, Helsinki, and Saint Petersburg, and every settlement on the rocky coastal rind of Greenland is shoveled into the sea by heavy spatulas of ice.

With much of the world's freshwater imprisoned in frozen form on the continents, sea level falls by as much as 400 vertical feet (120 m). The site of every twenty-first-century port is stranded far inland, the long, slender thumb of Florida doubles in width, and the present location of every shallow-water coral reef in the tropics sprouts weeds and trees. The associated cooling weakens monsoons, locking much of Africa and southern Asia into chronic droughts.

This is what a climate historian is likely to have in mind when discussing climatic change. Compare it to what most experts expect modern warming to bring us in the Anthropocene future and you'll understand why a paleoecologist's panic button might not be so easily pressed.

But wait. Isn't global warming supposed to trigger the next ice age? Isn't that what we saw happen in the apocalyptic enviro-thriller movie *The Day After Tomorrow,* in which the greenhouse effect suddenly shuts down climatically important ocean currents in the North Atlantic and triggers a superglaciation?

The movie isn't totally wrong, in that the warm Gulf Stream really does help to keep northwestern Europe from becoming cooler than it already is. It's part of a huge global conveyor belt system of interconnected currents that draws solar-heated tropical water into the cold surface of the North Atlantic, where it cools off and then sinks for a deep return journey southward. Some scientists worry that future climatic changes could disrupt that conveyor and trigger a sudden regional cooling; hence the movie scene in which a fierce wind seizes Manhattan with remorseless fangs of frost. But as gripping as that storyline is, serious questions remain about the real role of the conveyor in past and future climate change.

The engine driving the conveyor goes by several dry technical names, most recently the meridional overturning circulation, or MOC. It is also sometimes called THC, an abbreviation that is in no way connected to marijuana smoking (and tetrahydrocannabinol) but rather, reflects the upgrading of a simpler concept, that of thermohaline circulation, whose basic premise is that changes in temperature and saltiness drive major circulation currents of the oceans.

Warm water on the surfaces of the tropical oceans loses moisture to evaporation, which makes it saltier than average seawater. When the Gulf Stream flows from the hot latitudes between West Africa and the Caribbean into the cooler North Atlantic, it doesn't easily mix with those northern waters because its tropical heat content makes it less dense (warming makes both water and air expand). But the Gulf Stream gradually releases much of that heat into the cooler air over the North Atlantic, and when it finally does chill down its extra load of salt leaves it denser than usual.

That extra density makes some of the Gulf Stream water sink beneath the surface and continue its riverlike meanderings at greater depths. By the time it resurfaces, the deep flow has wormed its way around the southern tip of Africa and entered the Indian and Pacific oceans. Back on the surface again, the current recurves back across those oceans, rounds the tip of South Africa, and returns to the North Atlantic, picking up new loads of equatorial warmth along the way. Additional branches also operate in the Southern Ocean and Arabian Sea, adding extra loops to the tortuous path of the global conveyor.

There's a lot more to the picture than that, however, and when illustrations of this common version of the THC concept appear in professional slide presentations, they can become what one speaker at a recent meeting of the British Royal Society called "oceanographer detectors," because they make specialists in the audience "go visibly pale at the vast oversimplification."

The THC model is not so much wrong as incomplete. Most scientists have now switched the focus of ocean-climate discussions to the more comprehensive MOC formulation because temperature and salinity aren't the only drivers of ocean currents after all; winds and tides are at least as influential. THC-style flow does occur, but midlatitude westerly winds and tropical easterly trades do much of the actual pushing.

So why does marine MOC affect climate? As heat rises into the air from the Gulf Stream, it warms the westerly winds that blow toward Europe. Without those ocean-tempered winds, London might be as cold as … well, look at a map to see what lies at the same latitude on the opposite side of the Atlantic, and you'll find snowy Labrador.

With this basic introduction to the topic, you're already well enough equipped to take a pot shot at *The Day After Tomorrow*. The prevailing winds over Manhattan blow offshore toward the Atlantic, not from it, so why should a Gulf Stream shutdown freeze the city? The film also unrealistically subjects Europe to severe winter conditions year-round. Even if it really did become a climatic equivalent of Labrador, northern Europe would still warm up quite a bit in summer, just as Labrador does.

In reality, a MOC slowdown alone couldn't turn Europe into a climatic twin of Labrador because it lies downwind of a temperature-modulating ocean rather than the interior of a continent. And because prevailing winds spin the North Atlantic surface current system clockwise regardless of what the salinity or temperature of the water is, some version of the Gulf Stream will exist as long as these winds continue to blow over it.

Although some computer models do simulate moderate conveyor slowdowns in a warmer future, a truly severe disruption would require extremely large floods of freshwater to pour into the sea, presumably from the melting of land-based ice. If, say, a major ice sheet were to slide off into the North Atlantic where some critical sinking zone is operating, then perhaps it might cap the ocean off with dilute, buoyant meltwater.

In 1999, oceanographer Wallace Broecker published a striking theoretical description of just such a total MOC collapse under perfect-storm conditions. Tundra replaces Scandinavian forests. Ireland becomes the climatic equivalent of Spitsbergen, an island in the Norwegian Arctic. When climate modelers working at Britain's Hadley Center several years ago told their computers to "kill the MOC," the virtual air outside their lab cooled by 8°F (5°C) within ten years, at least on the digital screen.

But Broecker maintains that such a scenario is unlikely today, because those theoretical events only played out in a world that had already been cooled by a prolonged ice age. Nowadays, however, we don't have nearly enough readily meltable ice left in the Northern Hemisphere to do the job. To reset that stage we'd have to cover Canada, northern and central Europe, and Scandinavia with thick ice caps, and that would require colder, rather than warmer, conditions in the future.

Most computer models that have been upgraded so they more accurately represent the role of winds in ocean circulation foresee little, if any, cooling in the North Atlantic region from MOC disruptions during the Anthropocene. As the latest Intergovernmental Panel on Climate Change (IPCC) report concluded, "it is very unlikely that the MOC will undergo a large abrupt transition during the 21st century," and most experts believe that future greenhouse warming will overwhelm any minor regional effects related to MOC. In light of such findings, Broecker has tried to tamp down some of the worst exaggerations of the ocean-climate link that have been made by nonspecialists, but it's a tough struggle that pits scientific restraint against the lure of a good story.

One case in point is a study commissioned by the U.S. Department of Defense that presented a wildly extremist view of MOC collapse as a grave and imminent threat to national security. In their 2003 report, the authors noted that they were presenting only the most severe of all possibilities, as is commonly done in military planning circles, but that disclaimer was easily missed amid the frightening scenarios that followed. In their depictions, global average temperature shoots up faster and faster until, in 2010 AD, the MOC begins to collapse. Less than ten years later, according to their model, northern Europe cools by 5 to 6°F (3°C), devastating drought strikes the United States, and "a cold and hungry China peers jealously across the Russian and western borders at energy resources."

In response, Broecker wrote an open letter for publication in *Science* that expressed his dismay over the hyperbole. "I take serious issue with both the timing and the severity of the changes proposed," he wrote, pointing out that such extreme changes would take a long time to develop and would require glacial-type conditions, not global warming, to trigger them. Furthermore, he cautioned that computer models still can't fully reconstruct complex MOC disturbances of the past, much less those of the future. He concluded his letter with this admonition: "Exaggerated scenarios serve only to intensify the existing polarization over global warming."

Nonetheless, the idea of a total collapse of MOC is so emotionally gripping that it has become firmly lodged in public consciousness. In that context, oceanographers are watching closely for signs of conveyor responses to modern warming, just to be on the safe side. In 2005, for example, a team of British researchers described a 30 percent slowdown in MOC flow since 1957. The news caught fire among lay and professional audiences alike, but follow-up studies found that the slowdown alert was a "false alarm," as Richard Kerr put it in a deflating news brief for *Science*. The pattern of MOC flow is extremely variable, and a more careful look at the numbers showed that the reported trend was indistinguishable from random fluctuations.

If MOC changes are unlikely to freeze Europe, will ice ages play any role at all in an Anthropocene world? The answer is a qualified yes, but if they do reappear, it won't be the fault of ocean circulation disruptions. The main drivers of large-scale glaciation are the movements of Earth itself as it makes its annual elliptical dance around the sun.

The way many descriptions read in the popular media, you'd think that stopping our greenhouse gas emissions would prevent climatic change altogether. In fact, climates will always change whether we exist or not, just as they have even on Mars where similarly periodic frosts, thaws, and floods have left their signatures in deposits of red sand, gravel, and dust. Fortunately, because much of that change is cyclical, we can predict some of it by letting it play out on computer screens.

The fastest moves in the planetary dance are wobbles. Imagine a whirling top as it slows down and progressively loses its balance. The top begins to dip and swing around in progressively wider circles as it spins more slowly on its axis. Earth does that, too, though not because it's going to tumble over any time soon. In the wobble cycle, the North Pole draws a full loop roughly every 21,000 years (technically speaking, there are actually two modes of the cycle, 19,000 and 23,000 years long).

This has climatic effects because it changes how sunlight intensity, or insolation, affects different parts of the planet's curved surface. Each year, winter comes to the Northern Hemisphere when it leans away from the sun, and northern summer reigns when it leans toward the sun. Every 21,000 years or so, the wobble cycle brings the Northern Hemisphere its annual dose of summer only when we're farthest away from the sun on our egg-shaped orbit. When that happens, northern summers become slightly cooler than usual and less snow melts as a result.

Keep in mind here that these events don't happen because the sun itself changes. Instead, it's because sunlight affects the seasons and hemispheres differently over time. Those effects are amplified by geography because most major landmasses are crowded into the northern half of the globe and dry, solid ground accumulates ice sheets more readily than oceans do. For these reasons, ice ages typically begin in the Northern Hemisphere; the last one was born in the ice-friendly insolation target areas of northeastern Canada and northwestern Eurasia.

But that's not the whole story. Several longer cycles also influence the comings and goings of monster ice sheets.

As Earth wobbles, it also tilts more or less steeply in ways that amplify seasonal temperature differences. The slower tilt cycle takes 41,000 years for the North Pole to rock back and forth between 22.1 and 24.5 degrees of arc. When this cycle tilts the planetary axis less steeply, it aims each pole less directly at the sun during its seasonal summertime, so it warms less than usual. For reasons as yet unknown, this was the dominant pacemaker of ice age recurrences until about 1 million years ago, when the wobble cycle and a third, even slower cycle joined forces with the tilt cycle.

That third pulse, the eccentricity oscillation, changes the shape of Earth's orbital route around the sun. The path becomes more or less egglike over the course of about 100,000 years; it also changes in other ways every 412,000 years. Because the sun sits off center within that ring, snuggling a bit closer to one end of the oval than the other, Earth's distance from the sun varies a great deal through the seasonal circuit, and distortions of that route caused by the eccentricity cycle accentuate those changes. When the orbital ring is most distorted, a good deal less solar heat reaches us at the farthest end of the egg.

As all these cycles operate at once, they interact in ways that are easily visualized by comparing them to water waves. I first learned about this from my friend and colleague, ice core researcher Paul Mayewski, who directs the Climate Change Institute at the University of Maine in Orono. He explained how most of the ragged jumps and wiggles in his polar climate records originate.

"It's like waves on a lake," he began. I imagined orderly ranks of swells rolling along under a brisk breeze. "The rising and falling of the main swells are like the slow eccentricity cycle. Now imagine that a motorboat wake joins the pattern. Those waves are smaller and closer together, so they don't line up perfectly with the larger, wider ones."

I envisioned an irregular, bumpy surface like the ones that I often encountered during the waterskiing days of my youth. It was easy to keep my balance on a single predictable wave pattern, but when the driver doubled back on our trail or another boat dragged its own chop across our path, it spawned a crazed tangle of leaping, plunging waves. Where two crests briefly collided they bounced skyward, and where two troughs briefly met they bounced lower. Add forward and crosswise motions to such a collision zone and, as I can personally attest, a fallen water-skier will bob around in it like a cork.

"That's where a lot of long-term climate variability comes from," Mayewski continued. "When different cycles occur simultaneously, they harmonize and strengthen each other sometimes and they weaken or cancel each other at other times. And the more cycles you mix into the climate system, the more erratic it becomes." Mingling like waves through the ages, Earth's insolation cycles account for a surprising amount of natural climatic instability, and when they produce an exceptionally long and low temperature combination they can trigger a full-scale ice age.

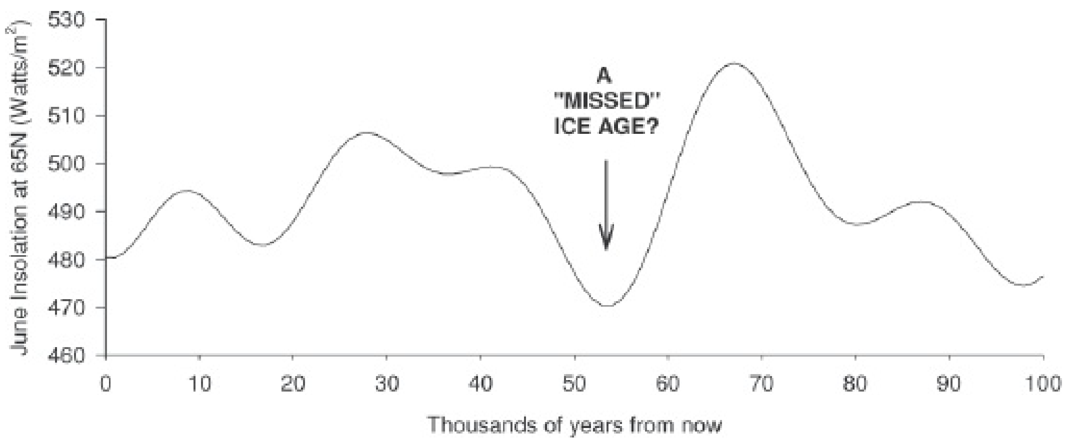
These cyclic patterns were worked out by James Croll, a nineteenth-century Scottish scientist, and later refined early in the twentieth century by a Serbian civil engineer, Milutin Milankovitch. The fit between theory and history isn't perfect, and many of the past's shorter temperature perturbations had other causes. Furthermore, we still don't know exactly why northern glaciations have affected so much of the world at once; the slow gyrations of Earth tend to cool northern summers while warming southern ones, so you might expect ice ages to affect only half of the planet at a time. But the basic hypothesis of insolation-driven ice age pacing is still well supported in the geologic record. Take, for example, the history that was recently revealed by one superlong ice core from Antarctica. It represents 800,000 years of climatic change, and it also captures eight glacial cycles, reasonably in line with the 100,000-year rhythm of the eccentricity cycle.

Croll and Milankovitch worked with paper and pencil and devoted countless hours to hand-calculating past insolation values, a mind-numbing task that computers now repeat in seconds. But most interesting in the context of future Anthropocene climate are the models that run those cycles forward in time. By tracking Arctic insolation patterns into the future, we can predict when ice ages should come back to haunt us again—or, rather, when they would occur in the absence of our carbon pollution.

The wobble cycle is now trying to make northern summers slightly cooler than usual, which is one of the preconditions for launching a new ice age. And if we think of the last 11,700 years of postglacial conditions as just the latest in a series of similar interglacial warm spells, then common sense suggests that we're about due for a new cold snap.

During the 1960s, a temporary global cooling episode and a few scientists who incorrectly attributed it to the return of icehouse conditions launched a brief flurry of "fear the global cooling" excitement in the media. That response, of course, was misguided because the decadal time scale under consideration was far too short to represent Milankovitch-scale cycles, and what at the time may have felt like the start of a neoglaciation was in fact merely a brief pause in the twentieth-century warming trend.

But we can do much better than that today. Well-trained specialists now devote their careers to calculating the patterns and climatic effects of orbital cycles. Among the most influential of these are André Berger and Marie-France Loutre, a pair of climatologists at the Institute of Astronomy and Geophysics in Louvain-de-Neuve, Belgium. Their charts and tables of insolation data are widely cited in the scientific literature, and the graph shown here was drawn with data that were kindly provided by Dr. Loutre.



Solar insolation at 60 degrees North, showing an anticipated cooling event ca. 50,000 AD that might have triggered the next ice age in the absence of lingering fossil fuel emissions. *Data courtesy of Marie-France Loutre.*

So, when is the next ice age scheduled to arrive? A Berger-Loutre chart that appeared in *Science* in 2002 lays it out clearly. Today, the Arctic has entered a phase of relatively weak summer insolation that, in earlier times when the eccentricity cycle was stronger, might have been deep enough to call another ice age down upon us within the next few thousand years. But this episode will be too mild to do the job, even without our greenhouse gases working against it. In other words, we've just dodged an icy bullet, thanks to a slight, temporary diversion of our route around the sun.

Berger and Loutre's work also shows that the effects of the 412,000-year eccentricity cycle have been weakening in recent millennia, which helps to flatten out the depths of cooling pulses. The more symmetrical our orbit becomes as a result of changes in that longest of cycles, the narrower the range of seasonal temperatures on Earth. This will set an even calmer tone for cyclic climate changes in the more distant future of the Anthropocene.

Roughly 25,000 years from now, our orbit will be about as close to circular as it ever gets, and the power of the other cycles to warm or cool the ice masses of the Arctic will be as weak as it ever gets. Under those conditions, we'll still face brief regional disturbances, such as the North Atlantic Oscillation, El Niño, and the sheer orneriness of local weather that we know today, but they'll only raise short-lived climatic ripples on the flattened surface of the longer orbitally driven patterns. With the gentle urging of slightly higher axial tilt than we experience today, the curve of northern summer insolation will simply add a very mild rise to a puny peak—more like a low hilltop—about 25,000 years from now.

Although that low blip will cause only a mild thermal boost, it nevertheless does mean that Arctic summers were already slated to warm very slightly in coming millennia even without our influence. If Berger and Loutre are correct, then this may be unwelcome news to fans of low sea levels and heavy ice cover on Greenland.

According to the calendar of orbital cycles, the next serious risk of an ice-spawning chill during Arctic summer isn't due until about 50,000 AD, but here is where we humans enter the scene. Most climate models will only trigger an ice age at that distant point in future time if the CO_2 content of the atmosphere is no higher than 250 parts per million (ppm).

With CO_2 concentrations as of this writing at 387 ppm and rising, they clearly won't be going back below that critical threshold for a very long time. In fact, as will be explained in Chapter 3, those values will still hang well above 250 ppm in 50,000 AD, and they won't return to such preindustrial conditions for tens of thousands of years beyond that.

These two factors together—the inherent weakness of the next cooling cycle and the longevity of our carbon pollution—lead to one astounding conclusion. Not only have we warmed the world during this century with our carbon emissions; we've also stopped the next ice age in its tracks.

According to recent computer model studies, this may be only the beginning of our influence over the coming and going of ice ages, depending on what we do during the next century or two. If we hold ourselves to a relatively moderate sum total of fossil fuel emissions before switching to alternative energy sources, then we skip the next glaciation in 50,000 AD. But more of those natural cooling pulses will develop later on. When the next big one strikes the Northern Hemisphere some time around 130,000 AD, the greenhouse pollution legacy of a moderate-emissions scenario will have faded to insignificance, leaving nothing to resist glaciation. Once again, ice will bury the northern sectors of the northern continents. Or rather, it will do so unless we burn through all of our remaining coal reserves during the next century or so. If we go down that profligate path instead, there won't be any ice ages for a very long time: not in 50,000 AD, not in 130,000 AD, and not during the other insolation minima of the next half million years.

How should we react to this news? When I imagine our carbon footprint kicking the door closed on an ice age, my initial reaction is one of shock mingled with a twinge of fear. But a second, rather confusing response follows when I imagine our carbon emissions saving the northern United States, Canada, and much of northern Eurasia from being crushed under gigantic ice sheets.

It would be stretching the bounds of credibility to say that greenhouse pollution is anything but a vexing problem. But on the scale of planetary disaster, an ice age is to global warming as thermonuclear war is to a bar brawl. We're certainly justified in worrying about the environmental disturbances that are coming our way, but even this situation is arguably better than losing entire nations and ecosystems to total icy destruction. What if we had to choose between the two options?

In fact, we do face that very choice as we weigh our possible responses to modern climate change. Most of the more extreme negative effects of today's fossil fuel emissions will be felt within the next millennium or so, but what if those same fumes later go on to save much later generations from having to endure otherwise inevitable ice ages?

At first, this ethical dilemma might seem outlandish, a silly kind of joke. Speaking of it too flippantly feels disrespectful of those who may suffer from the climatic changes of today and in the near future. It also feels like tossing raw meat to the habitual contrarians who seek any excuse to avoid controlling fossil fuel consumption. But the facts are plain, and I believe they're worth considering carefully.

Unfortunately, the large time scales involved in this subject complicate discussions of it. It's much easier to imagine what climate change might do to ourselves or our grandkids than what it might do to people 130,000 years from now, and this can make it difficult for some individuals to take the matter seriously. For them, weighing the value of their own lifetimes against those of unknown citizens of the far future is as ridiculous as weighing the value of a living child against that of a cartoon character; such distant people and times are simply too remote to seem real.

On the other hand, many of us do enter that deep pool of inquiry when we consider doing things for the sake of future generations, though our entrance is usually more of a toe dabble than a dive. In fact, thinking and acting on behalf of future-dwellers isn't the simple endeavor that it may seem to be, especially if you don't restrict your attention to those closest to us in space and time.

For one thing, you have to decide who those beneficiaries will be. Does your list include everybody who will be alive in, say, 2500 AD or just a select subset of them? You might be willing to give up your gas-guzzling car in order to keep the climate of a direct descendant's world similar to that of your own. But what if that choice also harms someone else, perhaps by making some future nation much wetter or drier than it would otherwise be: will you favor your own lineage over those of others? And if you choose to favor your own descendants, you still have to decide which ones to focus on because various generations will prefer different things at different places and times in the future.

If we imagine the Anthropocene in its entirety, it gives us a very large and diverse collection of future people to consider. Many of them will inhabit a warming world, but most will live on the long cooling tail-off of atmospheric CO_2 recovery. Perhaps citizens of 130,000 AD might decide that, after so many millennia of ice-free oceans and high-latitude commerce, they'd rather keep things the way they are rather than let CO_2 concentrations return to preindustrial levels, particularly with a new ice age looming. Maybe by then our long-lived carbon emissions will have begun to seem less like pollution and more like insurance against global cooling.

Then again, maybe not. But who are we to decide their fate, anyway?

We will be messing with planetary temperatures for a very long time, well past the temporal limit of 2100 AD, but we still have time to head off the most extreme consequences if we choose to do so with a long-term view of the future in mind. One of the most important decisions that our generation will ever make is the critical choice