PROLOGUE

Global Warming in Geologic Time

Global warming could be one of humankind's longest lasting legacies. The climatic impacts of releasing fossil fuel CO_2 to the atmosphere will last longer than Stonehenge. Longer than time capsules, longer than nuclear waste, far longer than the age of human civilization so far. Each ton of coal that we burn leaves CO_2 gas in the atmosphere. The CO_2 coming from a quarter of that ton will still be affecting the climate one thousand years from now, at the start of the next millennium. And that is only the beginning.

The excess CO_2 in the atmosphere at the next millennium may not be the exact same molecules that came from our power plants. Some of the CO_2 from fossil fuels will have been taken up into trees, or deposited in soils. Some will have dissolved in the oceans. But, as this book will explain, the CO_2 concentration in the atmosphere at the next millennium will be higher if that coal is burned than if it is not. About 10% of the CO_2 from coal will still be affecting the climate in one hundred thousand years.

Over the last few centuries, mankind has been humbled by insights from the scientific enterprise. Darwin told us that humans are not biologically "special"; we are descended from monkeys, and they from even humbler origins. Copernicus discovered that the Earth is not the center of the universe, but rather revolves around the Sun, an ordinary star like billions of others. Geologists' reconstruction of the history of the Earth tells us that the world is much older than we are, and there's no evidence that it was created especially for us. Most of Earth history predates the arrival of humans. This is all very humbling. Global climate is a canvas upon which mankind may be painting one of his longest-lasting legacies. We're not so puny, after all. We are becoming players in geologic time.

The first section of the book is a snapshot of the situation we find ourselves in right now. In geologic time, a century is nothing, an eyeblink, so let's be geological and consider the last century and the next century to be "the present." The theory behind global warming has been around for about a century. Meanwhile, the CO_2 concentration in the atmosphere has been steadily rising. This was discovered about a half-century ago. Just in the last few decades, the temperature of the atmosphere has begun to rise in a way that can be satisfactorily explained only by the greenhouse theory, which has the implication that it will get even warmer if CO_2 continues to rise. The first section of the book contains an explanation of what the forecast calls for, and why.

The second section of the book is about the past. A tenet at the foundation of geology is that the present is the key to the past. The idea is that processes that can be observed today might also be responsible for things that happened in the past, given the vast stretches of geological time. An ice sheet grinds up the rocks into dust, which blows away and deposits someplace else. Eventually, after tens of thousands of years, you have a layer of glacial flour many meters thick.

In this book we are operating on a somewhat different philosophical premise, using the past as the key to the future. Our motivating interest here is the forecast for global warming. How bad does it sound? How likely is it? Is global warming something new, or is this something that happens all the time?

Global warming is not the first climate event in Earth history. There were even larger climate changes in the past. There were sudden climate flip-flops, a switch in a few years from one climate to another that lasted a thousand years. There was also the slow, ponderous transition from the tropical world of the dinosaurs to the icy world of today.

Reconstructed climate changes of the past can be used to test the models that are used to forecast the future. Climatology is not an experimental science, in that we don't do experiments with the real climate system, at least not intentionally. So one approach to understanding the climate system is to reconstruct how it varied in the past, and how it responded to getting poked in various ways. A grant proposal would probably describe the paleoclimate record as a "natural laboratory." A graduate student would probably say that we are using the past to tune our chops for forecasting the future.

Climate changes of the past also help visualize and calibrate the forecast for the future. The global average temperature of the Earth might be 3 °C warmer in the year 2100 than it was in 1950. This doesn't sound like much; as I look outside it is probably at least 3 °C warmer at this moment than it was early this morning, and the world doesn't seem to be ending. On the other hand, the climate changes that civilized humanity has witnessed have all been 1°C or less. Earth has warmed almost this much already because of human activity, but this is nothing compared with the forecast for 2100.

The second section of this book describes climate changes in the past, as they are relevant to the global warming forecast for the future. The first three chapters (4, 5, and 6) describe three different modes of natural climate variability, which operate on three very different timescales. Chapter 7 brings together the present and the past. The impatient reader could even skip ahead to Chapter 7 without losing the thread of the argument too much. Think of Chapter 7 as a sort of Executive Summary So Far.

Against this backdrop, in Section 3, we turn our attention to the deep future of the global warming climate event. The excess CO_2 in the atmosphere is absorbed and transformed into carbon in trees, mucky soils, and dissolved in the ocean, and so the warming begins to subside. The oceans are a big player in this story, absorbing a majority of the CO_2 we release, on a timescale of a few centuries.

Early earth scientists believed, perhaps without giving it too much thought, that CO_2 would invade the ocean more quickly than this, perhaps fast enough that the CO_2 concentration of the atmosphere would be essentially imperturbable by human activity. This is a blue planet, after all. The ocean covers three quarters of the the surface of the Earth.

But most of the water in the ocean is cold, deep abyssal water, which sees the atmosphere only maybe every thousand years. The pathway for fossil fuel CO_2 into the deep ocean is through the surface ocean in very cold places like near Antarctica or Greenland, which cover only a small fraction of the Earth's surface. This bottleneck is the reason for the centuries it will take for fossil fuel CO_2 to dissolve in the oceans.

Several centuries seems—to me, personally—like a pretty long time. Mozart lived several centuries ago. But for human-induced climate change, this is only the beginning. It turns out that, after a new slug of CO_2 has spread out in whatever way it chooses between the atmosphere and the ocean, there will still be excess CO_2 left in the atmosphere.

The ultimate fate of that leftover CO_2 will be to react with dissolving rocks. Chemically, igneous rock acts like a base, able to neutralize and thereby absorb CO_2, which is an acid. Eventually, the carbon winds up as limestone shells on the ocean floor. Carbon emerges from the solid Earth during fossil fuel combustion, and it returns to the solid Earth as limestone.

The kicker is that it will take thousands of years, even hundreds of thousands of years, for these chemical reactions with rocks to completely scrub the planet of our extra CO_2. Most of the excess CO_2 in the atmosphere goes away in a few centuries by dissolving in the ocean, but the rest has to wait. The atmospheric CO_2 peak has a long tail (Figure 14 in Chapter 8).

Mankind has a kind of vested interest in time spans of centuries. I personally can visualize centuries. I like to think that Benjamin Franklin's childhood was not unimaginably different from my own. (OK, so I probably watched more TV than he did.) I know people who knew people who knew the beginning of the last century. I can look the last century in the eye.

Looking forward, a century is about how far I can really imagine also. Sixty years is grandchildren. One hundred is great grandchildren or great, great grandchildren. After that, they're on their own, am I right?

Climate change science and politics are also very focused on the century time horizon. There are records of temperatures, measured by thermometers, going back about a century. The Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment forecast of global warming, described in Chapter 1, is particularly focused on climate change between now and the year 2100.

It makes perfect sense to focus our attention on a time span that is imaginable given our own century-timescale lifetimes. Even if we lived to be a thousand years old, or ten thousand, the century timescale would be an important one to watch, no doubt about it. One reason is that fossil fuel CO_2 is released on a timescale of centuries. By the year 2100, traditional oil and gas will be gone. It might take a few centuries to burn all the coal, however, and the coal is where most of the carbon is. Atmospheric CO_2 goes up and then comes most of the way back down, as it is absorbed in the oceans, within a few centuries. Therefore the largest climate changes will consist of a climate storm, several centuries long, significantly worse than the forecasts for the year 2100. Eventually, the storm will fade, mostly, into the long tail.

Much of the action in the global warming forecast takes place on timescales of centuries. When it comes time to make practical decisions about avoiding human-induced climate change, the century timescale is the first one to watch, no question.

But just out of curiosity (if for no other reason), let's consider climate changes on timescales that are much longer than that. Earth is more than a few centuries old. Human civilization is unique in Earth history but we are not the first climate provocateurs this old Earth has seen. Climate changes in the past can tell us a lot about the deep future. They have had time to play out, unlike our own global warming climate change, which is just beginning.

The deepest and most profound climate changes in the recent geologic past seem to take place on timescales of millennia and longer. The great ice sheets grow and usually melt on timescales of millennia, a huge response to the wobbles in the Earth's orbit. The natural carbon cycle acted as a positive feedback, amplifying the response to the orbit.

The climate of the Earth is so dramatically sensitive to the ten-thousand-year orbital wobbles that it might also put on a pretty good show in response to the long tail of the fossil fuel CO_2. I will try to convince you that human climate forcing has the potential to overwhelm the orbital climate forcing, taking control of the ice ages. Mankind is becoming a force in climate comparable to the orbital variations that drive the glacial cycles.

The Earth today is colder than the average over geologic time. Most of Earth's history has been ice-free. Over millions of years, the climate of the Earth drifts back and forth between an icy climate such as we have today, and a "hothouse" climate state. Forty million years ago, the Earth was in a hothouse climate called the Eocene Optimum. The climate was tropical to the poles, driven by atmospheric CO_2 concentration maybe 10 or 20 times higher than today.

The slow progression between hothouse and icy climates is driven by the cycling of CO_2 into and out of the solid Earth. CO_2 is released from the Earth in volcanic gases and hot springs at the bottom of the ocean. CO_2 is taken up by weathering reactions, the same reactions that will generate the long tail of the fossil fuel CO_2.

On a timescale of a million years or longer, the climate of the Earth is determined by the solid Earth, breathing in and out CO_2. The difference between an Eocene hothouse and an icy climate such as ours is determined by factors that affect carbon release or uptake, such as the arrangement of the continents, the uplift of mountains, the evolution of plants, and doubtless many other factors.

Volcanoes release much less CO_2 every year than we do, so the near-term future is going to be dominated by us. Human industry has taken its place alongside the natural climate forcing agents, with the distinction that we push things around 100 times faster than the natural ones typically do. Ultimately, the amount of fossil fuel available could be enough to raise the atmospheric CO_2 concentration higher than it has been in millions of years.

The sea level rise forecast for the coming century is 0.2 to about 0.6 meters. This forecast includes the effects of water expanding as it warms up and the water from melting mountain glaciers in places like Alaska. The forecast explicitly does not include what will ultimately be the most important process—the melting of major ice sheets in Greenland and Antarctica. Sea level changes in the past were perhaps one hundred times larger for a given warming than the IPCC forecast for the coming century. The large variations in the past were driven by growing and melting ice sheets.

IPCC refers to this possibility as "future rapid dynamical changes in ice flow," and concludes that ice sheet collapses are unlikely in the coming century, but impossible to predict reliably. The current state-of-the art computer models of ice sheets predict that the ice sheets will not melt into the ocean very much in the next hundred years. However, there are examples from the past of ice sheets collapsing into the ocean over only a few centuries. There are also rumblings in the ice today that suggest that ice sheets may know a few tricks about melting that the ice sheet models have still to figure out.

During the melting of the ice sheets, about fourteen thousand years ago, there was a time interval called Meltwater Pulse 1A during which the equivalent of three Greenland ice sheets melted into the ocean in just a few centuries. Sediments from the North Atlantic tell us of times called Heinrich events, between thirty and seventy thousand years ago, when the Laurentide ice sheet on North America collapsed within a few centuries, releasing "armadas of icebergs" into the Atlantic, floating as far south as Spain. If the Greenland ice sheet began to collapse into the ocean like this, it would be unstoppable, a century-long train wreck.

The ice today is rumbling. Seismometers on the ice feel more ice-quakes than they used to. Models of the Greenland ice sheet take centuries to respond to changes in climate, but the flow rates of the real Greenland ice sheet are accelerating already. The real ice sheets are far more sensitive to climate than the ice sheet models are. This is no evil conspiracy, but just unfinished business. Computational glaciology is a field on the move.

But on timescales of millennia and longer, no fancy new melting tricks are even required to drive alarming sea level changes. Ice sheet models do not predict Meltwater Pulse 1A or the Heinrich events, but they do predict the eventual melting of Greenland if the local summertime temperature were 3°C warmer. Greenland by itself would raise sea level by 7 meters if it melted.

Sea level in the geologic past was much more responsive to changes in global climate than what IPCC predicts for the year 2100. Past sea level varied by 10–20 meters for each 1°C change in the global average temperature. The IPCC business-as-usual forecast for 3°C would translate to 20–50 meters of sea level rise. The changes in the map of the Earth would be obvious even from space. It may take thousands of years for sea level to change this much, but the long tail of the fossil fuel CO_2 gives us all the time we need.

Why should we mere mortals care about altering climate 100,000 years from now? Climate change is forecast to the year 2100, a date that very few people now reading this book will see, but a time span considerably shorter than 100,000 years.

The rules of economics, which govern much of our behavior, tend to limit our focus to even shorter time frames. Values are related across time using interest rates. A $100 obligation in 100 years might be dealt with by investing $5 today, at an inflation-adjusted interest rate of 3% per year. A $100 cost in 500 years shrinks to 0.003 cents today. Analyzed within the framework of economics, a climate impact 100,000 years from now becomes laughably irrelevant to any rational decision-making. I'm imagining the financial guys on television laughing smugly at how irrelevant it is, ha ha ha.

And yet, human cultural memory begins to approach the longevity of our proposed climate adventures. The earliest written records date to 5500 years ago, and oral tradition may carry some grain of history from earlier still. How would it feel if the ancient

Greeks, for example, had taken advantage of some lucrative business opportunity for a few centuries, aware of potential costs—such as, say, a stormier world, or the loss of 10% of agricultural production to rising sea levels—that could persist to this day? This is not how I want to be remembered.

Ancient economists might have assured us (as Bjørn Lomborg does today) that the proper course should be to skimp on cleanup, and invest the money instead. Get rich and deal with it. An investment made by the ancient Greeks will have blossomed into a real chunk of change by now, more than enough to pay us off for any damages inflicted. That sounds like a lot of trickle-down, to me.

It could be that future civilizations might simply adjust to the new climate regime. If humans had evolved in the Eocene, no doubt we would find it comfortable. But there are ways in which a hothouse world might be a real trade-down. We did not evolve in the Eocene, and our descendents might find it uncomfortable, just as we would. Large regions in continental interiors could dry out. Hurricanes could get stronger. Sea level rise could inundate 10% of the carrying capacity of the planet, or more. In the long run, it could be a steep price to pay for a century or so of fossil fuel energy.

If climate change turns out to be a disaster, there have been proposals to geo-engineer a return to a cooler climate. Large volcanic eruptions inject a haze of droplets and particles into the stratosphere, which reflects sunlight and measurably cools the climate for several years. We could put additives into commercial jet fuel that would produce stratospheric particles deliberately.

This and most other proposals for climate geo-engineering require an ongoing effort. The particles settle out a few years after the planes stop flying. If society some centuries down the line failed to pay its climate bill (a bill that we left to them, thank you very much), all of our accumulated CO_2 emissions would begin to impact climate within just a few years. Geo-engineering solutions seem rather puny next to the hundred-millennia lifetime of global warming.

The only geo-engineering scheme that deals with the persistence of CO_2 is to extract CO_2 from the atmosphere, to really clean it up. The CO_2 could be buried in the Earth, after reacting it artificially with rocks perhaps. The problem is that once CO_2 is diluted by releasing it to the atmosphere, it takes energy and work to un-mix it. Releasing our fossil fuel CO_2 to the atmosphere now is a phenomenally stupid strategy, if the eventual plan is to clean it back up.

Persistence is a factor in many other environmental issues. Nuclear power creates waste that must be stored and guarded for 10,000 years. Everyone knows that. The pesticide DDT is not very dangerous to animals when it is first applied, but its persistence in the environment allows it to build up over time to toxic concentrations in birds and mammals. Current pesticides avoid this problem by degrading more quickly. Some, such as the organophosphates, are more immediately toxic to animals, but that was the necessary trade-off. Freons, used in refrigerators, were engineered to be inert, and as a result, after they are released they survive long enough to reach the stratosphere, where they catalyze ozone destruction. New Freon-substitute chemicals are engineered to break down more quickly.

The long lifetime of fossil fuel CO_2 creates a sense of fleeting folly about the use of fossil fuels as an energy source. Our fossil fuel deposits, 100 million years old, could be gone in a few centuries, leaving climate impacts that will last for hundreds of millennia. The lifetime of fossil fuel CO_2 in the atmosphere is a few centuries, plus 25% that lasts essentially forever. The next time you fill your tank, reflect upon this.