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Sophie Duncker , Alan Marshall , Conny Brock , Katrin Fox
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INTRODUCTION

When Alligators Go North

A Warning from the Past

Ellesmere Island is in the very far north of Canada, above the Arctic Circle. It lies just to the west of Greenland, and like its bigger neighbor it is almost entirely glaciated. If you are on your way to the North Pole by way of Canada, this will probably be your last stop (see Map I.1). Few scientists had made their way to Ellesmere when Mary Dawson, a paleontologist at the Carnegie Museum of Natural History, launched her first expedition there in 1973. Dawson, forty-two at the time, was fascinated by the possibility that there had once been a land bridge between North America and Europe, and she hoped to find evidence that terrestrial species had migrated across it millions of years ago. Accompanied by a coworker, she hauled her gear to a remote camp and began scouring the desolate, frozen territory for fossil remains.[1]

Her initial efforts met with little success, but on a return visit in 1975 she struck paydirt. One after another, she found fossils of ancient mammals, turtles, plants – and alligators. *Alligators*. By analyzing the oxygen isotopes embedded in bone material, Dawson and her colleagues were able to estimate the temperature conditions that made semi-tropical life possible hundreds of miles north of the Arctic Circle. They found that, during the time of the alligators, summer temperature on Ellesmere averaged a balmy 68°F (20°C), and even average winter temperatures didn't dip below freezing. Was this because the island was further south back then? No: ancient

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Map I.1 Map of Ellesmere Island.
Source: New World Encyclopedia.

Ellesmere was a few degrees south of its current position, but still well above the Arctic Circle. Somehow the far north had roughly the same climate then as the southeastern United States has today, with cypress swamps where you might find not only large reptiles but also hippopotamus-like mammals wading in to gnaw on aquatic plants. If you find this stunning, imagine the surprise of Dawson's team when they stumbled upon the fossil evidence.

They kept coming back to Ellesmere and nearby islands, working under challenging conditions and deepening our understanding of an extraordinary period in Earth history. (Dawson herself fought off a wolf attack in 1977.[2]) Her last visit was in 2002 – she's now an emeritus Curator of Vertebrate Paleontology at the Carnegie Museum – but a team from the University of Colorado headed by Jaelyn Eberle has continued where she left off.[3] There is another astonishing fact to reveal, but first we need to put Ellesmere's alligators in context.

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Arctic lushness dates from an unusual episode in the geological record, the Paleocene–Eocene Thermal Maximum (PETM). This occurred approximately 56 million years ago, when temperatures soared for about 170,000 years, a long time from a human perspective but just a brief moment in Earth history.[4] Just how and why this happened is a matter of dispute, but decades of research have progressively culled the list of possible explanations and are narrowing the differences in estimated temperatures and environmental conditions.[5] One reason it is taking time to reach consensus is that the geological brevity of 170,000 years means there are relatively few traces for today's researchers to locate and analyze, and different remains require different methods and modeling frameworks.

How warm did it get during the PETM? Temperatures rose 5–8°C from a previously warm epoch, making the average temperature at the PETM peak 12 to 18°C warmer than today.[6] When alligators roamed the north, sea-level temperatures at the North Pole averaged between 14 and 19°C year-round,[7] which of course meant not only that there was no sea ice in the Arctic but that humans, if they had existed, would have enjoyed comfortable summer swimming conditions at their polar getaways. Balmy weather at the pole meant torrid conditions in the tropics, however. A recent analysis of a site in Tanzania, which at the time of the PETM was 70 kilometers offshore, found that surface water temperatures were as high as 36–43°C, or 97–109°F, suggesting that inland temperatures were even steamier.[8] As we will see later, conditions of this sort would render a significant portion of the globe uninhabitable by humans, at least if they are not enclosed in a technological cocoon.

There is little doubt the temperature extremes of the PETM were primarily the result of large emissions of greenhouse gases, carbon dioxide (CO_2) and methane (CH_4), into the atmosphere. Several explanations exist for its cause. For a time there was speculation that a cyclic change in the Earth's orbit around the sun might have played a significant role, but as measurement of the timing of the event and the composition of atmospheric carbon has become more precise, other explanations have gained ground.[9] A plausible hypothesis, for instance, is that the triggering event was the separation of the North American and European landmasses east of present-day Greenland, which might have resulted in a period of intense volcanic releases of greenhouse gases into the atmosphere. The initial warming resulting from this cataclysmic process may then have led to further releases of carbon previously sequestered in soils or very cold, deep marine deposits, although this is currently a matter of considerable dispute.[10] This is our first hint that *feedback mechanisms* may play an important role in historic, and future, climate fluctuations, a topic we will return to shortly.

Of critical importance to modern-day humans is the question of how much additional carbon dioxide did it take to turn the Earth into a PETM planetary sauna and how close are we today to replicating it? Of course, the amount of carbon dioxide in the atmosphere millions of years ago is not directly measurable today, so researchers have to find indicators that point to it indirectly.

A (relatively) convenient approach takes advantage of the fact that chemical elements are not uniform in nature. They can differ in the number of protons and electrons they contain, and the term “isotope” is used to designate a specific combination. Carbon-13 (written as ^{13}C) is one such isotope, whose six protons and seven neutrons sum to thirteen, and it is associated with a particular molecular history, especially methane; by measuring the proportion of the carbon preserved from an earlier period that shows up as carbon-13 it is possible to estimate how much of it originated from various methane-generating sources like decaying plant matter and magma releases. The point is that, on release, this methane would have found its way into the atmosphere, where, as we will see in the next chapter, it would have been transformed into carbon dioxide, augmenting the greenhouse trapping of solar radiation. Even after this additional carbon dioxide leaves the atmosphere many thousands of years later to be incorporated in carbon-bearing sediments, fossils or rocks, its telltale ^{13}C isotope records its sojourn as methane and then atmospheric carbon dioxide.

Once the quantity of prehistoric methane releases can be estimated, the next step is to determine how much of this additional carbon would have accumulated in the atmosphere and for how long. This can be estimated using models of the global carbon balance (stable relationships between the amounts of carbon in the atmosphere, soils, ocean and living organisms). Because different research sites and carbon-bearing substances yield different isotopic proportions, and different climate models perform this conversion into estimates of atmospheric carbon dioxide somewhat differently, there is a range of estimates of how carbon-saturated the PETM atmosphere was when alligators dipped into waters that sport polar bears today. The latest research gives us a lower bound of about 1,200 parts per million (ppm) carbon dioxide and an upper of about 2,000 ppm.[11] Note these are estimates of *peak* carbon dioxide concentrations; as we will see, it is possible that less than this is needed to set the process of extreme climate change in motion.

So, if the PETM was triggered by unusual releases of greenhouse gases and produced a global heat wave that lasted for over 100,000 years, how did it end? Why didn't the planet just stay hot? As you would expect, this is another matter of dispute, since the record that has come down to us is so fragmentary. One possibility is increased weathering, where carbon is stripped from soils or precipitated into rock formations and buried beyond the reach of the Earth surface carbon cycle. It is increasingly agreed, however, that a significant role was played by a profusion of living organisms, which pulled carbon from the atmosphere and redirected some of it to deep sea or deep earth burial.

What does that mean specifically? Here is where a remarkable fact about the PETM comes into play. Recall the far north experienced near-tropical conditions for many thousands of years. The Arctic Ocean was not only free of ice, it was a welcoming habitat for plants and animals usually found far to the south. One such new inhabitant was *Azolla*, a fern that floats freely on open waters with moderate temperatures and limited salinity. With the Arctic sea accepting massive inflows of freshwater from north-flowing rivers in Canada and Siberia – a reflection of altered precipitation patterns – and enjoying alligator-friendly temperatures, it was eventually covered with a mat of this sea fern.[12] Tangles of ferns, not ice, would have obstructed your trip to the North Pole. *Azolla* serves as a poster child for the explosion of biological growth during the PETM, although even more carbon would have been funneled into increased growth of marine plankton invisible to the naked eye. While most of the carbon pulled out of the atmosphere by this "biological pump" would have returned through transpiration and decay, some small amount each year would have migrated down into the sea floor, no longer available for greenhouse service. After tens of thousands of years, enough carbon would be withdrawn in this fashion to help bring atmospheric carbon dioxide concentrations down to a more normal level.[13]

A Warning from the Future

And so, from alligators to *Azolla*, this completes our first exposure to the disturbing topic of catastrophic climate change. What we know is that, spurred by singular natural processes, like the pulling apart of tectonic plates – processes unlikely to be repeated for many millennia to come – much of the Earth became uninhabitable for organisms like modern-day humans. But the truly frightening prospect is that human beings, through their own actions, could bring about a similar result. Instead of volcanoes we have coal, oil and natural gas companies drawing long-buried carbon from the earth and sending it into the atmosphere. Where are we on the road to the PETM? Consider the most recent data posted by the US Environmental Protection Agency (EPA), shown in Figure I.1. This time path considers only carbon dioxide, the main form that carbon appears in the atmosphere. Carbon also shows up in methane, whose heat-trapping effects are far greater but whose life span is also much shorter. Carbon dioxide, however, is a stable gas, and its carbon exits the atmosphere only as a result of the flows between air, land and water we will look at in the next chapter, while methane reacts with oxygen, resulting in the separation of its hydrogen and the formation of new carbon dioxide. This process is complete in a few decades, so measuring just carbon dioxide over a timescale like that in Figure I.1,

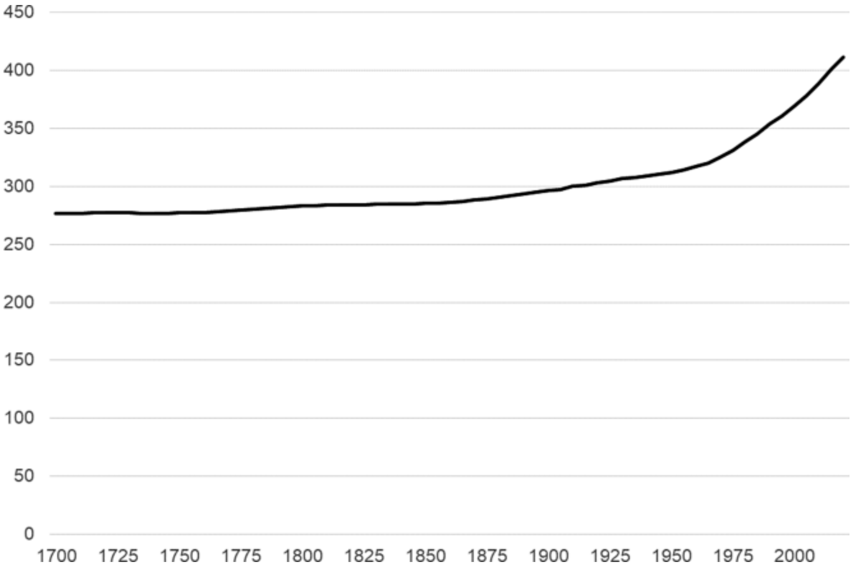

Figure I.1 Atmospheric CO_2 accumulation since 1700 in parts per million (ppm). The carbon concentration in the atmosphere has increased from about 275 ppm in 1700 to over 400 ppm today. Multiple measurements in a given year are reported as arithmetic averages. Direct measurement began in 1959.
Source: US EPA (2021).

with its global carbon dioxide concentrations over the past 300-plus years, captures most of the “older” methane as well. (There are also other, highly potent greenhouse gases with intermediate life spans like nitrous oxide, but we will set them aside for now.)

For many tens of thousands of years, the carbon dioxide concentration has fluctuated between 180 and 280 ppm, as ice ages came and went. For the past thousand years it remained stable at around 275 ppm – until the late eighteenth century, when it slowly began to rise. The rate of increase gradually picked up as the industrial revolution took hold, and fossil fuel use became widespread. For the past half-century it has taken off at a full gallop, and each year brings us into new, unexplored territory.

The most recent annual average is 410 ppm, nearly a 50% increase over the preindustrial level. Extraordinary as this is, however, it still leaves us well short of the 1,200 ppm that can serve as a guess of likely carbon dioxide concentrations during the PETM, but there are two more factors that need to be considered. First, carbon dioxide concentrations in the atmosphere continue to grow year by year, as people extract, burn and release carbon in various forms. Because carbon dioxide (and some other) greenhouse gases are very long-lived, in the absence of any further large-scale human intervention annual net additions of atmospheric carbon are effectively permanent.[14] While there have been slight ups and downs, during the past decade the rate of growth in carbon dioxide concentrations was a bit over 0.5% (0.00575) per year – until, of course, the global economic slump triggered by the coronavirus.

Let’s extrapolate this trend. Taking 410 ppm as our starting point in 2019 and 0.575% as our growth rate, unless we change course we will hit 437 ppm in 2030, 490 ppm in 2050 and 652 ppm by 2100. But what about the economic slowdown due to the pandemic? We will return to that question later, but for now, let’s assume that the growth in atmospheric carbon dioxide falls by 25% as the world struggles with the coronavirus, and that this phase lasts for five years, after which growth returns to its 0.575% trajectory.[15] Making that adjustment gives us 434 ppm in 2030, 486 ppm in 2050 and 648 in 2100 – just a minor reduction. These numbers would be alarming, but not enough in themselves to cause us to worry about wandering alligators.

But there is a second factor that casts an even darker shadow over all our thinking on this topic. It is likely that the very high atmospheric carbon dioxide concentration of the PETM was not the result of a single triggering event and nothing more. Suppose the process that set it in motion began, as many think, with an upsurge of volcanic releases as two giant tectonic plates in the North Atlantic tore apart. That would have caused a big influx of carbon, previously sequestered within the Earth, into the atmosphere–ocean–biosphere carbon cycle, leading in short order to higher temperatures. But higher temperatures, in turn, would likely have caused further releases of stored carbon, as methane was released from soils, peats and underwater deposits. The benchmark against which we should measure our own "progress" in achieving higher atmospheric carbon dioxide is not the final peak realized during the PETM, whether this was 1,200 ppm or some other level, but the concentration resulting from the initial trigger that was sufficient to bring about *further* releases, creating a self-feeding process that stopped only when a much hotter planet struck a new balance.

To put numbers on it, suppose the peak was 1,200 ppm and the trigger alone brought the atmosphere to 600 ppm, after which the initial warming released the rest of the carbon that contributed the other 600. This should be taken with many grains of salt, since there may have been multiple triggers operating at different times and coexisting with many feedback mechanisms, and of course the numbers we are using are strictly hypothetical. The logic, however, is essential: it tells us that, if this example were true, the level of atmospheric carbon dioxide with "thou shalt not pass" written on it would not be 1,200 but 600 ppm. If we were to allow ourselves to exceed this limit, we would run a very high risk of initiating the same feedback processes that fueled the PETM.

What makes the situation so uncomfortable, however, is that, rather than a line, what we face is a slippery slope of increasingly dangerous and unforeseeable feedback risk. There is no perfectly safe level of atmospheric carbon dioxide we can still plateau at given past and unavoidable future emissions. Perhaps there are particular carbon dioxide concentrations we might regard as tipping points, and if we had perfect knowledge of the Earth's carbon system in prehistoric times as well as the present we could possibly identify them. But the system is extraordinarily complicated. We have models of it, but they embody assumptions that can't be fully tested because we don't have enough data, especially as we begin to alter the Earth's climate in ways it hasn't experienced in millions of years. We know only that peak atmospheric carbon dioxide during the PETM was somewhere between 1,200 and

2,000 ppm. That's not nothing, but it leaves a lot of uncertainty for what to expect in the coming century.

A frightening thought: Could we have already passed key tipping levels of carbon dioxide that make a full-on climate catastrophe unavoidable? Very unlikely. What if we add to the current level the near-future emissions that are baked in irrespective of policy? Still unlikely. But this is the wrong question. What we do know, even with our still-emerging knowledge of complex Earth systems, is that the longer we allow greenhouse gases to be emitted, the greater is the risk that we *could* trigger feedback responses that make runaway climate change a dire threat. Even intermediate scenarios, with feedbacks that intensify climate change but not on a PETM scale, involve taking unknown risks with unfathomable consequences. It is the premise of this book that it is simply unacceptable to continue blindly on the current course and let these risks mount year after year.

To be specific: I will argue for the position that climate change needs to be minimized as a matter of extreme urgency, and that this entails, above all, adhering to a carbon emissions budget that would steadily reduce the use of fossil fuels each year until they are largely phased out in just a few decades. The pace of this phaseout needs to be set by the necessity of keeping warming to a minimum, not by economic convenience. This will not be easy; in fact, it will be highly disruptive to the institutions, technologies and habits we have come to depend on – and which have brought us to this point. I am convinced it can be done, that we have the economic tools we need to extricate ourselves from a carbon nightmare, but there is little room for delay, obfuscation, magical thinking or compromise. I wish the message could be friendly and encouraging, but instead it's hard and offers little wiggle room. Perhaps there was a time, decades ago, when easier, more relaxed methods might have done the job, but not now.

Mapping a New Economics and Politics

Why begin with a tale of wandering alligators and hothouse temperatures 56 million years ago? This is not a treatise on paleoclimatology or Arctic environments. What I hope this story gives you, however, is a feeling for the scale of the crisis we face and its extraordinary implications in light of Earth history. The difficult part will be holding onto this frame when we wade, as we must, into the morass of economic and policy detail.

Many books have been published putting contemporary climate change into a planetary and geological perspective. (One of these, *Laboratory Earth: The Planetary Gamble We Can't Afford to Lose* by the late Stephen Schneider, was the book that first convinced me of the centrality of this issue.[16]) I have little to add to them. The problem, however, is that they don't draw out the economic and political implications of this perspective, while the much greater number of policy-oriented books on climate change, although inspired in a general way by the science, put the constraints of economics and politics first. What would it mean to consider today's policy debates through the lens of Earth history and global environmental processes – the same lens through which we viewed the PETM? That's what the rest of the book is about.

In particular, I will focus on the strange dual role of economics, an indispensable tool for formulating and evaluating policies, yet also a primary source of misunderstanding. Carbon emissions are produced, every bit as much, and often in the same moment, as automobiles, restaurant meals and bank loans. Economics is the branch of knowledge that best explains how and why these things are produced and therefore also how to produce them differently or not at all. In addition, the economy is intricately interconnected, so that changes in some products or industries typically have ramifications throughout the system. This too is the province of economics.

But economics, at least in its dominant versions, brings a perspective to climate change that competes with the Earth history view. Consider the interesting case of William (Bill) Nordhaus of Yale University, winner of the 2018 Economics Prize "in honor" of Alfred Nobel.[17] This award was based on decades of work during which Nordhaus developed methods that have come to be standard for most researchers. As we will see in more detail later, his innovation was to marry models of economic "general equilibrium" with other equations representing the impacts of human activity on global warming. You would think this was exactly the integration of scientific understanding and human production systems we need in order to avoid the recurrence of PETM-like conditions.

The purpose of Nordhaus' modeling, however, was not to minimize the risk of a catastrophe but to ascertain the "optimal" level