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Once and Future Climate

A common failing of human beings, both as individuals and collectively, is their apparent inability to imagine a world or a life any different from the one they are experiencing at any given time. Arguably, this is the greatest obstacle faced by climate scientists trying to make national governments, institutions, businesses, and people generally wake up and pay attention to the massive threat they face—to appreciate what an appalling impact unmitigated anthropogenic climate change is slated to have on our world and our descendents. Maybe there is some sort of in-built safety mechanism, a sort of comfort-blanket, which makes us assume that tomorrow will be pretty much the same as today; that the world when we are middle-aged or old will be, broadly speaking, the same as it was when we were young. In recent centuries and in the fastest-developing nations, however, this has never been the case. Either by evolution or by revolution, the world to which we bid farewell at life's end is almost always transformed from the one into which we were born. Think, for example, of the many septuagenarians whose birth cries intruded on the prim, proper, and pomp-driven world of Victorian England, who lived to see—if not make the most of—the 1967 Summer of Love, and the first manned landing on the Moon two years later.

Whatever our ingrained comfort blankets assure us about continuity and the status quo, nothing ever stays the same, and our climate provides a prime example. It is barely a century since much of the northern hemisphere shivered in the bitter winters of the so-called Little Ice Age, during which a fractionally dimmed Sun fostered a cooler climate that persisted, with some short respites, from the 17th century to the end of the 19th. Now, our communal behaviour, augmented by a widespread denial of the possibility of change, is pushing us rapidly in the opposite direction, bringing us to the brink of hothouse conditions that, as things stand, are virtually certain to transform our planet and our society, making tomorrow's world very different from today's. Look back over a much longer time scale, and far greater variations in our climate are recognized. While these are a reflection of natural changes in the environment of our planet, rather than consequence of human activities, some past climates can provide a useful, and somewhat terrifying, guides to what our planet might look like by 2100 and in the centuries that follow. In particular, the post-glacial period provides us with the perfect opportunity to examine and appraise how abrupt and rapid climate changes drive the responses of the solid Earth, which form the focus of this book. Peering further back in time, to warmer episodes with more carbon-enriched atmospheres, supplies us with important clues about how much hotter our world might become and how far sea levels could rise. This, in turn, can help us evaluate the ultimate scale and extent of anthropogenic climate change, thus allowing us better to weigh up the chances of a future hazardous response from the Earth's crust.

It is more than two centuries since Scottish naturalist, James Hutton, laid down the principles of so-called uniformitarianism, a key tenet of the Earth sciences that assumes that the natural processes and mechanisms that we see happening today have always been the same and can therefore be used to explain what we observe in the geological record. This philosophy is succinctly portrayed by the phrase 'the present is the key to the past'. Earth scientists are also recognising that we can learn much about our contemporary world by looking to earlier episodes in Earth history. Furthermore, and in the context of climate change in particular, there is much we can learn about what our world might look like in 2100 and beyond by subjecting to detailed scrutiny periods in our planet's past when conditions were comparable to today's. If care is observed in selecting appropriate analogues and note is taken of various caveats, the past can—where the Earth's climate is concerned—provide a useful guide to the future. Nowhere is this better demonstrated than during the Cenozoic, our planet's most recent era and perhaps, from a climate point of view, its most dynamic.

Introducing the Cenozoic

Human's love categorising and pigeonholing, and the evidence for this is as compelling in the way we have divided up and labelled the 4.6-billion-year history of our planet as it is in the apparent need that many (mostly men it seems) feel for alphabetising and cataloguing CD collections. For example, since the end, of the Pre-Cambrian around 540 million years ago,—the immense span of time making up about the first seven-eighths of our planet's history—geological time has been divided into three eras: the Palaeozoic, the Mesozoic, and the Cenozoic, each itself comprising a number of geological periods, such as the Devonian, Triassic, and Cretaceous, to name just three out of a round dozen. From a climate viewpoint, the Cenozoic—meaning 'new life', from the Greek *kainos* 'new' and *zoe* 'life'—which is sometimes also referred to as the Tertiary, is perhaps the most fascinating period; it is certainly the most relevant in terms of providing a mirror within which visions of our future world may be glimpsed. The Cenozoic started with a bang, following on immediately after the asteroid impact, voluminous outpourings of lava—or a combination of the two—that resulted in the mass culling of the dinosaurs and countless other species 65 million years ago. The Cretaceous–Tertiary (K–T) or, more correctly, Cretaceous–Palaeogene (K–Pg) mass extinction literally marked 'the end of an era', defining the boundary between the Cretaceous, the last period of the Mesozoic Era, and the Palaeogene, the first period of the Cenozoic.

The Cenozoic climate is a real roller coaster, starting with sweltering conditions and gradually but inexorably cooling off, so that for the past couple of millions years our world has frequently been held firmly in the grip of ice. Today, in contrast, it is playing host to an episode of very rapid warming, and this not for the first time—as will soon become apparent. However rapidly the Arctic sea ice is currently dwindling, the waters of the Arctic Ocean remain bitterly cold and are prone to freezing at the drop of a hat. It is hard, therefore, to imagine a time, not too far back in the geological past, when these frigid waters played host to cruising crocodiles, turtles, and other species whose natural habitats today lie several thousand kilometres further south. Fantastic-sounding but true nevertheless. The Palaeocene—the earliest Epoch of the Palaeogene—was a sweltering world with ice-free poles and palm trees growing in Russia's

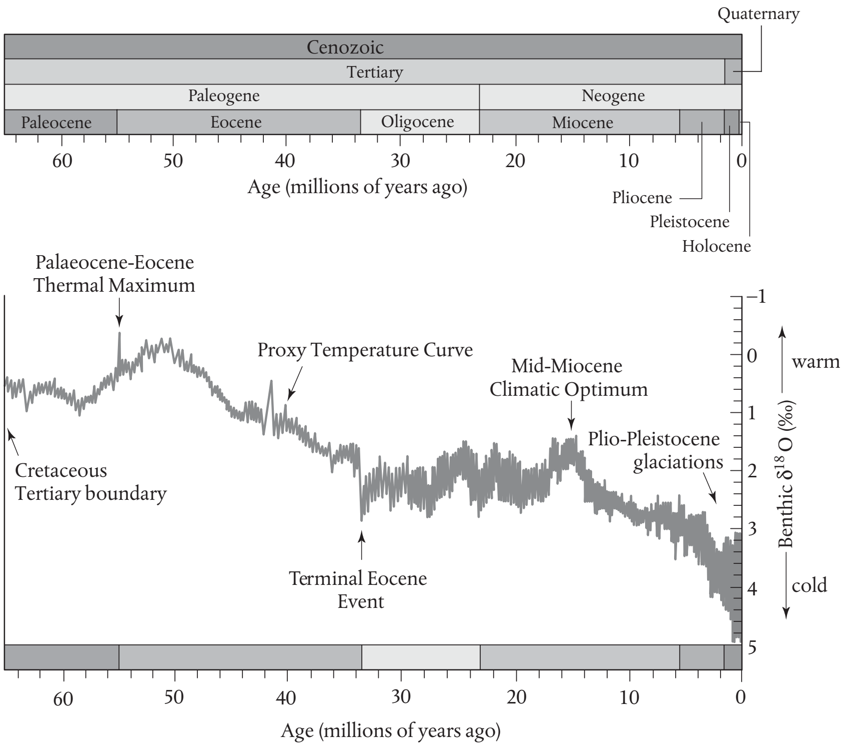

Fig 6. The roller-coaster climate of the Cenozoic Era was one of great contrasts, but the broad trend was towards a cooling of the planet. After temperatures peaked in the hothouse world of the Palaeocene-Eocene Thermal Maximum (PETM), and notwithstanding the odd respite, it was pretty much downhill all the way.

Kamchatka Peninsula. As far as evolution was concerned, it was a time of innovation, with new groups of organisms arriving on the scene to occupy the niches vacated during the K–T mass extinction. Indeed, the name of the epoch, from the Greek, refers to the 'older (palaios)—new (kainos)' transitional faunas of this time, before the emergence of modern mammals during the succeeding Eocene Epoch. The concentration of carbon dioxide in the Palaeocene atmosphere is not well established and it could well have been more than 1000 ppm or even significantly less. What is known, however, is that global average temperatures were as much as 15°C higher than they are today. Fossil finds provide evidence for subtropical vegetation growing in Greenland and in Patagonia in the southern hemisphere, while the ice-free poles in this clement Palaeocene world were characterized by climates that were cool rather than frigid, and covered by forest rather than the bleak and frozen tundra that stretches across most high latitude regions today. Towards the equator, warm and humid conditions encouraged the growth of widespread tropical and subtropical forests that probably looked little different from the rainforests of today, or at least the bits that have not yet been grubbed up or torched. To those who favour constant warmth above bracing changes in seasonal temperature, the Palaeocene would have been blissful. And it was to get hotter still—far hotter, as the planet's climate underwent an astonishing change, the like of which has been seen on very few occasions in the Earth's long history.

The great heat spike mystery

A warming path already established in the late Palaeocene saw a rising trend in temperature that was steady and nothing really to write home about. Suddenly, however, a little under 56 million years ago, and for reasons that are still not fully understood, the average global temperature shot up by 6°C over a time span as short as 10,000 years, with the poles heating up by 10–20°C over the same period and the surfaces of the oceans warming by up to 9°C in less than 10 millennia. In the Antarctic, sea-surface temperatures reached 20°C, with Arctic Sea temperatures climbing to a high of 24°C, in both cases substantially warmer than the rather meagre summer sea temperatures off the invigorating British east coast resort of Skegness. The sudden warming had a dramatic effect on ecosystems, most notably involving the emergence on land of a new mammal fauna that included the primates and horses, and a mass extinction of the tiny, single-celled, marine organisms known as foraminifera, that lived deep in the oceans. This so-called 'transient warming event', which lasted for as long as 170,000 years, is the most prominent in the whole of the Cenozoic Era. It also marks the transition from the Palaeocene Epoch to the Eocene and so goes by the name of the Palaeocene–Eocene Thermal Maximum, or simply, the PETM. Such sudden outbursts of heat are rare but not unique, and a few others are recognized further back in time, during the Cretaceous, Jurassic, and Triassic periods. As in the case of current warming, the ultimate cause of these warm 'spikes' in the global temperature record seems to be a sudden rise in the concentration of atmospheric carbon dioxide. The start of the PETM, for example, coincides with the addition of a huge mass of the gas to the atmosphere, estimated to contain between about 4000 and 7000 billion tonnes of carbon. For comparison, human activities in 2009 released greenhouse gases equivalent to about 8.3 billion tonnes, a drop in the ocean in comparison, although a drop that is repeated year after year. The great enigma of the PETM relates to the source of this vast quantity of carbon dioxide, and lively debate has for some time addressed where it could have come from and how it might have found its way into the atmosphere. A long list of candidate causes includes a comet impact charged with importing the extra carbon into the Earth system from beyond the atmosphere, although this has very few supporters. A second proposes the ignition and burning of vast areas of peatland, which seem to have been particularly abundant at the time. As more than 90 per cent of the world's biomass would need to be reduced to ashes to match the scale of the extra carbon dioxide in the atmosphere, this suggestion too is not a popular one. An increase in volcanic activity has also been put forward, but again the amount of additional carbon dioxide pumped out during even the most intense hike in volcanic action cannot match the required level. Nevertheless, according to one model at least, rising magma may still have had an important role to play, about which more later.

The favoured carbon-source candidate is, far and away, the wholesale release of methane from so-called gas hydrate or clathrate deposits. These are solid, ice-like, mixtures of water and gas—usually methane—stored in marine sediments and trapped in Arctic permafrost in truly prodigious quantities. Built from 'guest' gas molecules enclosed within cage-like structures built from water molecules, gas hydrates are stable at low temperatures and relatively high pressures. They can, however, become destabilized by warming or pressure reduction, resulting in dissociation and release of the methane in its gaseous state. Methane contains carbon and is also a very effective greenhouse gas in its own right, making it understandable that worries over how gas hydrates might be affected by anthropogenic warming have been growing. Bearing in mind that every cubic metre of gas hydrate can produce 163 times as much methane, it is also hardly surprising that the world's energy companies have been licking their lips at the prospect of getting their hands on these somewhat esoteric hydrocarbon deposits at a time when conventional supplies are dwindling. This confluence of concern and covetousness has driven a burgeoning programme of research so that far more is now known about these rather enigmatic deposits than a couple of decades ago. Notwithstanding this, it has taken some time to pin down just how much gas hydrate is out there. Usually expressed in terms of their contained carbon, initial estimates were in excess of 10,000 billion tonnes, an order of magnitude higher than the total carbon held in the atmosphere in the form of carbon dioxide and methane, and far more than in all other fossil-fuel sources combined.

Since these early approximations, global gas hydrate resources have been revised down considerably to something closer to 2000 billion tonnes of carbon. This is smaller than the 5000 billion tonnes of carbon locked away in other fossil fuel sources, but still about two and half times the amount of carbon currently held in the atmosphere. Hence the continued concern of climate scientists and the enduring interest of the energy companies.

Returning to the PETM, the evidence for a gas hydrate role in the sudden warming is strong. One strand of support comes from giant, submarine, sediment slides along the margins of the continents, particularly in the western Atlantic, hinting at the sort of widespread destabilisation expected as the solid hydrate breaks down to much greater volumes of methane gas. A second comes from the distinctive carbon signature associated with methane derived from gas hydrates.

Like many elements, carbon comes in a variety of forms, or isotopes, each of which has an atomic structure containing slightly different numbers of neutrons. By far the most common isotope of carbon (99 per cent of all naturally occurring carbon) contains six protons and six neutrons, and is known as carbon-12 or C^{12}. About one per cent of carbon comes in the form of isotope carbon-13 (C^{13}), which contains an extra neutron, while just a trace of natural carbon has two extra neutrons, making the isotope carbon-14 (C^{14}). Both carbon-12 and carbon-13 are stable isotopes, but carbon-14 is radioactive, ultimately breaking down to form an isotope of nitrogen. This property of carbon-14 forms the basis of the radiocarbon dating method, which has wide application in archaeology and geology. As the total number of protons and neutrons determines the mass of an element, carbon-12 is the lighter of the two stable carbon isotopes. The carbon held in methane contained in gas hydrates is much depleted in the heavier carbon-13 relative to the lighter carbon-12 isotope, so that its carbon 'signature' is enriched in the lighter isotope. On this basis, the addition of very large volumes of hydrate-sourced carbon to the PETM environment can be detected by analysing the carbon isotope composition of marine sediments deposited at the time. Such analysis reveals the existence of what is technically known as a Carbon Isotope Excursion (CIE) in ocean waters, which is another way of saying that their isotopic composition underwent a sudden and significant change with respect to the relative proportions of the three carbon isotopes. The CIE is described as negative where it involves enrichment in the lighter carbon-12 isotope. In the case of the PETM, a negative CIE is identified amounting to about four per cent, indicating the addition to the late Palaeocene oceans and atmosphere of a significant volume of carbon depleted in carbon-13 relative to carbon-12.

While the sudden change in the carbon isotope composition provides a convincing 'smoking gun' in relation to a gas hydrate role in the global temperature spike that marked the PETM, a couple of key questions remain to be answered before this can be accepted as the whole story. Were gas hydrates responsible, on their own, for releasing all the carbon that initiated the sudden warming at the end of the Palaeocene, and why and how was the wholesale breakdown of gas hydrates triggered? Current thinking suggests that there was almost certainly not sufficient gas hydrate around at the time of the PETM to explain all the additional carbon. As mentioned earlier, today's inventory of gas hydrate is unlikely to provide more than 2000 billion tonnes of carbon and in the warming Palaeocene world, gas hydrate reserves are likely to have been even smaller. If this was the case, then the rest—probably the bulk—of the extra carbon must have come from somewhere else. This hints at a situation wherein rapid warming, driven by carbon dioxide accumulating in the atmosphere from some unknown source, heats up the ocean waters to such a degree that wholesale dissociation of gas hydrate deposits is triggered in a positive feedback effect that releases large volumes of methane, warming the planet even further. Within this scenario, while gas hydrates contribute to warming at a later stage, their breakdown is a response to initial warming due to an event or events unknown. A recent study of the environmental conditions in the very late Palaeocene by Appy Sluijs of Utrecht University in the Netherlands, and his co-researchers, suggests that this is just what happened. Examination and analysis of the remains of particular single-celled organisms contained within marine sediments enabled the temperature of the ocean at this time to be determined, revealing that the planet started to warm significantly several thousand years prior to the CIE arising from gas hydrate breakdown. Unfortunately, the work of Sluijs and his team does not shed any light on the enigmatic source of the carbon that drove the initial warming. Others, however, have pursued the quest to pin down its origin, which has led them to the North Atlantic and to the dramatic geological events that were unfolding there during the late Palaeocene.

Prior to around 200 million years ago, the Atlantic Ocean did not exist. In the early part of the Jurassic Period, however, the ancient supercontinent of Pangaea started to fragment, opening a narrow proto-North Atlantic Ocean that separated the new northern supercontinent of Laurasia from its southern counterpart, Gondwana. By Palaeocene times, more than 100 million years later, the Atlantic was a wide ocean that extended southwards, separating South America and much of North America, in the west, from Africa to the east. Coincident with the PETM, the North Atlantic was undergoing its final extension, slicing northwards between Greenland and northern Europe. As might be expected, the splitting of a continent tends to involve quite a kerfuffle, and this was no exception. Accompanying the event, wholesale melting in the Earth's mantle underlying the region fed vast outpourings of lava across Canada's Baffin Island, Greenland, the Faeroes, and north-west Britain. In places, lavas were piled more than seven kilometres thick, while elsewhere magma intruded en masse into the local rock and sediments. Estimates suggest that the total volume of magma involved was staggering, ranging between 5 and 10 million cubic kilometres. Impressive, undoubtedly, but what has this to do with the PETM? According to Mike Storey of Roskilde University in Denmark, and colleagues, quite a lot. Storey and his fellow researchers propose that the puzzle of the initial PETM warming can be explained by the release of prodigious volumes of carbon-12 enriched methane as magma associated with the splitting of Greenland from Europe heated and baked carbon-rich sediments that floored much of the region prior to the tectonic upheaval. The timing is just about right, with the start of the PETM occurring a little after the beginning of the great, magmatic outburst. This link remains a hypothetical one and there is, as yet, no definitive evidence that connects the two events in a cause-and-effect manner. Nevertheless, the idea provides, at the very least, a useful stop-gap while other possibilities are investigated.

The PETM revisited?

Interest in the world of the late Palaeocene–early Eocene was sparked and sustained by the possibility that what happened at the PETM might provide us with a glimpse of how our world might end up should we fail to reduce greenhouse gas emissions rapidly and sufficiently enough. Most critically, this unusual event provides us with a laboratory within which to examine the effects and consequences of the wholesale release of carbon into our planet's atmosphere over a very short period of time. The bottom line is that the hothouse world of the PETM may mirror conditions on the planet in the coming century and beyond. To revisit some salient points, the PETM warming appears to have resulted from the release of 4000–7000 billion tonnes of carbon over a period of maybe 10,000 years, resulting in a global average temperature rise of about 6°C. It is sobering to reflect that human activities have generated around 500 billion tonnes of carbon, and continue to do so at a rate of more than eight billion tonnes a year. Even in the depths of the biggest recession since World War II, human emissions in 2009 rose by 1.3 per cent. In 2010, as the global economy perked up, this figure shot up by a staggering 6 per cent compared to the previous record year in 2008, with no prospect of a significant slow-down in sight, let alone any reduction.

In just a couple of centuries then, we have released up to one eighth of the amount of carbon that drove the PETM. Given the current rate of deforestation and the fact that conventional fuel reserves are estimated to provide around 5000 billion tonnes, it would not be at all unreasonable to imagine that eventually the carbon released by our activities will tally with that which triggered the PETM. The especially scary thing is that this would likely be accomplished in a fraction of the time. In addition, it may well be that we don't need to match, through our own activities, the carbon release at the PETM to trigger a sudden, rapid, and persistent rise in global temperatures. As the world continues to warm in response to anthropogenic emissions, so the conditions are predicted to become less favourable for life, the land, and the oceans to take up their share of the excess carbon. In another example of a positive feedback effect, a warmer world is likely to mean that these 'carbon sinks' suck up progressively less carbon, as a consequence leading to its more rapid accumulation in the atmosphere and even more swiftly rising temperatures. It is even possible that some carbon sinks may become carbon sources, reversing their current roles so as to add carbon to the atmosphere rather than subtract it. This is particularly worrying, bearing in mind the amount of carbon currently held in sinks: more than 2000 billion tonnes in plants and soils and a massive 40,000 billion tonnes in the waters of the world's oceans and the organisms that live within them.

More disturbing still is the fact that evidence is already coming to light that some carbon sinks are showing signs of becoming less effective. The oceans, for example, have—fortunately for us—already absorbed somewhere between one fifth and around one third of all the carbon produced by human activities, but they may not be able to continue to provide this service for ever. According to Samar Khatiwala at Columbia University's Lamont-Doherty Earth Observatory, and associates, the uptake of anthropogenic carbon by the oceans rose sharply after 1950, but the rate of uptake has started to decline in recent decades. The worry is that the sheer volume of carbon we are producing is showing signs of overwhelming the oceanic carbon sink, perhaps as warmer waters—that are also made more acidic as they absorb more carbon—find it more difficult to take up as much carbon as they used to. Should this trend continue, then more of the carbon we produce will stay in the atmosphere rather than becoming locked up in the oceans, so enhancing greenhouse warming.

Building estimates of carbon feedback effects into model projections of future climate makes for sobering forecasts of temperature rises in the decades ahead. In a dedicated issue of the Royal Society's Philosophical Transactions (A), published in late 2010, Richard Betts of the Met Office Hadley Research Centre and colleagues summarize how quickly, taking into account carbon-cycle feedback effects, the world might have to face a 4°C average temperature rise; the results are both astonishing and alarming. Assuming the pessimistic and fossil-fuel dominated SRES scenario, A1FI, the choice justified by the current rate at which emissions are climbing, Betts and co-researchers provide a best estimate that suggests that global average temperatures may reach 4°C as soon as the 2070s. Even worse, if positive feedback effects are particularly strong, this figure could be reached as soon as the early 2060s. Think about this for a moment; that is a temperature rise twice that widely charged with equating to a guardrail that must not be crossed if the most serious effects of climate change are to be avoided, arriving in less than 50 years. We are not talking here of centuries down the line, in the dim and distant future of our far-removed descendents, but of a time when my children—and perhaps yours too—will still be in the prime of life. Of course, it is possible that we will collectively come to our senses in the near future and initiate plans designed to make serious inroads into global emissions. From the perspective of August 2011, however, the prospects for such a change in thinking seem very poor. Consequently, it is perfectly possible that not long after mid-century our world will be well on its way to the hothouse Earth conditions of the Eocene, having passed the 2°C dangerous climate threshold as early as 2030 or soon after. The upshot could be a 5–6°C temperature hike, comparable to that of the PETM, by the end of this century. As it seems to have done during Palaeocene times, there is also the possibility that this initial anthropogenic warming could ultimately lead to the wholesale dissociation of gas deposits as the warming thaws Arctic permafrost and penetrates to ever greater depths in the oceans, leading to even greater warming. The fact that large volumes of methane are already venting into the atmosphere from methane-rich sediments beneath the shallow seas off the coast of Arctic Siberia cannot be anything other than bad news. If we do manage to conjure up another PETM-like event we should not expect temperatures to return to what we have long regarded as normal values any time soon. Remembering that the PETM lasted for perhaps 170,000 years, we would need to face up to the fact that it would likely be a hundred millennia or more before temperatures returned to 20th century values.

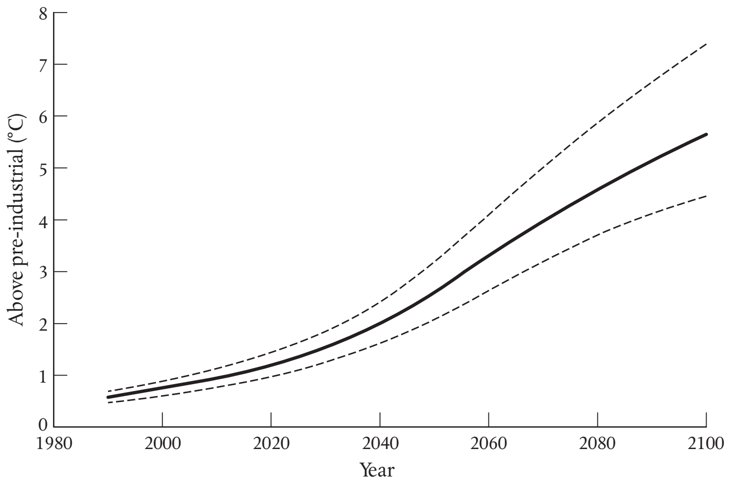

Fig 7. Assuming that emissions rise in line with the pessimistic and fossil-fuel dominated SRES scenario, A1FI, a best estimate suggests that the global average temperature could reach 4°C as soon as the 2070s (see thick central line, which shows the medium projection). Even worse, if positive feedback effects are particularly strong, this figure could be reached as soon as the early 2060s (see the upper dotted line).

Cool with warmer intervals

Even once the PETM waned, temperatures on Planet Earth remained far higher than they are today and the following five or six million years—a time known as the Early Eocene Climatic Optimum (EECO)—remained balmy and humid. After this, things started to go downhill as the whole character of the Cenozoic Era began to change. Global temperatures fell throughout the rest of the Eocene Epoch, and the Earth's climate became broadly cooler and drier. This was the start of a long road that would ultimately lead from the hothouse to the icehouse. The steady drop in temperatures was accompanied by relentlessly falling levels of atmospheric carbon dioxide that by the middle of the succeeding Oligocene Epoch were down to around

500 ppm. The long, steady, temperature fall throughout the Eocene was interrupted at the start of the Oligocene, some 34 million years ago, by a dramatic cooling known as Oi-1, which marked a major transition in the planet's climate. The temperature of deep ocean waters fell to below 3°C, down from 12°C during the warm conditions of the early Eocene, and large ice sheets started to form for the first time in Antarctica, leading to sea levels plummeting by 55 metres. In response to the rapid cooling, vegetation zones underwent a major transformation, with tundra and steppe replacing northern forests and the shrinking of tropical broadleaved forest. Various hypotheses have been proposed to explain why ice sheets started to build on Antarctica and analysis of their relative merits is outside the scope of this book. A widely held view, however, links conditions suitable for ice accumulation with the separation of the Antarctic continent from South America and Australia. This isolated the continent, leaving it surrounded by ocean, and paving the way for the formation of the cold Antarctic Circumpolar Current, which acted as a barrier to warmer waters from lower latitudes. This is suggested to have led first to the widespread accumulation of sea ice, and later to the progressive build-up of ice sheets on land.

The Cenozoic climate roller coaster switched direction suddenly once again at the very end of the Oligocene Epoch around 25 million years ago. This time a rapid rise in global temperatures saw the Antarctic ice retreat and sea levels shoot up once again. As the Oligocene was succeeded by the Miocene Epoch (the first epoch of the Neogene Period) a little under 24 million years ago, another change of direction led to a brief cooling episode, known as Mi-1, which saw the Antarctic ice expand again and sea levels drop suddenly. This short-lived cold snap soon gave way to warmer and more humid conditions that persisted for the first half of the Miocene Epoch. The coniferous forests that had succumbed to the tundra during

Oligocene times made a comeback, and between 17 and 15 million years ago, during the so-called Mid-Miocene Climatic Optimum (MMCO) temperatures at mid latitudes were 3–6°C higher than today. Like the PETM, the MMCO may provide us with some useful clues about how anthropogenic climate change might develop in the decades ahead. As mentioned in the previous chapter, the MMCO was the last time that carbon dioxide levels in the atmosphere were higher than they are now. According to the University of California's Aradhna Tripati, and her co-researchers, concentrations were only in the region of 400–450 ppm, the sort of values we might expect within a decade if anthropogenic emissions continue to rise as they are doing. Assuming that atmospheric carbon dioxide levels and global average temperature are linked today in a comparable manner to how they were during the MMCO, then we can expect atmospheric carbon dioxide levels only slightly higher than they are now to eventually drive the global average temperature up by 3–6°C compared to pre-industrial times. This is substantially higher than the 2° rise that is often equated with keeping the concentration of atmospheric carbon dioxide below 450 ppm. These higher global average temperatures would almost certainly mean double-figure rises at high latitudes and wholesale melting of the Greenland and West Antarctic ice sheets. Such a prospect is reinforced by the observations of Tripati and colleagues that during the MMCO there was little land ice or sea ice in the Arctic, nor were there floating ice shelves in Antarctica. In fact, neither an extensive cover of Arctic sea ice nor a large permanent ice sheet on East Antarctica were able to form until carbon dioxide levels in the atmosphere fell below the 350–400 ppm threshold, during the period of rapid cooling and glacial expansion that followed the MMCO, while large ice sheets were not able to form on Greenland or West Antarctica until carbon dioxide levels in the atmosphere had dropped even further, to below 300 ppm.

To summarize, what the MMCO seems to be telling us is that atmospheric carbon dioxide levels just a little higher than they are now, and which we are virtually certain to achieve in the next few decades, will—if maintained for long enough—result in a global average temperature rise towards the top of the range projected in the IPCC's Fourth Assessment report. Wholesale melting of polar ice is likely, perhaps resulting in sea levels that eventually match those of the MMCO, which were between 25 and 40 m higher than today. The warm world of the MMCO was not to last, and a sudden cooling of 6–7° around 14 million years ago heralded a significant build-up of ice at both poles. As the Miocene Epoch drew to a close a little over five million years ago, ice covered both Greenland and Antarctica, and while warm interludes were still to come, the transition to ice-house Earth was now well and truly underway.

The Pliocene: another glimpse of our future world?

As the Miocene Epoch gave way, 5.3 million years ago, to the Pliocene—the second of the two epochs making up the Neogene Period of the Cenozoic Era—the planet continued to cool, if at a somewhat reduced rate. The climate was still warm compared to today, and during the Middle Pliocene the Cenozoic climate switch-back reversed direction again so that around four million years ago global temperatures started to climb once more. Just over three million years before present, Pliocene temperatures peaked during the 300,000-year-long Mid-Pliocene Warm Period (MPWP), during which global average temperatures were about 2–3° higher than they are today. In common with the MMCO, this relatively warm episode during the Pliocene can be looked to for clues as to where contemporary climate change may eventually take us. The warmer climate of the MPWP saw conifer forests replace much of the tundra