‘If you read just one book about the menace of climate breakdown, make it this one’
Tim Radford

HOTSCIENCE

‘A must-read for anyone’ Mike Berners-Lee

HOTHOUSE EARTH

AN INHABITANT’S GUIDE

BILL McGUIRE

CONTENTS

CONVERSION TABLE FOR KEY TEMPERATURES

Temperature increase values		Absolute temperature values	
Centigrade	**Fahrenheit**	**Centigrade**	**Fahrenheit**
0.5	0.9	20	68
1	1.8	25	77
1.5	2.7	30	86
2	3.6	35	95
2.5	4.5	40	104
3	5.4	45	113
3.5	6.3	50	122

FOREWORD

This book was written mostly over a six-month period, during the course of which the COP26 (the 26th Conference of Parties) UN Climate Change Conference was staged in Glasgow. Putting it together has been quite a challenge, not only because there is such a vast amount of material out there, but also because both the science and the policy are constantly changing. In retrospect, having to squeeze a quart into a pint pot has actually worked in my favour, and hopefully yours too, by helping to concentrate the mind and forcing me to zero in on the core issues at the heart of the climate emergency. The end product is a small book with a big message.

It is fortuitous that the final pulling together of material coincided with the COP26 summit, providing – as it did – a more credible idea of where we are likely headed. It was billed by many, including me, as arguably the most important meeting in the history of humankind, and I attended with grateful humility and with this always in mind. Hopes were high that the outcome of the two weeks of discussion, debate and negotiation might be a glimpse of a realistic pathway out of the dark place we find ourselves in; an attainable route towards the goal of keeping the global average temperature rise (since pre-industrial times) this side of the 1.5°C (2.7°F) so-called dangerous climate change guardrail. Unfortunately, this was not to be.

True, there were plenty of fine promises, on everything from protecting forests to reducing methane emissions, cutting out coal and throwing cash at the majority, or developing, world to help fund carbon-reducing measures, but on the detailed mechanisms, legal frameworks and monitoring required to ensure fulfilment of these pledges there was next to nothing.

Some early post-COP26 modelling averred that, *if* pledges were all met and targets achieved, then we might be on track for 'just' a 1.9°C (3.4°F), or even 1.8°C (3.2°F), global average temperature rise. Firstly, however, this is a very big *if* indeed. Secondly, such predictions fly in the face of peer-reviewed research published pre-COP26, which argues that a rise of more than 2°C (3.6°F) is already 'baked-in' or, in plain language, certain.

The post-COP26 reality is this. To have even the tiniest chance of keeping the global average temperature rise below 1.5°C, we need to see emissions down 45 per cent by 2030. In theory, this might be possible, but in the real world – barring some unforeseen miracle – it isn't going to happen. Instead, we are on course for close to a 14 per cent rise by this date that will almost certainly see us shatter the 1.5°C guardrail in less than a decade.

This book takes as its starting premise, then, the notion that, practically, there is now no chance of dodging a grim future of perilous, all-pervasive, climate breakdown. It is no longer a matter of what we can do to avoid it, but of what we should expect in the decades to come, how we can adapt to a hothouse world with more extreme weather and what we can do to stop a bleak situation deteriorating even further.

I ought to make clear here that the terms 'hothouse Earth' or 'greenhouse Earth' are used formally, in a definitive sense, to describe the state of our planet in the geological past when global temperatures have been so high that the poles have been ice-free. A hothouse *state*, however, is not required for hothouse *conditions*, which are already becoming far more commonplace, and fast becoming the trademark of our broken climate. What I mean by hothouse Earth, then, is not an ice-free planet, but a world in which lethal heatwaves and temperatures in excess of 50°C (122°F) in the tropics are nothing to write home about; a world where winters at temperate latitudes have dwindled to almost nothing and baking summers are the norm; a world where the oceans have heated beyond the point of no return and the mercury climbing to 30°C+ (86°F+) within the Arctic Circle is no big deal.

To all intents and purposes, *this* is the hothouse planet we are committed to living on; one that would be utterly alien to our grandparents. The fact is that a temperature rise of 2°C – which is likely the minimum we are committed to – may not sound like much, but remember that this is an average temperature. In some parts of the planet, the increase will be far higher. In addition, even this small rise will drive extreme high temperature events beyond anything experienced in human history. A child born in 2020 will face a far more hostile world than its grandparents. Compared with someone lucky enough to be born in 1960, one study estimates that – on average – they will experience seven times more heatwaves, twice as many droughts and three times as many floods and harvest failures. The reality could very well be far worse, and it will be for the billions of vulnerable people living in the majority world. Looking at the broader picture, anyone younger than 40 today will suffer ever more frequent bouts of extreme weather that would be virtually impossible in the absence of global heating.

In the pages that follow, I have tried – using the most recent observations and latest peer-reviewed research – to shine a light on how our familiar world is already changing, and how it will be completely reshaped in the decades ahead. I have sought to do this by focusing on three facets of the climate emergency. First, to place the changes to our climate caused by human action in context, by taking a trip through our planet's 4.6-billion-year history, during which time conditions ranged from icehouse to hothouse and back again on many occasions. Second, to zero in on the current global heating episode and drill down into the evidence for the accelerating breakdown of our once stable climate. Third, to dissect the wide-ranging consequences of contemporary heating in more detail, from storm, flood, fire and drought to mass migration, water wars and health issues, along with hard-to-predict 'stings in the tail', such as Gulf Stream collapse and methane 'bombs'. A concluding section looks ahead to possible futures, addresses what we need to do now to minimise the impact of dangerous climate breakdown and considers whether technology can save us. It also rams home the message that – even at this late stage – it remains vital that we cut emissions to the bone as soon as we possibly can.

As a trained geologist, I have always tended to set more store by observation and measurement than modelling or simulation, although both certainly have their place, particularly in trying to pin down future climate scenarios. Consequently, the content of this book is driven as much by current observation of climate trends and knowledge of past episodes of climate change as it is by model-based forecasts of what we might expect in the decades and centuries to come.

This is important because there is little doubt that our climate is changing for the worse far quicker than predicted by earlier models. It is also the case, research has revealed, that climate scientists – as a tribe – tend to gravitate towards a consensus viewpoint rather than go out on a limb, and they are inclined to make forecasts that underplay the reality. This does not help us minimise the impacts of the dangerous climate breakdown that we now know is on our doorstep. Far from it. In order to be as prepared as we can be, we need to plan for the worst even as we hope for the best.

A note on terminology. 'Global warming' has a cosy feel to it that is far from justified by the reality, while the rapidly increasing incidences of extreme weather show that our once stable climate is not simply changing, but well on its way to failing. To reflect this, I will be mostly using the alternative terms 'global heating' and 'climate breakdown'. Both are coming into general usage because they far more accurately describe what is happening to our world and our climate.

GROUND ZERO

1

Cromford, England, 1771

Two hundred and fifty years ago, a man called Richard Arkwright sparked a revolution. No violence was involved, there was no blood. The Sun shone as if nothing had happened, but its rising and setting bookended a day that changed the world for ever.

Arkwright, originally a lowly barber, wigmaker and tooth-puller from Preston, Lancashire, had a big idea and put it to work in the small Derbyshire village of Cromford, just down the road from my home up here in the Peak District.

Having made a tidy bit of cash as a result of a waterproof dye he had invented for wigs, Arkwright developed an interest in the cotton industry, which was burgeoning at the time, especially in Lancashire. A canny operator, he was quick to see that making yarn by hand, using an apparatus known as the Spinning Jenny, could never keep up with the huge and growing demand for the product. His big idea was to develop and patent a mechanised spinning device known as the water frame. Not only could this make yarn more speedily, but the product was also stronger and of better quality.

Traditionally, women spun the yarn and their menfolk wove it into cloth, all within the confines of small cottages. But Arkwright's invention changed all this. The water frame spinning machines were far too big to fit into a home, and – as the name testifies – they needed flowing water to operate.

Arkwright's solution was to construct a large building close to the River Derwent to host his spinning machines, and power them by means of water wheels. The new facility looked just like a water mill used to make flour from grain and soon became known simply as Cromford Mill. Spinners and weavers living in Cromford village, close by the new installation, saw their lives change overnight. Instead of spinning at home, the women – and children as young as seven too – now headed every day to the mill to produce yarn using the water frames, while the men stayed at home to weave the yarn into cloth.

At a stroke, Arkwright – and his partners Samuel Need and Jedediah Strutt – had unleashed mass manufacturing on an unsuspecting world. To squeeze the most out of his workers, Arkwright instigated a system of overlapping thirteen-hour shifts, with bells at 5am and 5pm to rouse the unfortunate women and children and set them commuting, bleary-eyed, down the steep hill from their homes to the mill. Nothing less than a modern, mechanised, factory system was up and running.

The mechanisation of work previously undertaken by individuals or small groups, using human muscle and dexterity alone, spread like wildfire in the years that followed. Arkwright himself built new mills along the Derwent, in Lancashire and Scotland. Soon, the arrival of steam power freed new developments from needing access to flowing water, and new factories were built for the mass production of glass, chemicals and machine tools, such as lathes and steam hammers. Machine tool production boosted the revolution in work and manufacturing even further, so that within decades a national economy previously entirely reliant upon manual labour was transformed beyond all recognition.

Steam-powered machine technology revolutionised textile production, coal refining, metalworking and a multitude of other enterprises. At the same time, an explosion of new roads, canals and railway lines broadcast the revolution into every corner of the UK and, eventually, far beyond its borders.

Arkwright's revolution, born on that sunny Derbyshire day in 1771, was nothing less than the Industrial Revolution. In the century that followed, a tsunami of mechanisation and mass production swept across Europe and North America, destroying one way of life and replacing it with another; a seemingly unstoppable wave of change that continues to roar across the face of our planet today.

Arkwright's legacy

The work of the former wigmaker is recognised at the highest level by the fact that Arkwright's original Cromford Mill, and the others built in the late 18th century upon the banks of the River Derwent, now constitute a UNESCO World Heritage Site marking the unequivocal birthplace of the Industrial Revolution. Arkwright's legacy is widely hailed as a colossal achievement, of immense benefit to humankind, and so it is in many ways, but it also comes at enormous cost.

As Arkwright's baby has grown and developed, it has become an unstoppable beast. Increasingly, and in particular since the end of the Second World War, the wigmaker's revolution has underpinned a global economy governed by a conspiracy of largely unfettered, free-market capitalism and a desperate and growing urge to consume. This has driven an immeasurable rise in the quality of life in many countries. At the same time, however, billions have remained mired in poverty, while the gap between the haves and have-nots grows ever wider. The consequences of market-driven consumerism have also been dire, with widespread pollution, the large-scale degradation and destruction of the environment and an overheating planet the result.

A straight line can be drawn, then, from the opening of Arkwright's Cromford Mill to the ongoing climate and ecological emergency, the greatest existential threat our civilisation has ever faced. As far as climate change is concerned, the small Derbyshire village of Cromford is nothing less than ground zero. Here, in other words, is where all our problems began.

The climate emergency: how did we get here?

Time was, people were content to have what they needed for a good life; now it seems – at least in the industrialised nations – that we can never have too much stuff. On our tiny planet, a society based upon ever more consumption of rapidly diminishing resources cannot be sustained, which is why we find ourselves, today, in the midst of a climate and ecological crisis.

When Arkwright opened his mill 250 years ago, the concentration of carbon dioxide in the Earth's atmosphere was 280 parts per million (ppm). Carbon dioxide is the principal greenhouse gas, which acts to keep our planet warm and helps shield it from the bitter cold of space. But too much of it can lead to a dangerous rise in global temperature. The level of carbon dioxide goes up and down over geological time in response to natural processes. A level of 280 ppm is, for example, near enough what you would expect in the current interglacial period during which human civilisation has burgeoned. At the height of the last ice age, just 20,000 years ago, levels fell to around 180 ppm, and they would do so again during the next ice age, if it isn't kept at bay by humankind's adulteration of the atmosphere.

This is because Arkwright's legacy is not only the creation of an economic wonder capable of meeting all our wants and needs, but a prodigious exhalation of pollution that has seen an additional 2.4 *trillion* tonnes of carbon dioxide added to our planet's atmosphere. This raised levels in 2021 to a high of 420 ppm – a hike of 50 per cent – bringing with it a global average temperature rise of 1.2°C and an increasingly obvious upsurge in extreme weather events, as our once stable climate starts to break down.

Perhaps the most depressing thing about the growing climate emergency is that we have been put on notice time and time again about the potentially catastrophic impact of rising greenhouse gas levels in the atmosphere, but we have repeatedly refused to listen and chosen not to act.

No one can say we weren't warned

Way back in 1856, the US scientist Eunice Foote wrote a paper describing the astonishing heat-absorbing properties of carbon dioxide. The paper was based upon the results of a simple but effective experiment, which involved placing two jars, one filled with air and the other with carbon dioxide, in full sun. The jar filled with carbon dioxide heated up much more than the air-filled one, leading Foote to conclude that carbon dioxide in the atmosphere would absorb the Sun's heat in the same way.

She even speculated that 'if the air had mixed with it a higher proportion of carbon dioxide than at present, an increased temperature would result'. This was, effectively, the first prediction of global warming, made more than 150 years ago.

A few years on, in the 1860s, the Irish scientist John Tyndall took Foote's work further. On the basis of hundreds of experiments on the properties of a range of gases, Tyndall noted that variations in the level of atmospheric carbon dioxide, along with water vapour and methane – both also greenhouse gases – 'must produce a change of climate'.

Fast forward to the end of the 19th century and we find Swedish physicist Svante Arrhenius laying the groundwork for modern ideas that link carbon dioxide levels in the atmosphere and global temperature. Arrhenius recognised that a halving of carbon dioxide levels could explain the fall in temperature associated with an ice age. He also forecast that a doubling of carbon dioxide levels would result in the global average temperature climbing by 5–6°C, a figure he later revised downwards to 4°C.

The amount by which our planet will warm for a doubling of the atmospheric carbon dioxide level (compared to Arkwright's time) is known as the 'climate sensitivity'. Even today, there is considerable debate about how high this number is, with estimates mainly ranging from 1.5°C to 4°C. Most recently, climate models have coalesced around a figure of around 3.7°C, astonishingly close to Arrhenius' prediction.

During the 20th century, it slowly became clear that not only *could* increasing levels of atmospheric carbon dioxide warm the planet, but that this was actually happening. In the late 1930s, the British engineer and amateur climate scientist Guy Callendar demonstrated that both land temperatures and carbon dioxide levels had risen over the course of the previous 50 years and proposed that the two were linked. Callendar's ideas were met with widespread scepticism, but later studies proved him to be spot-on.

In the 1950s, the Canadian physicist Gilbert Plass examined the links between increasing carbon emissions due to human activities and global temperatures more closely. In an especially prophetic interview with *Time* magazine in 1953, he is quoted as saying: 'At its present rate of increase, the CO_2 in the atmosphere will raise the earth's average temperature 1.5° Fahrenheit every 100 years ... for centuries to come, if man's industrial growth continues, the earth's climate will continue to grow warmer.'

While this initial estimate of the rate of temperature increase is much too low, the quote still points to an extraordinary level of far-sightedness. Plass later went on to forecast that the value of climate sensitivity would be 3.6°C and that atmospheric carbon dioxide levels in 2000 would be 30 per cent higher than in

1900, pushing up the global average temperature by 1°C. As previously mentioned, the current estimate of climate sensitivity is 3.7°C, while atmospheric carbon levels in 2000 were actually 37 per cent up on 100 years earlier, leading to warming of around 0.7°C. These, then, are amazingly impressive predictions.

In 1956, another US scientist called Roger Revelle, working in the same field, testified before Congress that the Earth was a spaceship which – due to increasing carbon emissions – was threatened by rising sea levels and desertification. An article describing Revelle's research, published the following year, used the term 'global warming' for the first time, concluding that Revelle's findings pointed to large-scale global warming with the potential to cause radical climate changes.

After the 1950s, research linking global warming with carbon dioxide emissions and their ever-increasing accumulation in the atmosphere moved fast. Most critically, in 1961, US scientist Charles Keeling demonstrated that carbon dioxide levels were climbing incrementally, but steadily, year on year. He used his measurements to define what has become known as the Keeling Curve, a graph that continues to record the remorseless rise of atmospheric CO_2 from 315 ppm, when Keeling began his measurements, to 420 ppm in 2021.

As understanding of what was happening gathered pace, so too did the urgency of the warnings. In 1966, the US Nobel Laureate chemist Glenn Seaborg cautioned that the rate at which carbon dioxide was being added to the atmosphere (6 billion tons a year at the time) could lead to marked changes to the climate that could be beyond our control.

A couple of years on, a Stanford University report written for the American Petroleum Institute in 1968 flagged the seriousness of global warming, concluding that significant temperature changes were almost certain to occur by the year 2000 and that these could bring about climatic changes. This publication is especially notable in that it was completely ignored by the fossil fuel industry that commissioned it. Not only did it take no action whatsoever, but in the decades that followed, oil companies launched a multi-million-dollar drive of obfuscation and denial designed to sow confusion and undermine public confidence in climate science and stymie the need for urgent action to tackle global warming.

Notwithstanding frigid scare stories in the tabloids that a new ice age was on the way, support for the idea of global warming and its link to carbon emissions continued to build within the climate science community throughout the 1970s and into the 1980s. In a seminal presentation to the US Senate Committee on Energy and Natural Resources in 1988, illustrious climate scientist James Hansen, who at the time was working for NASA, warned that global warming was happening now and was without doubt a consequence of escalating greenhouse gas emissions. Hansen's testimony is widely recognised as being a pivotal moment that marked the beginning of the global warming policy debate that continues today. At a stroke, it also ensured that awareness of the threat escaped from its climate science silo and entered the public arena, wherein its profile has grown ever since.

As the broader ramifications became increasingly clear, the term 'global warming' was replaced, at least in scientific and technical circles, by 'climate change'. This updated terminology was important as it broadened the focus of debate from what was happening to our planet – a steady rise in global temperature due to carbon emissions – to incorporate the consequences of warming – the large-scale modification of our climate.

The Intergovernmental Panel on Climate Change

Unfortunately, more widespread knowledge and understanding of our changing climate has only translated very slowly, too slowly, into action. The same year as Hansen's testimony, the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC), with the aim of evaluating climate change science, coordinating research findings and promoting wider understanding of climate change.

To this day, the IPCC remains *the* arbiter of climate science, and – when it comes to understanding and recording what is happening to our climate – its assessment reports engender almost biblical reverence. The panel's principal operational objective is to provide governments at all levels with scientific information that they can use to develop climate policies. To say that the formulation of such policies has taken place at a snail's pace would – in all honesty – be insulting to molluscs.

When the IPCC's first assessment report was published in 1990, today's younger climate scientists and politicians were still at infant school, or even babes in arms. The report noted, with certainty, that emissions arising from human activities were substantially increasing the atmospheric concentrations of the greenhouse gases carbon dioxide, methane, chlorofluorocarbons and nitrous oxide. The authors went on to forecast significant rises in global temperature and sea level if the world continued with business as usual. Calls to action accompanied the launch of the report but fell on deaf ears.

More than 30 years on, many of those ears – and quite a few new ones – remain deaf. Business as usual continues in most countries, and global greenhouse gas emissions have maintained – barring a small Covid-related downward blip in 2020 – their year-on-year climb. In the interval between the publication of the IPCC's first and sixth assessments, the first part of the latter of which was released in 2021, total greenhouse gas emissions have risen by 43 per cent, from a little under 35 billion tonnes to more than 50 billion tonnes. Over the same period, the atmospheric concentration of carbon dioxide has shot up from 354 ppm to 420 ppm – an increase of nearly 19 per cent. Worse still, according to the US National Oceanic and Atmospheric Administration, the warming influence of the whole basket of greenhouse gases has climbed a staggering 47 per cent since the IPCC first appeared on the scene.

This is probably the best place to reinforce the point that carbon dioxide is not the only greenhouse gas on the up. Atmospheric levels of other gases have surged over the past few decades too, most notably methane, which, as a greenhouse gas, punches far above its weight when it comes to its warming potential. Methane is produced by natural means, including releases from wetlands and ocean and lake beds. It is also a product of farting livestock, rice paddies, the oil and gas industry and thawing permafrost (the enormous tracts of permanently frozen ground at high latitudes) – all linked to human activities – which explains why methane levels have climbed two and a half times since Arkwright's time.

Over a period of twenty years, a tonne of methane causes 86 times as much atmospheric warming as a tonne of carbon dioxide. It is lucky, then, that it hangs around for much less time, so that only 250 kilograms would be left in the atmosphere after twenty years. Nonetheless, close to one-third of the warming since pre-industrial times can be attributed to rising concentrations of the gas. It is alarming to realise that when the warming effect of all greenhouse gases is taken together, it is equivalent, today, to an atmosphere containing 500 ppm carbon dioxide.

If world leaders had taken purposeful avoiding action in 1990, when the IPCC launched its first report, we could well be on top of the problem now, with fossil fuels largely consigned to the dustbin, renewables dominant and emissions under control and on the way down. But this never happened. Instead, despite successive IPCC assessments flagging the increasing urgency of the threat, serious action to tackle what is now, without doubt, an emergency situation failed to materialise.

The fifth IPCC assessment was released in 2014 with the aim of informing negotiations in the run-up to the COP21 summit in Paris the following year. The meeting was hailed an unqualified success – at least by those involved. Amid much cheering and back-slapping, the representatives of 146 countries signed up to the Paris Climate Accord (now ratified by 194 nations), which required them to submit so-called action plans for emissions reductions and promise to 'pursue efforts' to limit the global average temperature rise since Arkwright's time to 1.5°C. These efforts, such as they are, have been ineffective.

In August 2021, the IPCC released the first part of its sixth assessment report, 'Climate Change 2021: The Physical Science Basis' – the remaining three parts are to come in 2022. This initial publication addressed the current state of our climate and what we can expect of it in the decades to come, and its timing was designed to inform discussion and debate at COP26 in late 2021. Because the contents of IPCC assessments are subject to political oversight by representatives of more than 190 nations, the findings presented therein are regarded by some, and rightly so, as being consensus-based and conservative. If anything, this made the conclusions of the latest report that much more frightening, and it is not an exaggeration to say that its publication changed the landscape of the global heating debate for ever.

This time, the IPCC pulled few punches and issued a blunt message. Due to the carbon already released by human activities, it warned, major climate changes are inevitable and irreversible on the scale of a human lifetime. Furthermore, in the absence of immediate, rapid and large-scale reductions in emissions, limiting the global average temperature rise, since Arkwright's time, to 1.5°C or even 2°C would be impossible.

Glasgow and beyond

For all the impact it had on negotiations at COP26, you might wonder if those involved in the summit had even seen the IPCC sixth report, let alone digested its terrifying message. Post-Glasgow, therefore, keeping this side of the 1.5°C dangerous climate breakdown guardrail remains practically impossible. Instead, according to the highly respected Climate Action Tracker, the world continues to follow a path, based upon current policies and action, towards a hothouse future that would see a global average temperature rise of 2.7°C by 2100. This is a 'best' estimate, so the reality could be a bit cooler, or almost a full degree hotter. If the short-term pledges made in Glasgow were made good, the best-estimate temperature rise would still be far too high at 2.4°C, the worst-case reaching 3°C. Even if longer-term goals promised in Glasgow were also met, the rise would still be in excess of 2°C. While these hikes may not seem large, remember that they are global averages that – as I will discuss later – disguise the true picture. Be in no doubt, anything above 1.5°C will see the advent of a world plagued by intense summer heat, extreme drought, devastating floods, reduced crop yields, rapidly melting ice sheets and surging sea levels. A rise of 2°C and above will seriously threaten the stability of global society.

The depressing news is that, as of April 2022, none of the world's biggest economies – which together generate 80 per cent of carbon emissions – are on target to keep the promises they made in Paris to stop the global average temperature rise topping 1.5°C. The UK, along with Costa Rica, Nepal and a handful of small African nations have made commitments that are almost compatible with achieving this goal, but they aren't there yet. Indeed, the UK is showing worrying signs of backsliding. Meanwhile, countries like Australia, Brazil, Canada, China, Germany and the United States continue to develop fossil fuel infrastructure, making it impossible to achieve the emissions cuts needed to fend off dangerous climate breakdown.

More than 140 countries have so far committed to delivering so-called net zero greenhouse gas emissions, meaning they will cut their carbon output significantly and offset the rest by planting trees or adopting some other means of absorbing excess emissions. Some have posted net zero targets that are so distant as to be almost meaningless, although more than 130 have coalesced around 2050. Even so, this is far too late. The global average temperature rise is slated to exceed 1.5°C within a decade, and there is – according to the UK Met Office – a 10 per cent chance that at least one year could see this temperature exceeded by 2023.

It now seems to be pretty much accepted by national governments that the world will overshoot the 1.5°C guardrail much sooner than even the earliest net zero targets. As a result, there is increasing talk of resorting to technological fixes to suck up any excess carbon still being pumped out by the net zero target year in order to attempt, eventually, to bring the global average temperature rise down to below 1.5°C. The problem is that such fixes don't yet exist at anywhere near the scale required and – as I will discuss later – all those proposed are costly, environmentally damaging, risky or downright dangerous.

Most critically, many countries, despite being supposedly committed to achieving net zero by the middle of the century, have no road map to show how they will get there. Inevitably, this translates into a lack of serious action to cut emissions in the near-term (up to 2030) showing up their longer-term net zero plans to be little more than a lot of (ahem!) hot air.

Nasty surprises

While the world's climate scientists are making a reasonable fist of forecasting how far temperatures will rise and how quickly, getting it right is – due to the complexity of the climate system and the interconnectedness of its different elements – a huge ask. Even the most optimistic would agree that there will be surprises in store as our world continues to heat up, and probably not good ones.

One thing that keeps climate researchers awake at night is the idea that we have passed one or more points of no return, or 'tipping points' as they are known in the trade. Bringing temperatures down on an overheating planet is a bit like trying to turn the *Titanic*, and there may well be situations where – whatever we do in terms of slashing emissions – we can no longer avoid the iceberg.

A good, and especially apposite, example is the Greenland Ice Sheet, the wholesale melting of which threatens a major hike in global sea level. At more than a quarter of a *trillion* tonnes a year, the current rate of ice loss is already astonishing. But there could be worse news. Some researchers think that we may already have passed, or be close to passing, the ice sheet's tipping point. This would mean that, even if temperatures stopped rising today, melting would continue to accelerate until Greenland was ice-free and sea levels around 7 metres higher as a result. This would not necessarily happen rapidly, but it would be baked-in, and so ultimately inevitable.

Then there are so-called positive feedbacks loops. These involve responses to rising temperatures that act to heat up the planet even more. For example, as have had baking surface temperatures insulated by the strong greenhouse effect arising from their carbon-soaked atmospheres. But over time, the conditions on the two planets diverged dramatically. While the higher temperatures due to its closer proximity to the Sun meant that Venus had its water boiled off, our world – set fair in the Goldilocks Zone – hung on to its water in the form of oceans. These, in turn, absorbed much of the carbon dioxide, subduing the greenhouse effect and hauling down surface temperatures. Venus became a hellhole, a place where it is hot enough to melt lead, but, here on Earth, increasingly favourable conditions brought forth life and, ultimately, ourselves.

It is testimony to the importance of our planet's location, slap bang in the middle of the Goldilocks Zone, that life made an appearance so early in its history. Tiny, tubular forms found in rocks as much as 4.28 billion years old are claimed to be the fossilised remains of organisms that lived around hydrothermal vents in oceans that probably formed not much more than a 100 million years earlier. If true, then life must have sprung up extraordinarily rapidly. Even while our world was still being pounded by giant asteroids and comets, the biosphere was already a thing, its primitive and tenacious early forms clinging to existence in the face of global geological mayhem.

Life may have started early, but it was a very long time before it became commonplace, and it needed an oxygen-rich atmosphere to do so. Over a period of half a billion years or thereabouts, single-celled, photosynthesising cyanobacteria gradually pumped up the level of atmospheric oxygen on Earth – a development known as the Great Oxidation Event. The higher levels of the gas proved deadly to many early life forms, but new ones that depended upon oxygen sprang up to take their place. Multicellular forms first appeared on the scene a couple of billion years ago, and life hasn't looked back since.

Today, after more than 4 billion years of unconscious experimentation, the different elements of our world – the atmosphere and oceans, the solid Earth beneath our feet and the life that is all around us – have come to an innate arrangement that keeps our planet's environment in balance. The eminent chemist James Lovelock calls this set-up Gaia – after the ancestral mother of all life in Greek mythology – and it operates as a kind of superorganism through a system of self-regulating checks and balances that work together to sustain a habitat favourable to the maintenance of life.

The problem is that Gaia is now sick and getting sicker. While taking ice ages and other natural climate shocks in its stride, widespread environmental damage and diversity loss has meant that Gaia is struggling to handle the vast quantities of carbon being pumped out by humankind's activities at a rate unprecedented in Earth history. Lovelock himself is pessimistic that Gaia can get on top of the situation in the short term, and he has expressed the view that civilisation will be hard-pressed to survive the ongoing breakdown of our climate. It is a view that we would be well advised to take heed of in the critical decades that lie ahead.

All change

The road from planet-wide magma ocean to the climatically comfortable world that gave birth to humankind has been long and bumpy. During this interminable journey, our planet has, for all sorts of reasons, switched from icehouse to hothouse and back again on many occasions.

Broadly speaking, the Earth's climate is modulated by a natural thermostat with just three settings, which correspond to different conditions and temperature regimes. When set on 'greenhouse', our world is ice-free and tropical conditions extend even to the poles. This has been the case for three-quarters or more of our world's long history. For much of the rest of the time, the thermostat has been set on 'fridge', resulting in lower temperatures and the growth of ice sheets at the poles, sometimes extending down to lower latitudes. The most extreme setting is 'freezer', which sees the Earth becoming entirely or almost entirely covered with ice. This setting has only been clicked on twice, both occasions – fortunately for us – long before we appeared on the scene. The first time was during the Huronian glaciation, between 2.4 and 2.1 billion years ago, when ice may have covered the entire surface of the world, leading to a so-called Snowball Earth state.

The cause is widely held to be a weakening of the greenhouse effect as increasing amounts of atmospheric oxygen, exhaled by cyanobacteria during the Great Oxidation Event, reacted with atmospheric methane, breaking it down into water and carbon dioxide. Although both of these are greenhouse gases, they are nowhere near as good at retaining heat as methane, so the result was a progressive and deep cooling. Falling temperatures would have been helped considerably by the fact that the Sun was much fainter at the time, with its brightness down 16 per cent on today's levels.

The thermostat was turned to freezer setting again between 720 and 635 million years ago, during the appropriately named Cryogenian Period. This was the deepest, coldest ice age our planet has ever experienced, with the global average temperature reaching −12°C and equatorial temperatures as low as in the Antarctic today. Repeated pulses of severe cold resulted in the planet being largely covered by ice on a number of occasions, although recent research suggests that there was still open water in equatorial regions. The drivers of this so-called Slushball Earth are complex and disputed. Certainly, the Sun was still dimmer, by about 6 per cent compared to today, which would have helped cooling. Other than this, the primary cause is thought to be, once again, a big drawdown in carbon dioxide levels, sucked from the atmosphere either by weathering processes – which extracted carbon via chemical reactions between rocks and the atmosphere – or by new, more complex life forms using it to build their skeletons.

Since the beginning of the Cambrian Period, which began 541 million years ago, the Earth's thermostat has been stuck, for most of the time, on the ice-free greenhouse setting. The Cambrian is perhaps best known for the extraordinary diversification of lifeforms, known as the Cambrian Explosion, which is likely to have been at least partly facilitated by the warm, shallow seas that covered much of the planet. The thermostat was briefly flicked to fridge on two occasions during this period, bringing ice-age conditions that persisted relatively briefly, but for most of the time global temperatures averaged 27°C or more, sometimes rising above a steamy 30°C, compared to just 14.9°C today.

Notwithstanding a rare cooler episode, greenhouse conditions reigned from the beginning of the Triassic Period, 250 million years back, to the massive asteroid impact that ended the Cretaceous Period 66 million years ago, a time span that coincided almost exactly with the appearance, rise and demise of the dinosaurs.

Shortly thereafter, at least on a geological timescale, the global average temperature spiked at a time known as the Palaeocene–Eocene Thermal Maximum (PETM) – more on this later – after which it was all downhill. Our world's climate has been broadly following a cooling path for the past 50 million years or so, as the thermostat has inched towards fridge. The first glaciers had formed in Antarctica by around 45 million years ago, and 20 million years on the Antarctic Ice Sheet was well and truly established. As planetary cooling continued, so ice began to conquer the Arctic region, including Greenland, around 7 million years later.

This extended period of cooling is likely to have been caused – to a large degree – by the formation of the Himalayas, as the Indian tectonic plate crashed into Eurasia. Rapid uplift of this colossal mountain range resulted in a huge increase in chemical weathering that removed carbon dioxide from the air, progressively reducing the insulating effect of the atmosphere.

By 2.6 million years ago, our world was in the grip of what we know as the Ice Age, also known as the Pleistocene. During this time, the glaciers expanded beyond their polar fastnesses on numerous occasions – eight in the last 750,000 years alone – bringing frigid conditions to temperate latitudes. But this is not to say that the climate was bitter all the time. In fact, glacial episodes alternated with so-called interglacials, during which the ice retreated, and temperatures were often as warm, if not warmer, than today.

The advance and retreat of the ice was far from random, and the timings can be explained by cyclic variations in the Earth's wavering passage around the Sun. During its journey through space, our planet wobbles in a number of different ways and on a range of timescales, which together result in long-term variations in the geometry of the Earth's orbit and axis of rotation. Not only are these variations predictable, but they fit perfectly with the timing of glacial advances and retreats.

The last glacial episode peaked just 20,000 years ago, following which time our planet has been warming again. Officially, we entered a new interglacial – known as the Holocene (from the Greek for 'completely new') – a little under 12,000 years ago, but that isn't the end of the story. We are still in the Ice Age, and the cold is slated to return – if nature were left to its own devices – probably within 10,000 years. The thing is, global heating, driven by human activities, has put a spanner in the works to the extent that the next glacial episode is virtually certain to be postponed, perhaps indefinitely.

The key message we need to take away from this roller coaster ride through Earth history is that, while other factors may be involved, including variations in solar output, the geometry of the Earth's axial tilt and orbit and the disposition of the continents, it has always been the level of greenhouse gases in the atmosphere – particularly carbon dioxide – that has determined whether our climate is warm or cold. As carbon dioxide concentrations touch 420 ppm, and continue their upward path, it is a message we ignore at our peril.

From Narnia to Eden

At the height of the last glacial episode, the level of carbon dioxide in the atmosphere was a lowly 180 ppm. Just 8,000 years later – the blink of an eye when measured against the great span of geological time – it was 260 ppm.

Twenty thousand years ago, the global average temperature was at least 6°C lower than it is today, ice sheets kilometres thick buried large parts of North and South America, Europe and Asia, and sea levels were down 130 metres. By a little under 12,000 years ago, the Earth had undergone an almost miraculous transformation, which saw our planet metamorphose into the clement world upon which our civilisation has flourished. One of the most dynamic periods in the history of our world saw rocketing temperatures melt the great continental ice sheets like cheese under a grill, pouring prodigious volumes of meltwater into the ocean basins – 52 million cubic kilometres in all.

The environmental and climatic mayhem that defined the transition from Narnia to Eden marked the very end of the Pleistocene Period. What followed could not have been more different. In sharp contrast, at least until human activities intervened, the Holocene has been marked by a relatively stable climate with little variation over time in either global temperature or the level of atmospheric carbon dioxide.

Even so, there was still plenty going on. The dregs of the great ice sheets continued to melt, bringing the seas up to present-day levels, mostly during the early Holocene. At the same time, those parts of the Earth's crust that had been severely depressed beneath the ice at high latitudes were bouncing back rapidly – a mechanism known as post-glacial rebound. This effect spawned a vigorous response from the solid Earth, with magnitude 8+ earthquakes shaking Scandinavia, and up to a 100-fold rise in volcanic eruption rates in Iceland.

Post-glacial rebound continues today in those regions once covered by the great continental ice sheets. In apparent defiance of the global trend, uplift rates remain high enough in places – for example, along the coasts of Sweden and Finland – to give the appearance that sea level is currently falling. This, however, will not last, as accelerating sea level rise, driven by global heating, will soon overwhelm the rate of bounce back.

It is no coincidence that the extraordinarily rapid rise of humankind occurred during the Holocene, the ameliorating climate encouraging the switch from hunting and gathering to farming. This, in turn, brought people together in larger communities that led ultimately to the establishment of the first cities. While certainly stable in comparison with the climate of the preceding Pleistocene Period, the Holocene has still thrown up surprises, some of which are thought to have played critical roles in spurring on the development of human civilisation.

Most notable was a cold snap known – somewhat uninspiringly – as the 8.2 ka event ('ka' being shorthand for 'kilo-anni' or thousands of years, because it happened that long ago). The cause was the catastrophic emptying of a huge and expanding glacial lake in North America into the North Atlantic. The shock of an influx of some 160,000 cubic kilometres of cold freshwater raised sea levels by up to 4 metres almost overnight and slowed or stopped the Gulf Stream, triggering a centuries-long spell of cooling.

Temperatures fell by as much as 5°C in some parts of the world, bringing to parts of Asia and Africa drought conditions that may have lasted for centuries. While extreme drought is never welcome, in this case it seems – as far as societal development is concerned – to have been a blessing in disguise. This is because it looks as if the paucity of water may have encouraged the development of irrigation in ancient Mesopotamia and the bringing together of people in larger social groupings to cope better with food scarcity. The timing certainly seems to jibe with demographic changes across the region that involve the growth of bigger communities.

The 8.2 ka event was one of a series of cold snaps, known as Bond Events, which intervened periodically to reduce the general warmth of the Holocene. The underlying cause of the others is not certain but may be related to cyclical variations in the North Atlantic currents, or to episodic reductions in the Sun's activity. Certainly, the most recent event, a modest cooling of the northern hemisphere between the 16th and 19th centuries known as the Little Ice Age, does broadly coincide with a period of reduced solar output known as the Maunder Minimum.

Taking the Holocene as a whole, the global average temperature followed a rising trend until around 5,000 years ago. Then, during the so-called Holocene greenhouse gas, and rice production today is responsible for around 10 per cent of agricultural methane emissions.

Altogether, it is estimated that the prehistoric switch from a hunter-gatherer lifestyle to one of relatively sedentary farming resulted in a global average temperature hike of a shade under 1°C, and perhaps up to 2°C at high latitudes. Considering that the entire population of the planet at the time may have been just 5 million or so, this is an extraordinary feat. It also throws into stark relief the potential climate mayhem we can wreak with an early 21st-century population just shy of the 8-billion mark.

If the pattern of carbon dioxide levels during other interglacials is anything to go by, the amount of the gas in our atmosphere should have been falling for the past 10,000 years or so and should, by now, be below 250 ppm. Instead, of course, it is going through the roof. As noted previously, carbon dioxide levels in the atmosphere peaked at a little under 420 ppm in 2021, up 50 per cent on Arkwright's time, and the highest concentration for around 15 million years. Unless drastic action is taken to reduce emissions, we can expect the level of carbon dioxide in the atmosphere to reach 560 ppm – twice the pre-industrial concentration – by the 2070s, or even earlier, bringing the prospect of severe and sustained hothouse conditions on our planet.

So long as we persist in growing the insulating shroud of greenhouse gases around the Earth, so the rate of melting of the polar ice sheets will continue to accelerate, sea levels will continue to increase and extreme weather will exact an ever greater toll. The longer we maintain the human greenhouse, the more perilous the future of our race will become, the more drastic will be the measures required to bring greenhouse gas levels down and the longer it will take to rewild our climate back to its natural interglacial state.

3

HOT AND STEAMY WITH A CHANCE OF COLLAPSING ICE SHEETS

Earth's climate today

On 29 June 2021, the unassuming Canadian village of Lytton, in southern British Columbia, registered an astonishing temperature of 49.6°C (121°F), beating the previous record for the highest temperature ever recorded in the country by the huge margin of almost 5°C. It was also the highest temperature ever recorded north of the 50th parallel, and hotter than anything ever experienced in Europe or South America. The following day, the village was gone, wiped from the face of the Earth by one of the many wildfires triggered by the searing temperatures.

Barely two weeks later, on 12 July, a slow-moving line of thunderstorms dumped up to a month's worth of rain on London, bringing widespread flash flooding that caused sewers to back up and travel chaos. But far worse was to follow. Over the next three days, the same low-pressure system stalled over eastern Belgium, Luxembourg and western Germany. Warm, moist air sucked up from the south fed a biblical deluge that brought the worst floods in 1,000 years to some parts of the region and unprecedented and shocking scenes as the power of water devastated well-off communities in the heart of Europe.

Without warning, the wild weather cultivated by global heating wasn't battering some distant land but taking its awful toll just across the Channel. Suddenly, it was too close for comfort; all too easy to imagine the images of raging torrents, stranded corpses and demolished homes transposed to our own communities.

More than 1,000 lives were lost as a direct consequence of the unprecedented North American heatwave, while the European floods took close to 250 lives and caused damage totalling in excess of $11 billion. But these instances were just two in a long line of extreme weather events in 2021 that destroyed lives and livelihoods right across the planet. Devastating floods also swamped great tracts of Turkey, China, Japan, India, Pakistan, the United States and New Zealand. Meanwhile, some of the greatest wildfires ever seen raged across Siberia and California, while record-breaking droughts became even further entrenched across the western United States, Central Asia and southern Africa. It was not only Canada that experienced unparalleled heat. All-time temperature records were shattered across much of North America and Southern Europe. Sicily smashed the European record with 48.8°C (120°F), while the heat in California's appropriately

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