NEXT
LEVEL
CLIMATE
THINKING
AND
ACTION

CLIMATE ACADEMY

Chapter Eight

Tipping Points - Physical

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Introduction

The Velodrome

Indoor track cycling. What a sport.

The Olympian demands that the athletes push themselves through on the track are astonishing. Any win in such an event takes a cyclist to the limits of what a human being can exert and endure.

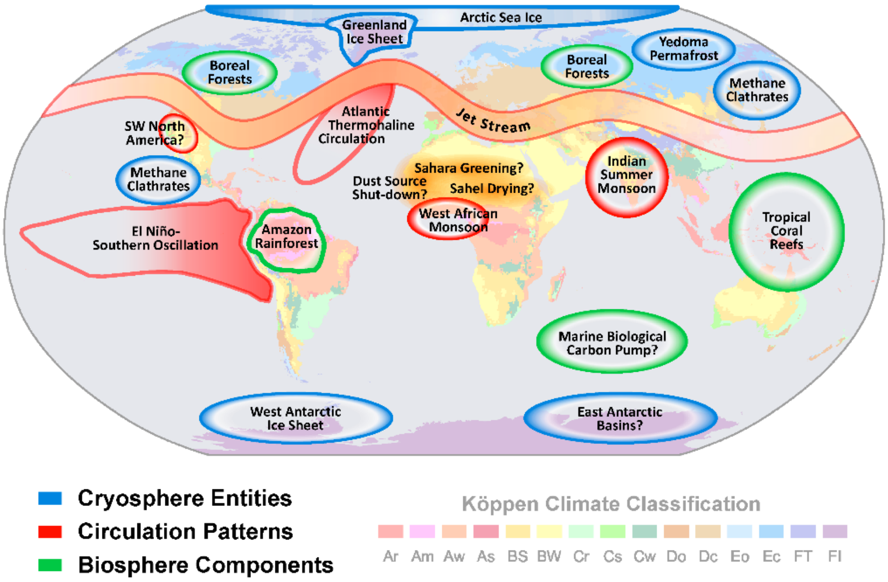
It is also a sport that has witnessed some truly memorable crashes, especially in the team events. If you are brave enough to look through the gaps in your fingers at a YouTube compilation of velodrome crashes, you will see a truly horrendous combination of Lycra, speed, metal and wood.

Thankfully, such carnage is not that common. The cyclists are able to sustain speeds of over 80kmh whilst jockeying to gain small pockets of slipstream with incredible skill and concentration. However, when a crash does happen, the fine margins that the athletes trade in whilst hurtling around the track, look awfully thin.

A pile-up often starts with a tiny wobble or a small miscalculation. However, because there is so much kinetic energy packed into a compact space, the effects of these small moments of imbalance have major consequences. One rider can trigger a chain reaction that can send numerous bikes and bodies flying into the air.

Planet Earth

(Opposite) is a graphic of the major cogs that determine life on planet Earth. They all exist and morph in an interconnected balance with each other. It could be called the 'meta' map of natural world. These cogs can be classified into groups. At the broadest scale, there are three.



The planetary systems that relate to ice, such as the permafrost areas in the polar north and the massive ice sheets in the polar south, are known to science as the Cryosphere[1,2].

There are also major biological systems: with components such as the vast Boreal Forests, Amazon Rainforest and tropical coral reefs.

Other systems in place around the planet exists as patterns of energy flow. These circulations, such as the Jet Stream and the AMOC (Atlantic Meridional Overturning Circulation), could be understood as conductors who control the mood and movement of all the other players in the planetary orchestra.

Put all these components together into a map, and the major controlling hubs of life on Earth become clear. These blocks of energy, these flows and patterns are what determine everything else that goes on. These are the underlying cogs that have been locked in place with each other, in a settled equilibrium, for thousands of years.

Indeed, it is important to stress that these cogs are interconnected. For example, about 4000 years ago the amount of solar energy reaching the Northern Hemisphere slightly faded, due to a change in the tilt of the Earth. This phase caused the horizontal flow of the Jet Stream to loop up and down in a more exaggerated way, which in turn intensified the strength of both the El Niño/La Niña cycle and the intensity of the Monsoons in India. These natural rhythms

[1] The Cryosphere also includes the world's glaciers, such as the Himalayas and the Andes. Although they are minor cogs in terms of the interplay of planet Earth's physical forces, they are absolutely critical to the livelihood of billions of humans who need fresh water to survive. The dangers posed by their rapid retreat does not need underlining.

[2] Over the long term mountain glaciers could only contribute 40cm of sea level rise and are therefore much less significant than the 120m* . However, because of their small size they respond much faster to changing conditions and are currently responsible for 25-30% of sea level rise – a third of which is from Alaska alone. (Zemp et al. 2019).

in the climate systems are well documented by physicists[3]. We could say that inside our little pocket of geological time, such variations are 'normal'.

If we think back to the velodrome, they are like the natural patterns of the cyclists as they move around the track. The peloton will always stretch and compress at different times in the race as the riders play out their individual tactics in a reaction to the movements of the group. No two races are the same, but there is a common predictable pattern of ebb and flow that plays out, with a certain amount of elasticity.

However, this predictability flies out of the window when a crash happens. One rider can be following his game plan, feeling in a strong position, and setting themselves up to make a move off the end of a bend when their back wheel suddenly gets hit by another bike. The chain reaction through the peloton will shred the race script, and it will just come down to luck if a rider survives the wreckage.

The moment that the rider loses balance can be understood as a tipping point.

Climate Change Modelling

When the Industrial Revolution began, it was inconceivable that humans could have such a definitive impact on the Earth. The start of the industrial age was well before the surge in population from 1 billion towards 8 billion, and well before the phenomenal acceleration of resource extractions that technology made possible.

Yet, for decades now, it has become very clear that human interference with the planet is not just a matter of small details. What is at stake now is the stability of the entire operating system. It is clear that we are approaching some definitive tipping points in the natural world that would have seismic impacts within the life time of young people reading this text[4].

The deep complexity of the climate systems will always present an awesome challenge to scientists, it is an area of research that demands not only an understanding of Physics, Chemistry and Biology, but also a specialized understanding of the hinges between all three components, underpinned by mathematics. Indeed, when these scientists started their research into climate modelling back in the 1970s, the sheer scale and the chaotic character of their subject meant that even some of their academic colleagues viewed their work with a dose of skepticism, and held some of their papers at arms-length[5].

Like any science, climate scenario modelling papers are carefully wrapped in different layers of probability. Any conclusions are put forward with due modesty and tentativeness; the rules of peer reviewed scientific publications are rightly stringent and exacting.

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[3] One of the most basic rhythms in the background of all these parcels of planetary change was identified by the Serbian geophysicist Milutin Milankovitch. Before the help of an IBM was available, with a pencil, paper and tremendous level of skill and mental stamina (he did much of his work as a prisoner of war ***), he defined the various repeated patterns of the Earth as it orbits around the Sun. These Milankovitch Cycles happen on huge time scales. For example, it takes 100,000 years for the Earth to switch from a rugby ball to a more football shaped orbit, and back again. There is also a 41,000 year oscillation in the tilt of the Earth, and a 25,771.5 year pattern to its 'wobble' (more technically known as the 'Axial Precession').

[4] There is already a body of evidence that suggests that certain points of no return have been crossed with the Antarctic Ice Sheets **. Nature **

[5] **Use Nicolas' example**.

Despite these formidable obstacles, this branch of Physics now speaks with genuine authority. It is also an area of science that has been given a fantastic boost by the exponential rise in computer processing power since the 1970s. Indeed, the Nobel committee awarded Syukuro Manabe, Klaus Hasselmann and Giorgio Parisi[6] with the joint Physics Prize in 2021 in recognition of the robust and groundbreaking nature of their work.

In fact, climate science is just like any other scientific discipline – the central conclusions are extremely secure. As former NASA scientist Professor James Hansen, "We know as much about the climate as we do about the human body".[7] [8]

For example, in Biology we all know that continually overeating will lead to obesity, which in turn leads to an increased probability of fatal diseases. This most basic fact of anatomy is not then dismissed if our doctor is not able to predict which biscuit, on what day, will lead to a heart attack, at a precise moment in the future. Likewise, we don't need a PhD in Physics to know that jumping off a motorway bridge into a busy traffic will prove to be fatal. We would not know what gender of driver, nor which model and colour of vehicle will hit us. However, it is clear that our life expectancy will shrink to seconds if this idea was to become a commitment.

In conclusion, there are some clear lines that we should not cross over if we want to avoid triggering a cascading sequence of events that will throw the major forces of the planet into a chaotic condition. These lines are well understood.

A glance back at 'The Absolute Basics' will also show that a reading of 413ppm for the concentration of Carbon Dioxide particles in the dry air is profoundly unprecedented. As Peteri Talaas, the former Director General of the WMO stated in October 2021, "The last time the Earth experienced a comparable concentration of CO_2 was 3-5 million years ago, the temperature was 2-3°C warmer and sea level was 10-20 meters higher than now. But there were not 7.8 billion people then".[9] It is simply not possible to shunt up the level of extra watts in the Earth's planetary systems so abruptly and so decisively and not expect a major reaction somewhere down the line. It is naïve to think that a balanced equilibrium could remain in place when the fundamental co-ordinate of all life on Earth has just jumped far outside of its background pattern of movement. The last time anyone checked the global 'Wise-o-meter', we were still getting a painfully low climate score.

It is not an exaggeration to state that climate scientists are looking at all the hockey-stick graphs through the gaps in their fingers, as they understand the jeopardy of the current situation.

[6] Parisi was awarded half the prize, with Manade and Hasselmann awarded the other half.
[7] "Merchants of Doubt" (20**) documentary.
[8] Indeed, Professor Hansen's groundbreaking research into climate modelling and commitment to climate justice deserves special note, even if the Nobel Prize committee has so far looked past him.
[9] https://public.wmo.int/en/media/press-release/greenhouse-gas-bulletin-another-year-another-record

Main Text

Going through the gears

We are prone to have a false sense of security about the future, because it is natural for us to assume that it will more-or-less match the past. Our limited imagination about what could happen ahead of us is normally useful, because it makes our lives efficient and livable. It would be exhausting to continually think through the vast range of possibilities and all their consequences. However, this blind-spot can be dangerous. Sometimes it is important to pause, and do the big macro thinking. The threat of climate change insists that we take a step back and look at the pathways that we are on. The acute dangers of tipping points require us to be attentive to how close we are to pushing the system out of balance.

This need to step back is partly due to the fact that we are predominantly *linear* minded bipeds. This is hardly surprising, since most of the time we only have to deal with linear change. For example, if we walk one kilometer, we have a good sense of being half way to our home that was 2km away; if we go and get a beer at half-time in a football match we have a good sense of how long our team needs to stay ahead to win the match; and if we earn €10 an hour for chopping vegetables, the it is obvious that 4 hours in the kitchen will earn us €40.

Simple.

The problem is that we are being blind-sided by a different kind of change – the *exponential* variety.

And this kind of change operates in a very different gear.

Exponential Change

Exponential change is a much tougher type of change to hold clearly in our minds. Exponential changes play out in modes that make less intuitive sense to us.

An often quoted example of this type of change involves a legend about an Indian King who is given a beautifully carved chessboard. When he gratefully asked the court advisor who gifted it what he could offer him in return, the advisor said that he simply wanted to be given a single grain of rice on the first square, two grains and the second, and four on the third… and so on. This seemingly modest request was accepted by the King. However, it soon turned out to be impossible to fulfil. The 21st square on the board required over a million grains, and the 41st square required over a trillion, and there was simply not enough rice in the world to properly fill the final 64th square. More precisely, it would have required 2^{64} -1 (or 18,446,744,073,709,551,615 grains). Or maybe 18 quintillion grains of rice if the modest vizier would be willing to round his request down a bit.

In our real world, the formidable ability of the fruit fly (*Drosophila melanogaster*) to multiply in number in our kitchen during the summer months is a notable illustration of exponential growth. One lazy failure to deal with a banana skin can trigger a crazy hygiene war with every scrap of food for days after[10]. A failure to deal with a small outbreak at the start makes it very difficult indeed to contain the problem as the exponential growth kicks in. A truth that political leaders did not easily grasp at the start of the COVID-19 pandemic.

Indeed, the build-up of massive pressures on the planetary systems has happened as *fast* exponential growth. One of the best places to stand and look at the massive dimensions of the human impact on Earth is to take a look at the important dashboard developed by the Stockholm Resilience Centre[11]. The scientific curves that hook upwards dramatically from 1950 in "The Great Acceleration" illustrate so many of the pressure points that have developed. The dashboard covers both the Earth System trends (from CO_2 readings and ice melts, to bio-diversity loss and ocean acidification) and Socio-Economic trends (from population growth and primary energy use, to transportation expansion and fertilizer use).

Yet the odd truth is that this growth has mostly happened in single digit annual increases - these seemingly unremarkable additions, when compounded on top of each other are hugely significant. Mathematics informs us that if something grows at 3.5% per year for 20 years, it would have doubled in size[12]. The surge in population and industrial activity since 1950 has therefore given us plenty of time to take the planetary systems to the brink of various tipping points. As Professor A.A. Bartlett bluntly (and repeatedly[13]) put it, "The greatest shortcoming of the human race is our inability to understand the exponential function."

As noted in the 'The Absolute Basics' (Module 1) the amount of extra energy in the atmosphere is now equal to 600,000 Hiroshima A-Bombs per day – and that does not include the monumental level of extra energy that has also been absorbed by the warming oceans. We have achieved something spectacular in a very unspectacular way. Indeed, policy decisions still seem to operating in this blind spot - despite all the warnings of science, we are set to accelerate emissions further until at least 2030. It would be easy to consider that the increased emissions of 2.1%* in 2021, did not look like much to worry about. Yet the hard truth is that we are projected to match the *entire* emissions of human civilization up until now by the year 20__** with exponential growth rates such as these.

A Tipping point – a close-up view

We should really not be pushing the climate system into a situation where it is very tempted to flip. The danger we are now faced with is that the exponential growth in emissions can shift into a radically new gear, where that growth rate becomes unstoppably huge. The major concern that overhangs the climate crisis is that if one part of the climate system goes into breakdown mode, this destabilization will drag other major elements of the Earth* with it.

But how do tipping points work? What are the smaller mechanics of the process?

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[10] More tragically, when my mother was diagnosed with terminal cancer it was difficult for everyone to handle the ambiguities about the timescale of the disease. The Macmillan Nurses offered the most remarkable support, and when I confessed my struggle with this particular issue, I was very helpfully advised that if I see a change in her condition in months, then I can be confident that she has months to live; and when the noticeable change shifts to weeks and days, the same will be true.

[11] "The Trajectory of the Anthropocene: The Great Acceleration", Anthropocene Review (16 January 2015)

[12] For the mathematically curious, the 'Doubling Time' for any percentage can be worked out with quite a simple equation.

[13] _ how many times -

It is informative to have a brief look at something beautiful. Trees. In the early summer of 2018 whilst driving south through Europe, it was very notable that the trees that edged the motorways were not their usual lush green. In fact, the scenery was dominated by yellows and bronzes, like a day in late October. It had been a truly odd year of weather, with prolonged periods of heat and drought. The heatwaves had caused havoc across the continent, and so now instead of driving past trees that should have been acting as a vacuum, sucking out CO_2 from the atmosphere, they were just frazzled bystanders to human traffic. A situation that was not just happening in the fields of southern Europe; it was a situation replicated across swathes of Scandinavian arctic land.

Indeed across the immense Boreal forests of the Northern hemisphere, there were widespread reports of unprecedented heatwaves, electrical storms and large-scale forest fires. The Boreal forests are one of the major cogs of the Earth's climate system, and in 2018 they were experiencing unprecedented heat stress.[14]

2019 was also characterized by similar extreme weather patterns. Indeed, NOAA reported that June 2019 was officially the hottest June on record for the globe. For Anchorage (in Alaska, USA), it was 0.95°C above the average,[15] and the citizens of that city also experienced a string of astonishingly hot days at the start of July 2019 that were 12.4°C above the average.[16] For various reasons of thermal dynamics, global warming is not happening at uniform speeds across the globe and Alaska is among the fastest warming regions on the planet[17][18]. Since the start of the Industrial revolution it has heated up by an average 2.7°C. In 2019, the WMO reported that: "Since the start of June, the Copernicus Atmosphere Monitoring Service (CAMS) has tracked over 100 intense and long-lived wildfires in the Arctic Circle. In June alone, these fires emitted 50 megatonnes of carbon dioxide into the atmosphere, which is equivalent to Sweden's total annual emissions. This is more than was released by Arctic fires in the same month between 2010 and 2018 combined."[19]

To the East, at the same latitude, Siberia had experienced similar wild temperatures and wildfires, and in July 2019 an area totaling the size of Belgium was ablaze.

The lack of photosynthesis by the side of a motorway is of course not significant at a global level. However, the lack of photosynthesis on such a monumental scale in the vast Boreal forests of the Northern hemisphere would have had a critical knock-on effect. It means that going forward into the future, there is an increased chance of more heatwaves and droughts. In turn, this means a higher probability of more wilted trees, forest fires and scorched earth – all of which pushes up the level of CO_2 in the atmosphere even higher… and so on.

The "and so on" is very important.

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[14] R. Kelly et al, "Recent burning of Boreal forests exceeds fire regime limits of the past 10,000 years". PNAS (August, 2013)

[15] Global Climate report 2019 https://www.ncdc.noaa.gov/sotc/global/201906.

[16] Alaska's exceptional heat wave delivers state's hottest days on record", Washington Post, July 9th 2019.

[17] In fact, the whole artic region is warming at much faster rate than the average 1.2°C https://data.giss.nasa.gov/gistemp/maps/.

[18] US Global Change Research Programme, "Fourth National Climate Assessment". Chapter 26, Alaska 2018.

[19] The average June temperature, in the parts of Siberia where wildfires are raging, was almost ten degrees higher than the 1981-2010 long-term average. WMO, "Unprecedented Wild Fires in the Arctic", July 12th, 2019

Destabilising such large components of the Earth's systems into self-reinforcing feedback loops like this poses the biggest risk of all – a triggering of irreversible, cascading impacts. In the end, the scale of the dynamics become so magnified that the natural forces in play simply reduce human efforts to mitigate the problem ineffective. It simply doesn't matter how many trees (puny) little humans want to plant, if the land and climate around us is trapped into a spiral of radical, inhospitable imbalance.

The example of the Boreal forests tipping into a different state "at 3°C" raises some important technical issues about the science of tipping points that must now be addressed.

A map of what lies ahead

If all the pixels of scientific research are put together, it becomes possible to form an overall picture of the future scenarios ahead. Of course, the moment that we zoom out to a very general level of summary, so many nuances and qualifications in the original research papers get lost. However, these wider vantage points are important.

Indeed, the Paris Agreement (2015), committed all the nations of the world to limit warming to well below 2°C (and as close as possible to 1.5°C). This agreement was informed by an understanding of the macro analysis - that the higher the temperature gets, the higher the risk is that the destabilization becomes *contagious* and *unstoppable*. Indeed, without diminishing the importance of the localized impacts of climate change, it is this *global*, *existential* threat that climate change carries which lies at the heart of the whole crisis.

As a very rough summary indeed: the corals of the Great Barrier Reef cannot endure a rise of 1.5°C and many glaciers will be doomed with a 2°C rise. As we just noted, the Boreal Biome (and Amazon rainforest) is under threat to tip at 3°C; and at 4°C the startling amount of methane in the permafrost is at risk of irreversible destablisation[20]. A world heated to an average of 5°C or 6°C would be unrecognizable to us, and utterly hostile to human life. A full and properly qualified account of these different stages of disruption can be found in the award winning book, "6 Degrees" by Mark Lynas.

There are very few scientific scenarios where any touching of a 4°C rise does not signal a irreversible destabilization. A rise of 2°C sustained over centuries also makes the risk of wider contagion and irreparable damage likely.

Qualifications

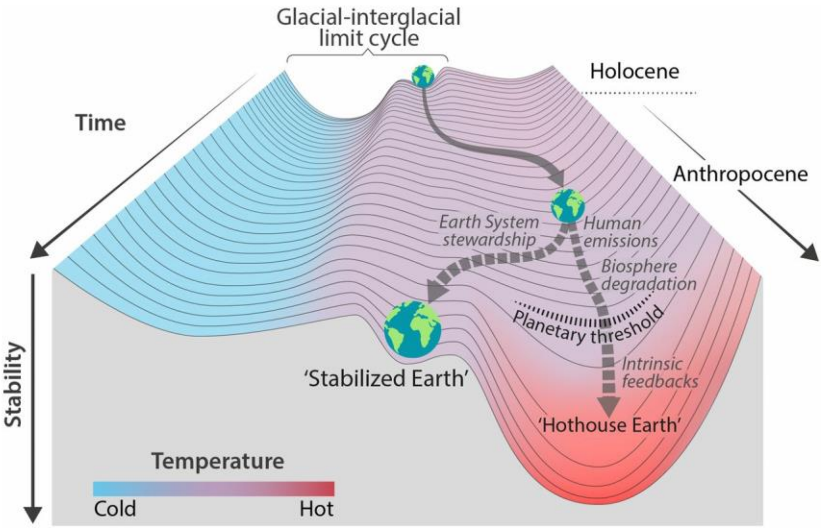
Now for some of those essential qualifications of the science - there are five major points to underline.

Firstly, as just indicated, there is also a huge difference between sustaining a 2°C temperature rise for 50 years and holding it for 500 years.

Secondly, any summary that captures scenarios for "2°C" or "3°C" is immediately simplistic. There is of course a huge difference between 3.1°C and 3.9°C that cannot be accounted for at the level of zoom that this book has.

[20] If *all* the methane locked inside the clathrates of the artic were to be unlocked it is calculated that such a thawing would cause greenhouse gas levels to jump by 1460-1600 gigatonnes. Such a seismic event would roughly double the level of GHGs in the atmosphere. (IPCC, Summary Report for Policy Makers 2019).

Thirdly, once a temperature triggers a major system change, even if the temperature is then later reduced, the chain of events will not go into reverse as it has passed its tipping point.



(from Steffan et al, 2018).

For example, the conditions for the collapse of the West Antarctic Ice Sheet[21] might already be close. However, if those parameters get do established at 3°C[22], it will still take centuries for the ice to actually turn into the catastrophic sea level rises of 57.9 meters [sic] that would follow from its collapse[23].

As polar climate scientist Roberto DeConto notes, "If the world warms up at a rate dictated by current policies we will see the Antarctic system start to get away from us around 2060… Once you put enough heat into the climate system, you are going to lose those ice shelves, and once that is set in motion you can't reverse it". Adding, "The oceans would have to cool back down before the ice sheet could heal, which would take a very long time. On a societal timescale it would essentially be a permanent change".

The good news is that the fuller melting of the East and West Antarctic Ice Sheets are not expected to occur for a century, or perhaps centuries. Good news, if you belong to this side of the century.

Fourthly, the vertiginous rise of greenhouse gas concentrations in the atmosphere is so sharp that it poses a few problems for Geologists who normally deal in long term patterns. Indeed, when a Geologist says "long-term" they really mean it - they are used to dealing with lots of zeros after a number when they think about blocks of time. The problem with the last (utterly miniscule) 50 years of the Earth's 4.6 billion year history is that the change has been so abrupt. Human beings are a stunning new addition to geological history – we have developed

[21] The East Antarctic Ice Sheet has a very different storyline towards collapse. The Basin of Ice in the East is sat on a much lower bedrock, but it is protected by a higher wall of rock around the fringe. Therefore, the glacier will remain untouched for longer, but once this protective wall is breached, and the warm sea water pours in, the collapse will be extremely rapid.

[22] DeConto, R.M., Pollard, D., Alley, R.B. *et al.* The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* **593,** 83–89 (2021)

[23] Morlighem, M. et al. Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nat. Geosci*. **13**, 132–137 (2020)

technology with astonishing capacity and scale to transform the planet. This has made it much more demanding to develop the reliable models.

Chaotic Change

And so, finally, to a third type of change. This kind of change is not linear, nor is it exponential. It is of a different order all together. It is chaotic change.

As stated in the opening section – we have inherited a climate system that is predictable and stable. We have a habitat whose longstanding rhythms have made it possible for us to advance our economic plans with such remarkable success. This stability is extensively understood by scientists and the latest climate research has also provided us with a reliable map for what lies ahead at different levels of temperature rise.

However, all of this understanding must be tempered by one hugely important background truth about dynamic systems. At it is most simple, chaotic change is a reality that can be understood without much trouble: if we were to observe two children throwing a message in a bottle off the back of a ship, it is not that difficult to foresee that the bottles could easily end up on beaches located in entirely different continents. As the ancient Greek philosopher Aristotle noted, "the least initial deviation from the truth is multiplied later a thousandfold".[24]

Our understanding of chaotic change, rather appropriately, suddenly jumped forward by accident in 1961.

On a cold winters' day in January of that year, Edward Lorenz, a leading mathematician and meteorologist, was sat at his work in MIT. Given his interest in these two fields, and his position at a leading university, it is not surprising to note that he could be found feeding 12 weather data sets into his LGP-30 (one of the earliest digital computers made by Royal Bee). Lorenz was working on advanced dynamic modelling systems to predict the weather.

He then went for a coffee, whilst the computer chewed over the numbers.

Whilst he was away from his desk a major moment in 20th century science happened[25].

Upon returning to his desk, an hour later, he saw that the LGP-30 had produced weather predictions that were seriously odd. The 2 months of modelling time inside the computer's head had finished with predictions of temperatures and rainfall patterns never seen on the planet before. It was not a technical failure, nor a failure of the underlying mathematical models. The uncomfortable truth was that Lorenz had simply made one tiny change in the data – at the fourth decimal place. Instead of inputting the figures to 6 decimal places and typing in "0.506127", he had rounded it down to "0.506". It demonstrated that tiny changes could result in the whole system jumping into a radically different state.

[24] Aristotle, "On the Heavens" (271b8)

[25] E. N. Lorenz, *The Essence of Chaos*, U. Washington Press, Seattle (1993), page 134

It was a shock to see that the climate system was perhaps not the stable, self-regulating world that people imagined. The sheer number of interconnecting cogs in the atmosphere and biosphere, cogs both massive and (pertinently here) miniscule, meant that such unpredictable results were possible.

It would come to be known as "The Butterfly Effect", after the title of Lorenz's lecture, "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas? [26] This new understanding of the underbelly of reality would have a formative impact a huge range of studies, from Physics, Biology and Sociology.[27] [28] Just because a system obeys certain laws, it does not mean that the outcome of an action can be predicted. This reality of this kind of change, chaotic change, does not mean that everything which happens in a system occurs by chance; the governing laws of physics and chemistry remain in operation, as do the laws of cause and effect. It is simply that small changes in dynamic systems can lead to drastic changes in results.

As Lorenz himself summarised, "When the present determines the future, but the approximate present does not approximately determine the future".[29]

Since the 1960s, all of the modelling involved in climate science has had the reality of the "Butterfly Effect" in the background. Chaos Theory adds to the jeopardy involved in our interference in the climate system. We were so fortunate to have inherited a climate that was so deeply entrenched in an equilibrium, but by rocking the boat so violently, we really do open up so many more pathways for the future to play out in radically different climatic scenarios.

To return one last time to the velodrome, the sudden spasmodic nature of the rise in greenhouse gases that we have caused is comparable to increasing the number of riders in the race. In such a situation, the chances of any one bike on the track becoming destabilized is much more likely - and therefore the probability that a major crash will happen is also increased.

Indeed, given that we are also trashing the planet in so many other ways at the same time, the risks are even more accentuated. The Anthropocene is a full-on assault on nature. The risk that a "3°C" rise will destabilise the Amazon rainforest is a risk that is seriously amplified by brutish deforestation and rampant bio-diversity loss. If we think about our overcrowded race track now, we might also imagine that we gave the riders several pints of beer to drink before they mounted their bikes.

This chapter is not claiming that these factors are not included already in the modelling done by advanced scientific research. All these layers to the climate crisis scenarios are well understood and accounted for in the peer reviewed papers. The point of these additional

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[26] Professor Lorenz lecture in MIT, December 1972, at the American Association for the Advancement of Science, 139th Meeting.

[27] Emmanuel Kerry commented, "By showing that certain deterministic systems have formal predictability limits, Ed[ward] put the last nail in the coffin of the Cartesian universe and fomented what some have called the third scientific revolution of the 20th century, following on the heels of relativity and quantum physics".

[28] It even turned out to have some very practical applications too – such as the analysis of football crowd movements in a stadium R.H. Leverone, "Crowds as complex adaptive systems: Strategic implications for law enforcement" (2016).

[29] Einstein commented, "As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality" (Sidelights on Relativity, 1920).

qualifications to the main thrust of this text, is to provide a fuller understanding of the situation we are in.

The truth about what lies ahead is well understood. Science has repeatedly advised us to not advance global warming, every increment increases risk. Now, having pushed the global temperature up by an average 1.2°C, the final lines in the sand have been drawn. We must absolutely not cross the 2°C threshold, and remain as close to 1.5°C as possible.

Conclusion

How little things can make a big difference

Ozone

Prof. Paul Crutzen understood the dangers of entering into a minefield of tipping points. He knew what he was talking about. His work, "in atmospheric chemistry, particularly concerning the formation and decomposition of ozone" was recognized by the Nobel committee who awarded him the prize for Chemistry in 1995.[30]

In 1976, Crutzen and his colleagues had discovered the rapidly depleting ozone layer; a set of observations that led to swift political action: the agreement of the Montreal Protocol (1987) just 11 years later.

Before his death in 2021, Crutzen frequently spoke out about the wider dangers of 'The Anthropocene'. His groundbreaking work on the ozone layer had highlighted a critical lesson – a lesson about unforeseen consequences.

Crutzen noted that humans had been extremely lucky with the fate of the ozone layer. Our global, industrial scale use of fluorocarbons had taken us close to the edge of an environmental catastrophe. The radical thinning of the ozone layer in the stratosphere had allowed the widespread invasion of ultra violet radiation (UV) through to the surface of the Earth over Antarctica. Although ozone (O_3) molecules only make up 0.00006% of the atmosphere, they stop 98% of the damaging UVB (and UVA) light penetrating and mangling up the DNA of living organisms. Although it is still damaged, with proper enforcement of the Montreal Protocol the ozone layer will eventually recover.

But here is the twist.

Our near-miss with the forces of nature was even closer and much more dramatic than most people think.

In the earliest days of engineering with fluorocarbons, a choice was made to use chlorofluorocarbons (CFCs), and not their close relative, Bromofluorocarbons (BFCs). The

[30] Shared with Maro Molina and Frank Sherwood Roland.

chemical engineers making that decision did so on the basis of the different profiles of the substances relevant for manufacturing various products (such as fridges and aerosols).

Unknowingly, we took the right choice for the stratosphere and avoided an absolutely catastrophic scenario. CFCs did damage the ozone layer, however, the much more aggressive BFCs would have blown an "ozone hole" in the stratosphere so big, and so fast, that we would have had almost no chance of knowing the damage we were causing until it was far too late.

We threw the dice without really understanding what was at stake. We got lucky, but this example should act as an important lesson in modesty.

Algae

Indeed, it is rather demanding to keep a proper eye on all the key variables involved in climate change. The climate modelling of the cryosphere was significantly revised in 2012 when the widespread formation of algae in the polar regions was studied in depth and under the new conditions of rapid global warming. The problem with algae in the arctic is that it is far darker than ocean ice (0.50-0.70 albedo value[31]) or fresh snow (0.8 albedo value). This darkness traps heat, which accelerates the warming, which encourages algae growth… and so on[32].

It is not that scientists were not aware of the dangers of algal growth and new, low albedo values in the polar regions, but the effects of photosynthetic organisms "had largely been ignored since early pioneering work".[33] An Abstract of further research states in its opening lines, "Some ecosystems can undergo abrupt transformation in response to relatively small environmental change. Identifying imminent 'tipping points' is crucial for biodiversity conservation, particularly in the face of climate change. Here, we describe a tipping point mechanism likely to induce widespread regime shifts in polar ecosystems."[34]

Little things can have a big impact, just talk to Scrat, the long-suffering Saber-tooth squirrel. His clumsy quest for the nut features that start of every Ice Age film – and he suffers relentlessly from the consequences of the tipping point that he triggers.

Take care!

Given the fact that such small junctions in dynamic systems can lead to such wild results, it would be prudent to write our climate policies with the "precautionary principle" in the foreground, not the distant background.[35] This principle could be summarized as "informed

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[31] An albedo value of "1" indicates that a surface is a "perfect reflector", and albedo value of "0" indicates that a surface is a "perfect absorber".

[32] Just as the Jet Stream feeds off the temperature gradients between the equator and the poles, the Gulf Stream is powered by rising and sinking waters due to temperature and salinity differences. Changes to ocean temperatures will therefore alter circulation regimes. These feedbacks are monumental in scale compared to the tiny little algae that can trigger them.

[33] Yallop, M., Anesio, A., Perkins, R. *et al.* Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet. *ISME J* **6,** 2302–2313 (2012).

[34] "Light driven tipping points in the polar system" Global Change Biology (2013), doi: 10.1111/gcb.12337

[35] This principle is the basis of European Environmental law – even if the EU still has climate policies that do not go far enough.

prudence".[36] Under the precautionary principle, it is those who carry out the action who have the burden of demonstrating that it will not result in damage or harm. Such a framing of economic growth and development cuts against some psychological instincts that we have to push boundaries and take risks.

In the velodrome, everything is simply geared for maximum speed. The bikes in indoor racing have no brakes. The sport demands maximum aerodynamic efficiency, and maximum speed is the goal to which everything else must be sacrificed. Likewise, the demands of the industrial economy have no other priority than profit and growth maximization. All other costs and concerns are external to this, and so long as the threat to these priorities can be pushed to the side, they will be. It is utterly unsurprising that we would find ourselves close to pushing nature over a tipping point. As stated at the beginning of the chapter, there was little reason to imagine that humans could actually have any significant print on the fundamental operating systems of the planet. Why would we need any brakes on economic growth? Why would we need to think about planetary boundaries?

However, in the end, this is where we are. "Informed prudence" might not be a catchy advertising slogan, but when the effects of a false step might be so crunchingly negative and irreversible it is hard to argue against it. At the end of the day, tipping points are the most fundamental threat posed to us by climate change. Sustaining prosperous, fulfilling and less material economic growth at a safe distance from these thresholds is the defining challenge of our time.

[36] Or more fully, "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically". (https://pubmed.ncbi.nlm.nih.gov/15968832/)