DISCUSSION PAPER

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Faster, Higher, Hotter

What we learned about the climate system in 2022

MARCH 2023

Breakthrough - National Centre for Climate Restoration | breakthroughonline.org.au

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Published by
Breakthrough - National Centre for Climate Restoration
Melbourne, Australia
breakthroughonline.org.au
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March 2023

Beyond all the hype and all the anxiety about climate policymaking, the upbeat newsmaking about energy transitions and the growing dread of civilisational collapse, what have we learned about the climate system in the last year? Here are some key observations drawn from research and data published in 2022.

SUMMARY

- Annual greenhouse emissions continue to increase, and may not peak till late this decade.
- Warming will trend past 1.5˚C around the end of this decade, regardless of the emissions path.
- Scenarios of overshooting and cooling back to 1.5˚C by 2100 scenario are largely based on speculative assumptions.
- The world is currently on a path to reach 2˚C of warming around mid-century.
- 2˚C degrees is not a point of system stability, but a signpost on a road to a hotter planet.
- We are heading towards 3˚C or more when likely system feedbacks and cascades are taken into account.
- System-level change and tipping points are happening faster than forecast , with a number of crucial climate system elements already passed tipping at the current 1.2˚C of warming.
- Risks are cascading, non-linear and underestimated; prudent risk management requires consideration of the bad-to-worst-case scenarios.
- Cooling the planet is vital if vital if Earth is to be kept below a level of warming where more system tipping points are activated and cascade into an avalanche of warming and system feedbacks that human actions will no longer have the capacity to rein in.

RECORD EMISSIONS

Covid supply-chain disruption and the war in Ukraine have distracted from the task of rapid emissions reductions and contributed to inflation, falling real wages and a political focus on cost-of-living pressures. The war has disrupted energy markets, driven a return to coal[1] whose use is at an all-time high, prompted an increase in emissions-intensive arms production and use, and become an excuse for governments to delay climate action.

Atmospheric levels of all three main greenhouse gases reached record highs in 2022.[2] Carbon Monitor reported emissions data for full year 2022 as: "Global CO_2 (carbon dioxide) increased by +1.6% in 2022 (+8.0% than 2020, and +2.1% than 2019)",[3] an all-time record. In November 2022, the Global Carbon Project had estimated carbon emissions from fossil fuels in 2022 would reach 37.5 billion tons of carbon dioxide, the highest ever recorded.[4] The latest International Energy Agency (IEA) projections show that global carbon emissions from energy are still growing and may peak in 2025, but are likely to plateau at a high level after that for a decade or more, rather than decline in any significant manner.[5]

Likewise, the UNFCCC estimated that total global greenhouse emissions, taking into account implementation of the latest commitments by nations, would in 2030 be "50.8% higher than in 1990, 10.6% higher than in 2010, and 0.3% lower than in 2019, as well as 1.9% lower than the estimated level for 2025, indicating the possibility of global emissions peaking before 2030".[6] Note that in this statement, emissions peaking by 2030 is judged a "possibility," not a high probability.

[1] https://www.washingtonpost.com/climate-environment/2022/12/05/carbon-emissions-peak-record-2022/

[2] https://www.theguardian.com/environment/2022/oct/26/atmospheric-levels-greenhouse-gases-record-high

[3] https://twitter.com/LiuzhuLiu/status/1618634495758065664

[4] https://www.washingtonpost.com/climate-environment/2022/12/05/carbon-emissions-peak-record-2022/

[5] https://www.theguardian.com/environment/2022/oct/27/carbon-emissions-to-peak-in-2025-in-historic-turning-point-says-iea

[6] https://unfccc.int/sites/default/files/resource/cma2022_04.pdf

THE 1.5˚C TARGET

The warming trend will reach 1.5˚C around 2030, irrespective of any emission reduction initiatives taken in the meantime, according to the IPCC's Sixth Assessment Working Group 1 *Summary for policy-makers* (Table SPM.1); and the UN Environment Program said there is no longer a credible path to holding warming below 1.5˚C in the short term[7] (without deploying immediate cooling interventions, which are nowhere on the policymaking agenda).

Prof. Bill McGuire says "continuing to argue for the viability of 1.5˚C is misleading and raises false hopes",[8] and *The Economist* editorialised that "the world is going to miss the totemic 1.5˚C climate target".[9]

Matthews and Wynes concluded that human activities have caused global temperatures to increase by 1.25˚C and "the current emissions trajectory suggests that we will exceed 1.5˚C in less than 10 years".[10]

In 2022, Prof. Will Steffen wrote that "the only reasonable conclusion… is that the lower Paris target of 1.5˚C is now out of reach… past inaction, and in particular, failure to begin significant emission reductions before 2020, have cost us dearly".[11] And Australian scientists said that:

> The latest science, viewed alongside continuing increases in global greenhouse gas emissions, suggests that limiting warming to 1.5˚C is now almost certainly infeasible. It would now require not only rapid emission reductions, but also the large-scale removal of carbon dioxide from the atmosphere. There is no evidence that this can be achieved at sufficient scale to meet the 1.5˚C target.[12]

OVERSHOOTING AND COOLING BACK 1.5˚C

Most policy talk about achieving the 1.5˚C target is somewhat a sleight-of-hand; it is actually about "overshooting", in which the temperature exceeds 1.5˚C, perhaps significantly and for several decades, with carbon drawdown helping reduce atmospheric greenhouse gas and temperature levels back to 1.5˚C in the latter part of the century.

The *Washington Post* reported on work which examined 1200 future emission paths, and found that only 112 get warming back down to 1.5˚C or less by 2100, once unrealistic near-term emission reduction assumptions are excluded.[13] [As noted above, greenhouse emissions are still increasing,not reducing.] Of the 112 paths, 86 were identified as "high" overshoot which involve "spending decades above 1.5˚C" which is "an unsettling prospect" because "it raises the possibility, for instance, of the world experiencing dangerous tipping points and even calamities such as the irreversible loss of the West Antarctic ice sheet".

[In fact there is convincing evidence that several such tipping points have already been passed,[14] and scientists have warned that warming in the 1.5–2˚C range risks "a cascade of feedbacks could push the Earth System irreversibly onto a 'Hothouse Earth' pathway".[15]]

The 26 "low" overshoot scenarios remaining have varying assumptions about the level of technological development of carbon drawdown methods. The Potsdam Institute has characterised such technology use as having "speculative," "challenging" or "reasonable" assumptions. When those 26 scenarios remaining were assessed under the "reasonable category" for all the five main drawdown methods — carbon capture and storage, land-based removal, carbon intensity, energy demand and less methane — no path was left. If, instead, technologies identified as "challenging" are considered, there are 11 scenarios available of the 1200 examined. What makes these 11 scenarios work? The *Post* reported:

[7] https://wedocs.unep.org/bitstream/handle/20.500.11822/40874/EGR2022.pdf

[8] https://www.theguardian.com/commentisfree/2022/nov/12/climate-target-cop27-breakdown-fossil-fuel

[9] https://www.economist.com/interactive/briefing/2022/11/05/the-world-is-going-to-miss-the-totemic-1-5c-climate-target

[10] https://www.science.org/doi/10.1126/science.abo3378

[11] https://link.springer.com/book/10.1007/978-3-030-78795-0

[12] https://climateextremes.org.au/briefing-note-15-can-we-limit-global-warming-to-1-5c/

[13] https://www.washingtonpost.com/climate-environment/interactive/2022/global-warming-1-5-celsius-scenarios/

[14] https://www.breakthroughonline.org.au/climatedominoes

[15] https://www.pnas.org/doi/10.1073/pnas.1810141115

> One common theme is much more dramatic carbon removal from the atmosphere, storing it either underground or in forests and agricultural landscapes. The majority of these scenarios require us to be able to subtract over seven billion tons per year from the atmosphere by 2050. This will require a huge scale up of interventions like carbon capture and storage, which only has an estimated capacity of about 43 million tons per year today. Capacity has roughly doubled in the past decade, but a far faster pace of change would be needed to achieve this outcome.[16]

LIKELIHOOD OF ACHIEVING THE 2°C TARGET

As noted above, the IEA has reported that emissions from energy may peak in 2025, but are likely to then plateau at a high level after that for a decade or more. And *The Economist* reported that emissions slashed today won't slow warming until mid-century.[17]

To keep warming to 2°C means achieving a 50% reduction in global emissions by 2030 according to the "carbon law" proposed in 2017[18] which, on the basis of equity, means zero emissions by 2030 for high-per-capita emitting nations.[19] Clearly, given the emissions data and projections, the world is not going to get anywhere near this. Current models, reported in the 2021 IPCC report, project around 0.3°C warming between 2020 and 2030, and more than 2°C by mid-century for the medium- and high-emissions scenario paths that the world is currently on. Current climate models show that the Earth likely will reach 2°C of global warming by the 2040s without significant policy changes.[20]

Significant players including big oil are back-tracking on previous emission reduction commitments,[21] whilst central bankers express scepticism about having a climate role to play.[22]

"Global warming of at least 2°C is now baked into Earth's future," wrote former NASA climate chief James Hansen in a memo co-authored with Makiko Sato and Pushker A Karecha: "That level of warmth will occur by mid-century."[23] And there are warnings that the rate of global warming over the next 25 years could be double what it was in the previous 50 years, in part due to the aerosol "Faustian bargain".[24]

[Short-lived atmospheric sulfate aerosols are a by-product of burning fossil fuel and have a cooling effect which has been masking up to 1°C of global warming. Reduced emissions of greenhouse gases and clean air policies will also reduce this aerosol cooling, so there is little prospect that decarbonisation policies will significantly bend down the temperature curve over the next two decades.[25]]

In addition, the paleoclimate evidence is that the last time CO_2 levels were similar to today, there were sea level fluctuations of 20-40 metres associated with global temperature variations between today's temperature and 3°C warmer.[26]

It should be noted here that 2°C is not a reasonable target. In a chapter in a book published in 2022, Steffen pointed out that even the current level of warming is dangerous:

> It is clear from observations of climate change-related impacts in Australia alone – the massive bushfires of the 2019–2020 Black Summer; the third mass bleaching of the Great Barrier Reef in only five years; and long-term cool-season drying of the country's southeast agricultural zone – that even a 1.1 °C temperature rise has put us into a dangerous level of climate change.[27]

[16] https://www.washingtonpost.com/climate-environment/interactive/2022/global-warming-1-5-celsius-scenarios/

[17] https://www.economist.com/science-and-technology/2020/07/11/emissions-slashed-today-wont-slow-warming-until-mid-century

[18] https://www.science.org/doi/abs/10.1126/science.aah3443

[19] https://theecologist.org/2020/jun/08/beyond-climate-comfortable-ignorance

[20] https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022EF003330

[21] https://www.bloomberg.com/news/articles/2023-02-08/in-the-struggle-for-big-oil-s-soul-the-american-vision-wins-out

[22] https://www.cnbc.com/2023/01/11/major-central-bankers-dispute-role-in-tackling-climate-change-as-they-battle-inflation.html

[23] http://www.columbia.edu/~jeh1/mailings/2021/NovemberTUpdate+BigClimateShort.23December2021.pdf

[24] http://www.columbia.edu/~mhs119/Temperature/Emails/July2021.pdf

[25] https://www.nature.com/articles/s41467-020-17001-1.

[26] https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0294

[27] https://link.springer.com/book/10.1007/978-3-030-78795-0

2°C DEGREES IS NOT A POINT OF SYSTEM STABILITY

Even sharp reductions in emissions will not be enough to avoid crossing the 1.5°C threshold, nor the 2°C threshold, given the record-breaking use of fossil fuels in 2022 and the forecasts.[28]

Yet it is a big mistake to think we can stabilise or "park" the Earth System at around 2°C and expect it to stay there, says Steffen.[29] Earth's climate history shows 2°C is not a point of system stability, but a signpost on a road to a hotter planet. When projections in late 2021 showed future warming of around 2.7°C, Potsdam Institute Director Johan Rockström responded: "I barely even want to talk about 2.7°C… If we go beyond 2°C, it's very likely that we have caused so many tipping points that you have probably added another degree just through self-reinforcing changes. And that's without even talking about extreme events." [30]

Similarly Hans Joachim Schellnhuber told an audience: "If the [climate system] tipping elements interact and cascades develop, then the heating could become independent [i.e. self sustaining] at 2°C. Whether that is the case is perhaps the most important question of science right now because it would mean the end of our civilisation."[31]

Earlier, in a landmark paper, scientists had pointed to "biosphere tipping points which can trigger abrupt carbon release back to the atmosphere.. Permafrost across the Arctic is beginning to irreversibly thaw and release carbon dioxide and methane… the boreal forest in the subarctic is increasingly vulnerable" and concluded that "other tipping points could be triggered at low levels of global warming… a cluster of abrupt shifts between 1.5°C and 2°C…"[32]

WE ARE HEADING TOWARDS 3°C OR MORE

With emissions peaking by 2030 only a possibility, and future emission reductions likely far from those needed to hold warming to 2°C, and with self-reinforcing warming already in play, it is clear the world is now heading towards 3°C, or perhaps more, warming. [Some models suggest a little less than 3°C, but these are not able to quantify all relevant mechanisms, feedbacks, cascades and non-linearities.]

In December 2022, in "World Scientists' Warning of a Climate Emergency 2022", a group of 12 scientists concluded that "current policies are taking the planet to around 3°C warming by 2100, a temperature level that Earth has not experienced over the past three million years. The consequences of global heating are becoming increasingly extreme, and outcomes such as global societal collapse are plausible and dangerously underexplored."[33] In November 2021, Nature journal reported on a survey which found that six in ten climate scientists expect the world to warm by at least 3°C by the end of the century.[34]

US security analysts say 3°C could result in a world of "outright chaos".[35] Chatham House's scenario in its *Climate Change RIsk Assessment 2021* had a mean warming of 2.7°C, and a plausible worst-case scenario of warming greater than 3.5°C.[36] The assessment warned that the world is "dangerously off track" to meet the Paris Agreement goals, that the risks are compounding, and that "without immediate action the impacts will be devastating" in the coming decades, especially for food security. The report concluded that impacts likely to be locked in for the period 2040–2050 unless emissions rapidly decline include a global average 30% drop in crop yields by 2050, and that more severe and extensive droughts will contribute to cascading climate impacts that will "drive political instability and greater national insecurity, and fuel regional and international conflict".[37]

[28] https://www.reuters.com/business/energy/emissions-set-rise-with-global-power-demand-iea-2022-01-14/

[29] https://www.theguardian.com/environment/planet-oz/2018/oct/06/earths-climate-monsters-could-be-unleashed-as-temperatures-rise

[30] https://www.forbes.com/sites/davidrvetter/2021/10/22/with-one-week-till-cop26-climate-talks-experts-set-out-whats-at-stake

[31] https://twitter.com/Jumpsteady/status/1194667496625836032

[32] https://www.nature.com/articles/d41586-019-03595-0

[33] https://academic.oup.com/bioscience/article/72/12/1149/6764747

[34] https://www.nature.com/articles/d41586-021-02990-w

[35] www.csis.org/analysis/age-consequences, accessed 22 December 2022.

[36] https://www.chathamhouse.org/2021/09/climate-change-risk-assessment-2021.

[37] https://www.chathamhouse.org/2021/09/climate-change-risk-assessment-2021.

SYSTEM-LEVEL CHANGE AND TIPPING POINTS ARE HAPPENING FASTER THAN FORECAST

Major elements of Earth's climate system are now increasingly influenced by self-reinforcing warming processes — or positive feedbacks — due to climate change caused by human greenhouse gas emissions. A "tipping point" or critical threshold exists where a small change causes a larger, more critical change to be initiated, taking components of the Earth system from one state to a discreetly different state.

Tipping point thresholds for the Arctic, Greenland, West Antarctica and coral systems, and for land sinks such as eastern Amazonia, have been reached before or at the current level of warming of 1.2˚C. An overview of the key research on tipping points may be found in the 2022 *Climate Dominoes* survey.[38]

And in September 2022, McKay et al. concluded that even global warming of 1˚C, a threshold that we have passed already, puts us at risk by triggering some tipping points.[39] New evidence on tipping points presented in 2022 includes:

- **East Antarctica:** Denman Glacier, in Australia's Antarctic Territory, was identified in 2022 as susceptible to collapse of its ice shelf and inundation of the glacier itself, which sits on a retrograde (below sea level) base: "The Denman Glacier is potentially at risk of unstable retreat triggered by transport of warm water to the ice shelf cavity."[40] In 2020, the *Washington Post* had reported NASA scientist Virginia Brancato as saying: "If I have to look at East Antarctica as a whole, this [Denman Glacier] is the most vulnerable spot in the area."[41]
- **West Antarctica**: On 13 December 2021, scientists announced that the Thwaites Glacier ice shelf in the Amundsen Sea area was fracturing and is likely to break apart in the next five years or so, resulting in a speeding up of the glacier's flow and ice discharge, possibly heralding the collapse of the glacier itself, and triggering similar increases across the Amundsen Sea glaciers; "the final collapse of Thwaites Glacier's last remaining ice shelf may be initiated… within as little as five years" (emphasis added).[42] A 2022 study showed that the the Pope, Smith and Kohler glaciers in the Amundsen Sea embayment of West Antarctica have experienced enhanced ocean-induced ice-shelf melt, glacier acceleration, ice thinning and grounding-line retreat coincident with high melt rates of ungrounded ice in the past 30 years. The retreat rates are faster than anticipated by numerical models.[43] The *State of the Cryosphere* report, released in November 2022, concluded that more than four metres of additional sea level rise was locked in "with sections of the West Antarctic ice sheet potentially collapsing even without any further emissions over the coming centuries".[44] And in work just published, an ingenious look at the genetic history of Turquet's octopus, to establish when different populations were moving and mixing together across Antarctica in past warm periods, led researchers to conclude that "even under global heating of 1.5˚C – the most ambitious goal under the global Paris climate agreement – the West Antarctic Ice Sheet could be consigned to collapse".[45]
- **Greenland**: In late 2022, scientists reported that Greenland Ice Sheet (GIS) glaciers are melting 100 times faster than previously calculated, according to a new model that takes into account the unique interaction between ice and water at the island's fjords,[46] whilst in August researchers showed that the Arctic has warmed nearly four times faster than the globe since 1979 and concluded it is likely climate models systematically tend to under-estimate this amplification.[47] A number of feedback mechanisms are driving ice-mass loss, including algal blooms darkening ice, the change in reflectivity resulting in greater heat absorption and enhanced melting of the surface ice by as much as 20%: "Ice algae have started to colonise larger parts of Greenland. They've become an x-factor in the

[38] https://www.breakthroughonline.org.au/climatedominoes

[39] https://www.science.org/doi/10.1126/science.abn7950

[40] https://doi.org/10.1029/2022GL100460

[41] https://www.washingtonpost.com/climate-environment/2020/03/23/denman-glacier-climate-change/

[42] https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/978762

[43] https://www.nature.com/articles/s41561-021-00877-z

[44] https://www.theguardian.com/environment/2022/nov/07/melting-arctic-sea-ice-summer-report

[45] https://www.theguardian.com/world/2023/feb/05/clue-to-rising-sea-levels-lies-in-dna-of-4m-year-old-octopus-scientists-say

[46] https://www.livescience.com/greenland-glacier-melt-model

[47] https://www.nature.com/articles/s43247-022-00498-3

melting process," says Prof. Jason Box.[48] At the end of 2021, Box said that GIS has passed a tipping point/point of system viability: "Technically, now [at 1.2˚C] Greenland is beyond its viability threshold… 1.5˚C [of warming would] mean the 'beyond the threshold' state is enhanced and the loss [of ice mass] becomes a complex, non-linear, amplified response guaranteeing the ice sheet remains beyond its viability threshold. [We are documenting] several physical processes and amplifiers that guarantee more rapid response of the ice than is currently encoded in climate models that project sea-level rise… we cannot yet rely on ice sheets models for credible sea level projections."[49]

- **Permafrost:** Permafrost carbon emissions and the dangerous climate feedback loops they will set off are not accounted for in most Earth system models or Integrated Assessment Models, including those which informed the IPCC's special report on global warming of 1.5˚C, nor are they fully accounted for in global emissions budgets.[50] If carbon-cycle feedbacks are accounted for, "such as tipping points in forest ecosystems and abrupt permafrost thaw, the estimated remaining budget could disappear altogether".[51]
- **Sea levels:** Events at both poles are not properly incorporated into current climate models. The evidence suggests that sea-level rises this century will be greater than currently considered feasible by policymakers. Evidence from climate history suggests the current global average temperature increase is enough for 5–10 metres of sea-level rise in the longer term, inundating small island states, agriculturally rich alluvial deltas and vulnerable coastal cities.[52]
- **Amazon:** In ground-breaking research published in 2021, Katharyn Duffy and colleagues mapped the relationship between increasing temperatures and carbon uptake in Amazon forests by analyzing more than 20 years of data from 250 sites that measure the transfer of CO_2 between plants, land and the atmosphere. They found that in recent hot periods the thermal maximum for photosynthesis had been exceeded. The land sink is now approaching a tipping point, and the sink could halve in as soon as two decades: "We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photo-synthesis." Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040.[53]

[48] https://promice.org/2022/01/05/algae-blooms-i-never-saw- the-ice-as-dark-as-this

[49] https://www.youtube.com/watch?v=P6LrGetz10g

[50] https://www.pnas.org/doi/10.1073/pnas.2100163118

[51] https://www.pnas.org/doi/10.1073/pnas.2115218118

[52] https://climateextremes.org.au/briefing-note-15-can-we-limit-global-warming-to-1-5c

[53] https://www.science.org/doi/10.1126/sciadv.aay1052

RISKS ARE CASCADING, AND UNDERESTIMATED

Feedbacks can drive abrupt, non-linear change that is difficult to model and forecast, with the Earth moving to dramatically different conditions. Such changes may be irreversible on relevant time frames, such as the span of a few human generations. Major tipping points are interrelated and may cascade, so that interactions between them lower the critical temperature thresholds at which each tipping point is passed.

Climate models do not yet incorporate key processes, and therefore are deficient, especially when projecting abrupt change, system cascades, and changes in the cryosphere and in the carbon cycle. Whether it be permafrost, Greenland or West Antarctica (and hence sea-level rises), the story is the same. Current climate models are not capturing all the risks[54], such as the stalling of the Gulf Stream[55], polar ice melt[56] and the uptick in extreme weather events. Thus Earth system and Integrated Assessment Model projections, and their use in determining carbon budgets, are not reliable.[57] It is important that observations, semi-empirical models, expert elicitations, and lessons from past climates are given more weight, given current model deficiencies.

In addition, the range of extremes being experienced today are greater than forecast in many instances. Prof. Andy Pitman, Director of the ARC Centre of Excellence for Climate Extremes, notes that global mean warming is badly understood. He says that as a general rule of thumb, global average warming of 4˚C (covering land and ocean) is consistent with 6˚C over land, and 8˚C in the average warming over mid-latitude land. That risks 10˚C in the summer average, or perhaps 12˚C in heatwaves. Western Sydney has already reached 48˚C. If you add 12˚C to the 48˚C you get summer heatwaves of 60˚C.[58]

It is well established that a tipping point may be abrupt and irreversible on relevant time frames, possibly leading to cascading events, even driving the system towards a "Hothouse Earth".[59] In 2022, Will Steffen explained that:

> The current trajectory is accelerating the [Earth] system towards [a point of] bifurcation, with the increasing risk that our pressures will push the system onto the 'Hothouse Earth' trajectory. The critical point here is that there is a point beyond which we lose control of the system and its own internal feedbacks drive it past a global threshold and irreversibly into a much hotter state… [60]

In 2022, Wunderling et al. published "Global warming overshoots increase risks of climate tipping cascades in a network model", which found that overshooting climate targets could significantly increase risk for tipping cascades.[61] Wunderling explained: "Even if we would manage to limit global warming to 1.5˚C after an overshoot of more than 2˚C, this would not be enough as the risk of triggering one or more global tipping points would still be more than 50% percent. With more warming in the long-term, the risks increase dramatically." Jonathan Donges added: "To effectively prevent all tipping risks, the global mean temperature increase would need to be limited to no more than one degree – we are currently already at about 1.2˚C." [62]

Many cascades are well established, for example, Arctic sea-ice loss driving enhanced Greenland deglaciation, which contributes to a slowing of the AMOC, which in turn is decreasing rainfall over parts of the Amazon, and enhanced carbon losses.

Now new research establishes a link between climate changes in the Amazon and the Tibetan Plateau.[63] The researchers explain: "Our research confirms that Earth system tipping elements are indeed inter-linked even over long distances, and the Amazon is one key example how this could play out… When it's getting warmer in the Amazon, it also does so in Tibet, hence for temperature there's a positive correlation."[64]

The importance of a paper published last year by ten authors, including Will Steffen, cannot be underestimated in bringing together a high-level analysis on climate risks and the need for climate research to focus on the worse-case, high-end possibilities. The paper is "Climate Endgame: Exploring

[54] https://www.smh.com.au/environment/climate-change/how-lucky-do-you-feel-the-awful-risks-buried-in-the-ipcc-report- 20210811-p58hut.html

[55] https://www.nature.com/articles/s41558-021-01097-4

[56] https://www.washingtonpost.com/climate-environment/2021/01/25/ice-melt-quickens-greenland-glaciers/

[57] https://www.breakthroughonline.org.au/dor

[58] Pitman, A 2021, pers. comm, 6 June 2021

[59] https://www.pnas.org/doi/10.1073/pnas.1810141115

[60] https://link.springer.com/book/10.1007/978-3-030-78795-0

[61] https://www.nature.com/articles/s41558-022-01545-9

[62] https://www.eurekalert.org/news-releases/975019

[63] https://www.nature.com/articles/s41558-022-01558-4

[64] https://www.pik-potsdam.de/en/news/latest-news/amazon-heat-drives-tibet-temperatures-climate-tipping-elements-connected-half-around-the-globe

catastrophic climate change scenarios"[65] and its key findings include:

- "Prudent risk management requires consideration of the bad-to-worst-case scenarios" because low-probability, high-impact extreme outcomes have damages are so large, as to perhaps be unquantifiable. Large uncertainties about dangerous surprises "are reasons to prioritize rather than neglect them".
- "Climate damages are likely to be nonlinear" and result in an even larger risk tail, with feedbacks in the carbon cycle and potential tipping points that could generate high greenhouse concentrations that are often missing from models. There are even more uncertain feedbacks, which, in a very worst case, might amplify to an irreversible transition into a "Hothouse Earth" state including "recent simulations suggest that stratocumulus cloud decks might abruptly be lost at CO_2 concentrations that could be approached by the end of the century, causing an additional ~8 °C global warming. Large uncertainties about dangerous surprises are reasons to prioritize rather than neglect them."
- Declining emissions does not rule out extreme climate change due to feedbacks in the carbon cycle and potential tipping points that could generate high greenhouse concentrations that are often missing from models. Examples include Arctic permafrost thawing that releases methane and CO_2, carbon loss due to intense droughts and fires in the Amazon, and the apparent slowing of dampening feedbacks such as natural carbon sink capacity. These are likely to not be proportional to warming; instead, abrupt and/or irreversible changes may be triggered at a temperature threshold. Particularly worrying is a "tipping cascade" in which multiple tipping elements interact in such a way that tipping one threshold increases the likelihood of tipping another.

[65] https://www.pnas.org/doi/10.1073/pnas.2108146119

NEW CLIMATE EXTREMES RECORDED IN 2022

2022 was a big year for breaking record, extreme climate events,[66] including:

- Large parts of the northern hemisphere were exceptionally hot and dry. Record-breaking heat waves were observed in China, Europe, North and South America.
- Europe experienced its hottest summer ever recorded, with prolonged and intense heatwaves affecting western and northern Europe, and persistent low levels of rainfall leading to widespread drought conditions, and wildfires especially in Spain and Portugal.
- The United Kingdom saw off-the-chart temperatures, shattering records kept nearly as far back as William Shakespeare's time, with a new national record on 19 July when the temperature topped more than 40°C for the first time.
- In East Africa, rainfall has been below average in four consecutive wet seasons, the longest in 40 years.
- A large area around northern Argentina, southern Bolivia, central Chile, and most of Paraguay and Uruguay experienced record-breaking temperatures during two consecutive heatwaves in November–December 2022.
- Prolonged heatwave conditions affected Pakistan and northern India in spring. In May, temperature exceeded 50°C (122°F) in Jacobabad, Pakistan, and more than a billion people in South Asia endured several months of almost uninterrupted temperatures above 100°F.
- China had the most extensive and long-lasting heatwave since national records began and the second-driest summer on record. Heat waves and drought stretched over eight weeks and dried up parts of the Yangtze River to the lowest level since at least 1865.
- In July and August, Pakistan saw record-breaking rainfall leading to large-scale flooding over one-third of the country causing widespread destruction and loss of life, with at least 1700 deaths and 33 million people affected. 7.9 million people displaced.

[66] Sources:
https://public.wmo.int/en/media/news/climate-and-weather-extremes-2022-show-need-more-action;
https://climate.copernicus.eu/copernicus-2022-was-year-climate-extremes-record-high-temperatures-and-rising-concentrations

- At Vostok station, in the interior of East Antarctica, the reported temperature reached -17.7˚C, the warmest ever measured in its 65-year record.
- 2022 took an exceptionally heavy toll on glaciers in the European Alps, with initial indications of record-shattering melt.
- The Greenland ice sheet lost mass for the 26th consecutive year and it rained (rather than snowed) on the summit for the first time in September.

CONCLUSION

In summary, emissions still have not peaked and are unlikely to be significantly lower in 2030 than 2020; trend warming of 1.5˚C is likely this decade; the emissions trend and reduction commitments are nowhere near keeping warming to 2˚C; and once the full range of feedbacks, non-linearities and cascades are taking into account, warming may well exceed 3˚C this century, a level of warming that will likely result in climate-driven collapse of ecological and social systems. The contradiction is stark: the world will sail past 1.5˚C, but 1.5˚C may be enough to trigger 'Hothouse Earth' cascades; indeed, it is evident that some tipping points have already been passed, and some cascading events are occurring already.

So what to do? Last year, in the concluding section of *Climate Dominoes*, I wrote the following. It seems just as apt today:

> Decarbonisation is not enough. Even sharp reductions in emissions will not be enough to avoid crossing the 1.5˚C threshold, and very likely the 2˚C threshold, given record-breaking use of fossil fuels. It is a big mistake to think we can "park" the Earth System at any given temperature rise – say 2˚C – and expect it to stay there. 2˚C may not be a point of system stability. Reducing the level of atmospheric CO_2 by carbon drawdown is vital, but the drawdown impact is relatively slow. The more damaging impacts, and risk of triggering non-linear events — associated with a higher level of warming for several decades in overshoot scenarios — are understated or ignored. The need to cool the planet in order to avoid cascade/collapse/ "Hothouse" scenarios needs to be taken seriously. There are proposals for more direct cooling of threatened systems — as advocated, for example, by the Climate Crisis Advisory Group and the Cambridge Centre for Climate Repair for the Arctic with marine cloud brightening — or of the planet as a whole, whether by mirrors or sulfates. Whilst not yet proven to be of net benefit, and/or cost effective, such proposals seem vital if Earth is to be kept below a level of warming where more system tipping points are activated and cascade into an avalanche of warming and system feedbacks that human actions will no longer have the capacity to rein in.[67]

[67] https://www.breakthroughonline.org.au/climatedominoes