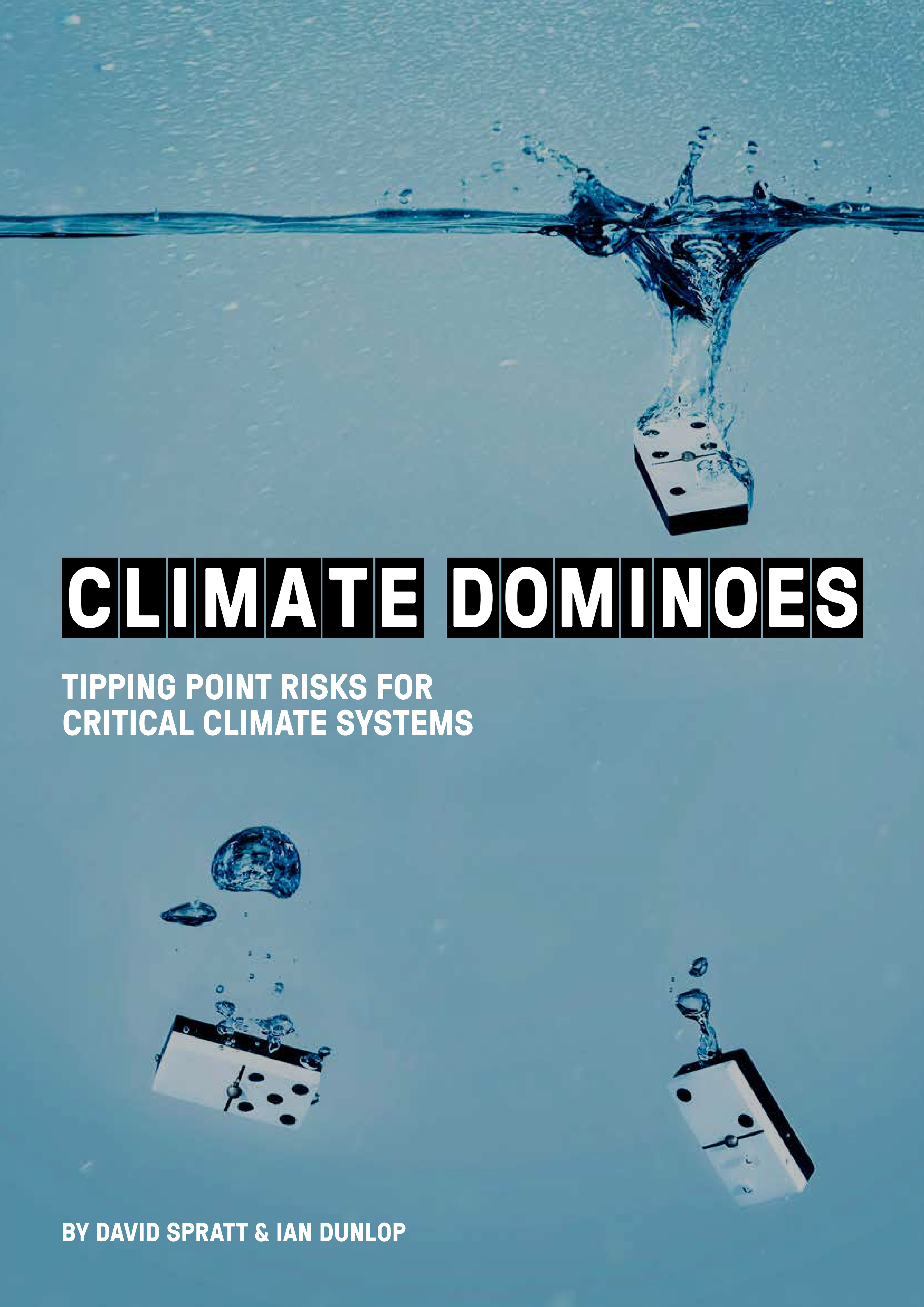

CLIMATE DOMINOES

TIPPING POINT RISKS FOR CRITICAL CLIMATE SYSTEMS

BY DAVID SPRATT & IAN DUNLOP

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FOREWORD

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Reports are the most important assessment of humanity's future on Earth to date. Never before have we had so much scientific evidence to demonstrate that we are in the midst of a global climate emergency.

The February 2022 impacts report serves as a stark warning that humanity's chances of outrunning the devastating impacts of climate change are uncomfortably low. As Co-chair Hans-Otto Portner stated: "The scientific evidence is unequivocal; climate change is a threat to human-wellbeing and the health of the planet. Any further delay in concerted global action will miss a brief and rapidly closing window to secure a liveable future."

And yet there is a blind-spot in the IPCC analysis, in that the severity of human influence on our planetary ecosystems is leading us toward a range of irreversible tipping points; uncertainties about which we have limited knowledge. The first of these, in the Arctic Circle region, appears already to have tipped, leading to the series of devastating extreme weather events around the Northern Hemisphere last summer.

This blind-spot is the subject of Breakthrough's latest *Climate Dominoes* report, which is a critically important analysis of the state of the world today and the immediate threat to our global economic systems from these tipping points. It is a sober call for all countries to follow a critical analysis pathway for dealing with climate change as the emergency that it is. It should be read and acted on by governments and their advisors, by the financial communities of the world, and by scientists, engineers, social scientists and philosophers. Precautionary action is needed now to avoid, to the extent possible, further tipping points being triggered.

This is a code red situation. No government is taking it seriously enough. We must urgently seek productive collaboration between sub-national, national, and international bodies to do more to combat climate issues equitably, with determination and speed.

Professor Sir David King FRS

Founder, Centre for Climate Repair, University of Cambridge

Chair, Climate Crisis Advisory Group

Former UK Chief Scientific Advisor and Special Envoy on Climate Change.

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AT A GLANCE...

- 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, mainly from burning fossil fuels. A "tipping point" or critical threshold may be reached, such that 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.
- 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.
- Research released in December 2021 has provided new evidence that West Antarctica's Thwaites Glacier has passed a tipping point for abrupt change, likely triggering a cascade of similar events on the peninsula. The Arctic, warming at four times the planetary average, is undergoing abrupt change, including on the Greenland Ice Sheet, which has passed a point of system stability.
- These 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 5–9 metres of sea-level rise in the longer term, inundating small island states, agriculturally rich alluvial deltas and vulnerable coastal cities.
- The land-based carbon stores are reaching a critical point, after which their efficiency decreases. There is considerable evidence that eastern Amazonia has "tipped" and is now a net source of carbon.
- Coral reefs are now bleaching so frequently that there is no longer sufficient natural recovery time between bleaching events so that they have entered a death cycle.
- A number of other climate systems, including some ocean and atmospheric circulatory systems, and northern hemisphere permafrost stores, are undergoing significant change, but there is not the knowledge to determine how close to "tipping" they may be.
- Tipping points thresholds identified for the Arctic, Greenland, West Antarctica and coral systems, and for land sinks such as easterm Amazonia, have been reached before or at the current level of warming of 1.2°C.
- The 1.5–2°C target range of the 2015 Paris climate agreement is demonstrably not a safe or appropriate goal for policymakers and advocates concerned about protecting the most climate vulnerable, and requires a major rethink about advocacy goals and what is possible and necessary to achieve them.

INTRODUCTION

Catastrophic and extreme climate events and new research findings make arresting headlines: "'The fuse has been blown, and the doomsday glacier is coming for us all", was the dramatic lead for Jeff Goodell's story in the December 2021 issue of *Rolling Stone* about just-released research on the fragility of Antarctica's Thwaites Glacier.

This new research shows that the West Antarctic glacial system has passed its tipping point for abrupt change, likely triggering a cascade of similar events on the Antarctic peninsula. And this at the current global average warming of 1.2°C, compared to the late nineteenth century.

Behind that headline is a question that goes to the heart of climate policy-making and advocacy: given that climate system tipping points are tumbling today, is limiting warming to 1.5°C safe for humanity?

As this report documents, Antarctica is not an isolated case. Similar stories are unfolding across Greenland and the Arctic, in forests and the Amazon, and for the world's coral systems. The changes at both poles will drive sea-level rises of many metres over time, inundating low-lying island states and countries such as Bangladesh, and the world's agriculturally-rich, large river deltas including the Ganges and the Nile, along with some of the world's largest and most crowded coastal cities. It will forcefully displace hundreds of millions of people. And that's for the current level of greenhouse gases, initiated by temperature conditions *significantly* lower than the widely-accepted 1.5°C goal.

The 1.5–2°C target never was — and is demonstrably now not — a safe or appropriate goal for policymakers or advocates. Limiting warming to 1.5°C will not protect the most climate vulnerable. Talking about 1.5–2°C and climate justice in the same breath is cognitively dissonant.

For more than a decade, leading scientists, basing their analysis on a careful study of Earth's past climates, have shown that to protect the world's people and nations and natural systems, warming has to be well under 1°C with carbon dioxide levels (CO_2) under 350 ppm,[1] and very likely warming of no more than 0.5°C. That is necessary to maintain the coral systems, ice sheet extent and steady sea levels — and coastal human settlement — of the climatically-stable Holocene conditions of the last ten thousand years.

Sir David King, working as an adviser to the UK government, had collaborated with the small-island states in the lead-up to the 2015 Paris climate conference, arguing successfully that global temperature should not go above a 1.5°C rise for safety. But in 2021, *The Independent* journalist Donnachadh McCarthy reported that King, the UK's former chief scientist, "astounded me by saying *he now realised this was wrong*, and believes the passing of the Arctic tipping point has been reached... He said the *1.1°C rise that we already have is too dangerous* — and candidly admitted he believed US climate professor James Hansen had been right after all in 1988, when he warned the US Congress that we should not pass 350 ppm. We have now breached 415 ppm and are heading fast towards 500 ppm, Sir David said (emphasis added).[2]

"Almost every month credible new evidence adds to the picture that major elements of the climate system have tipped. And their interactions are now leading to abrupt and cascading changes in Earth's climate system."

This report is a confronting look at the current state of play for major climate system instability, feedbacks and cascades. It is not easy reading, but we must grapple with the question of what needs to be done to protect human civilization from existential climate disruption. Director-Emeritus of the Potsdam Institute, Hans Joachim Schellnhuber, reminds us that "political reality must be grounded in physical reality or it's completely useless."[3]

“EVEN LIMITING GLOBAL TEMPERATURE INCREASES TO NEAR 2°C WILL LEAVE THE ARCTIC A MUCH DIFFERENT ENVIRONMENT BY MID-CENTURY WITH LESS SNOW AND SEA ICE, MELTED PERMAFROST, ALTERED ECOSYSTEMS, AND A PROJECTED ANNUAL MEAN ARCTIC TEMPERATURE INCREASE OF 4°C.”

— DR JAMES OVERLAND, OCEANOGRAPHER

OVERVIEW: WHEN TIPPING POINTS COLLIDE

As global heating reduces the extent of floating Arctic sea-ice each northern summer, heat-reflecting ice is replaced by heat-absorbing dark ocean water, adding energy to the Arctic system, and driving more melting. This is a "**positive feedback**", a self-reinforcing change. Examples abound in the climate system. On Greenland, for example, warming is reducing the height of the ice, and this lower elevation means it will melt more, because the temperature is higher at lower altitudes.

Sixteen years ago, James Hansen warned that: "The problem that we face now is that many [climate] feedbacks that came into play slowly in the past, driven by slowly changing forcings, will come into play rapidly now, at the pace of our human-made forcings, tempered a few decades by the oceans thermal response time." "[4]

Those feedbacks can drive **non-linear (or abrupt) change** that is difficult to forecast. That happened to Arctic sea-ice in the summer of 2007, when a collapse in the ice extent led one experienced glaciologist to exclaim that it was melting "100 years ahead of schedule";[5] actually, the scientific understanding was 100 years behind reality! The same thing is happening in Antarctica now, according to the new observations of the Thwaites Glacier.

A group of eminent scientists point 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". They say that other tipping points could be triggered at low levels of global warming with "a cluster of abrupt shifts between 1.5 °C and 2°C..." [6]

Positive feedbacks, with or without abrupt change, can drive a system past its **tipping point**, which is a critical threshold at which 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. In other words, the system has reached a point of fragility such that it will move to a different state due to its own internal dynamics, even if there is no further external forcing (such as additional warming).

An overview from Australia's Centre of Excellence for Climate Extremes describes a number of key aspects of tipping points:[7]

- The implications of tipping points are not thoroughly quantified in the major IPCC analyses.
- Some tipping point changes are irreversible on timescales of centuries to millennia.
- We do not know exactly how close we are to a tipping point, or even whether we have already passed it. We also do not always know if the changes are reversible, and if so, on what timescales.
- There are tipping points that while not yet triggered may already be fully committed to. For example, the warming required for the West Antarctic Ice Sheet to permanently melt might have already been reached.
- Climate models lack the mechanisms to robustly simulate many tipping points, and the interactions between tipping points that could lead to cascading impacts. Therefore our understanding of the risks is limited.
- Since the risk is hard to quantify, global negotiations around climate change have not appropriately taken into account the risks of initiating tipping points, which is essentially a gamble on the future of the Earth's climate.

Tipping may be irreversible on relevant time frames, such as the span of a few human generations. For example, ice sheets can disintegrate abruptly — and drive up sea levels — much faster than they can gain mass. So whilst sea levels could rise two or three metres this century — and rates as high as five metres per century have been recorded in the past — it could take thousands of years to reset the ice and get sea levels back down.

This is an example of hysteresis, or bifurcation of a system, where it may be more difficult, or impossible, to return to its previous state. Extinctions are an example of the latter. Carbon Brief explains:

"In some cases, there is evidence that once the system has jumped to a different state, then if you remove the climate forcing, the climate system doesn't just jump back to the original state – it stays in its changed state for some considerable time, or possibly even permanently." [8]

Major tipping points are interrelated and may **cascade**,[9] as illustrated. Interactions between these climate systems could lower the critical temperature thresholds at which each tipping point is passed.[10]

For example, Earth is approaching a temperature range above which the photosynthesis rate is projected to decline, affecting the storage of carbon in the terrestrial biosphere (the "land sink").[11] This will accelerate the warming rate, trigger further sea-ice loss, more melting on Greenland and freshwater injection into the North Atlantic, helping to further slow the Atlantic Meridional Overturning Circulation (AMOC), often known as the "Gulf Stream". This in turn would change rainfall patterns over the Amazon and further weaken its carbon stores and Earth's land sink. And so it goes on.

Physical interactions among the Greenland and West Antarctic ice sheets, AMOC and the Amazon rainforest tend to destabilise the network of tipping elements. The polar sheets are often the initiators of these cascade events,[12] with evidence that Greenland and West Antarctica have passed their tipping (see following sections).

In 2012, James Hansen warned of scientists' fear about the Arctic and the cascading of tipping points triggered in the Arctic: "Our greatest concern is that loss of Arctic sea ice creates a grave threat of passing two other tipping points – the potential instability of the Greenland ice sheet and methane hydrates… These latter two tipping points would have consequences that are practically irreversible on time scales of relevance to humanity." [13]

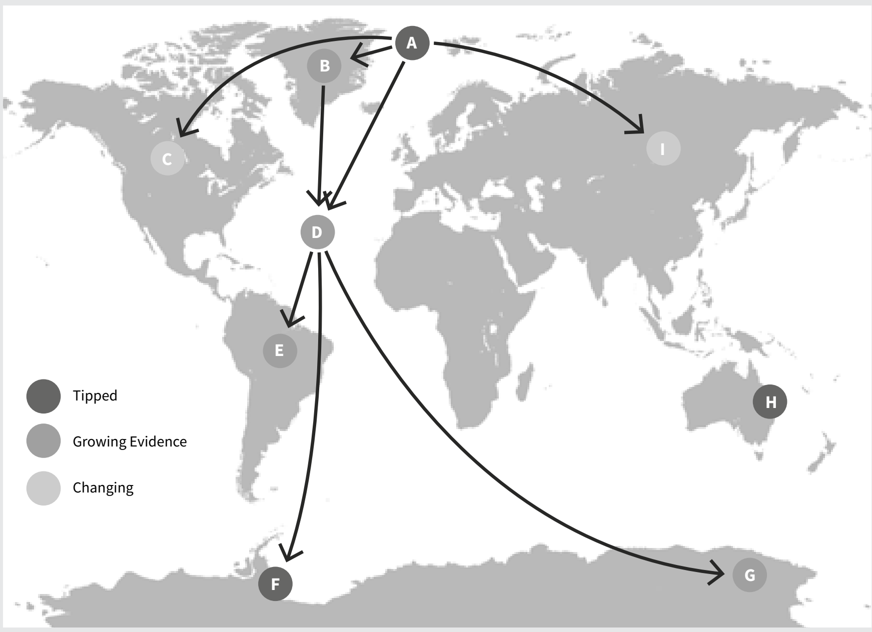
Cascading events may in turn lead to a "**Hothouse Earth**" scenario, in which climate system feedbacks and their mutual interaction drive the Earth System climate to a "point of no return", whereby further warming would become self-sustaining (that is, without further human-caused perturbations).[14] This planetary threshold could exist at a temperature rise as low as 2°C, possibly even in the 1.5°C–2°C range.[15]

The problem, elaborated in a 2019 paper, "Climate tipping points — too risky to bet against", is that time is close to running out: "We argue that the intervention time left to prevent tipping could already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is 30 years at best. *Hence we might already have lost control of whether tipping happens*. A saving grace is that the rate at which damage accumulates from tipping — and hence the risk posed — could still be under our control to some extent" (emphasis added).[16]

Likewise, former UK Chief Scientist Sir David King warns that: "What global leaders do in the next three-to-five years will determine the future of humanity."[17]

Tipping point analyst Prof. Tim Lenton says that the evidence from tipping points alone "suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute… If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization".[18]

CLIMATE TIPPING POINTS



A Arctic sea ice
B Greenland Ice Sheet
C Boreal forest
D Atlantic circulation
E Amazon rainforest
F West Antarctic Ice Sheet
G Wilkes Basin, East Antarctica
H Coral systems
I Permafrost

KEY TERMS

- **Positive climate feedback:** A process whereby an initial change in the climate system, for example warming generated by a climate forcing, causes a secondary change which in turn magnifies the initial effect and becomes self-reinforcing.
- **Tipping point:** A threshold at which a small change causes a larger, more critical change to be initiated, taking the climate system from one state to a discreetly different state. The change may be abrupt and irreversible on relevant time frames, possibly leading to cascading events.
- **Non-linear/abrupt change:** Sudden change rather than smooth progress, often associated with a tipping point.
- **Cascading events:** An unforeseen chain of events which may occur when one event in a system has a negative effect on other related components. For example, the mutual interaction of individual climate tipping points and/or abrupt, non-linear changes, which may lead to more profound changes to the system as a whole.
- **Hothouse Earth:** A planetary threshold in which a cascade of system changes makes warming self-sustaining, leading to conditions hotter than any experienced over the last few hundred thousand years by modern humans.
- **Climate forcing:** A physical process affecting the Earth's climate through one or more forcing factors. For example at present, a perturbation (change) in the Earth's energy system resulting from an imbalance between incoming and outgoing radiation caused by many factors but principally an increase in the "blanket" of human-caused greenhouse gases, with associated warming.

WEST ANTARCTICA AND THE "DOOMSDAY" GLACIER

The Thwaites Glacier in West Antarctica has an eastern ice shelf 45 kilometres wide as it flows into the Amundsen Sea. On 13 December 2021, scientists announced that the ice shelf 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 researchers explain: "Over the last several years, satellite radar imagery shows many new fractures opening up… which like a growing crack in the windshield of a car [can] suddenly break apart into hundreds of panes of glass. We have mapped [the] pathway the fractures might take through the ice [and conclude] the final collapse of Thwaites Glacier's last remaining ice shelf may be initiated … *within as little as five years"* (emphasis added).[19]

"There is going to be dramatic change in the front of the glacier, probably in less than a decade… both published and unpublished studies point in that direction," said glaciologist Prof. Ted Scambos.[20] In plain language, Thwaites is likely at a tipping point — though this can only be known after the fact — and no further warming is required for abrupt change to it and surrounding glaciers.

The concern is that the degradation of the ice shelf will allow more warm water to penetrate under the ice sheet, helping to free the underbelly of the glacier from the grounding line rock underneath, and allowing water to flow into the deep basin under the glacier, causing the glacier's collapse. This would raise sea levels by 65 centimetres, though the timing of such collapse — the "doomsday" scenario — is highly uncertain. Since neighbouring glaciers flow into the same basin, the demise of Thwaites could eventually lead to the loss of all of the West Antarctic Ice Sheet (WAIS), resulting in more than three metres of sea level rise, and putting at risk the lives and livelihoods of 250 million people.

A key 2014 study that received a lot of attention at the time concluded that a rapidly melting section of WAIS appeared to be in an irreversible state of decline, with nothing to stop the glaciers in this area collapsing. The study presented multiple lines of evidence, incorporating 40 years of observations that indicate the glaciers in the Amundsen Sea sector "have passed the point of no return", according to lead author Eric Rignot.[21]

Writing in *The Guardian*, Rignot emphasised:

"We had collected enough observations to conclude that the retreat of ice in the Amundsen sea sector of West Antarctica was unstoppable, with major consequences… its disappearance will likely trigger the collapse of the rest of the West Antarctic ice sheet, which comes with a sea level rise of between three and five metres."[22]

Rignot said that "at the current rate, a large fraction of the (West Antarctic) basin will be gone in 200 years"[23] and a Pollard, DeConto and Alley model from 2015 "accelerates the expected collapse of the West Antarctic Ice Sheet to decadal time scales, and also causes retreat into major East Antarctic subglacial basins", producing five metres in the first 200 years.[24]

New research from Milillo, Rignot et al. shows 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.[25]

BACKGROUNDER: ANTARCTICA IS "PRIMED FOR RUNAWAY DESTRUCTION"

The West Antarctic Ice Sheet (WAIS), comprising more than two million cubic kilometres of ice, is under pressure from a warming climate, with scientists saying its break-up — and an eventual global sea-level rise of 3–4 metres — is not a matter of if, but when. Glaciers including Pine Island, Thwaites, Smith and Kohler glaciers are discharging ice at an accelerating rate. This is primarily driven "from below" by changes in the sub-surface ocean circulation allowing warmer waters to intrude under the ice shelves.

Scientific attention is focussed on the fate of ice shelves, floating sheets or platforms of ice that are largely submerged and up to two kilometres in height. These are an extension of the land-based glaciers, and extend over the ocean. The "grounding line" marks the boundary between grounded ice (glacier) and the floating ice shelf. Generally, an ice shelf will lose volume by calving icebergs from the seaward-facing edge, but it can also be subject to rapid disintegration events, in which cracking can dislodge very large sections of ice. The formation of huge cracks along ice shelves leading to the loss of very large areas of ice have become widespread. One example along the Larsen C ice shelf was 100 kms long, half a kilometre wide and a hundred metres deep.

Warming Antarctic waters, driven by changed ocean and atmospheric circulation patterns, are melting and thinning the underside of ice shelves, making them more susceptible to disintegration. Ice shelves act as a "plug" that buttresses and slow the rate at which glaciers drain into the ocean, so the loss or diminution of the ice shelf will accelerate the pace of glacier movement and hence the rate of ice mass loss.

Because much of WAIS sits on bedrock that is below sea level (buttressed on two sides by mountains, and held in place on the other two sides by the Ronne and Ross ice shelves), melting of the submerged ice shelf allows warm ocean waters to proceed inland under the ice sheet. This creates hidden valleys of melting ice, puts pressure on the surface above, and contributes to large-scale rifting (cracking). This process also results in the grounding line being pushed further inland, in effect transforming the lower reaches of the glacier into an ice shelf.

What is happening now with Thwaites should not be a surprise, because such an event was foreseen 50 years ago. In 1968, pioneer glacier researcher John Mercer predicted that the collapse of ice shelves along the Antarctic Peninsula could herald the loss of the ice sheet. Ten years later, Mercer contended that "a major disaster — a rapid deglaciation of West Antarctica — may be in progress … within about 50 years". He said that warming "above a critical level would remove all ice shelves, and consequently all ice grounded below sea level, resulting in the deglaciation of most of West Antarctica". Such disintegration, once under way, would "probably be rapid, perhaps catastrophically so", with most of the ice sheet lost in a century. [26]

Credited with coining the phrase "the greenhouse effect" in the early 1960s, Mercer's Antarctic prognosis was widely ignored and disparaged at the time. Retired NASA climate research chief James Hansen says it was not clear at the time whether Mercer or his many critics were correct, but those who labelled Mercer an alarmist were considered more authoritative and better able to get funding. Hansen believes funding constraints can inhibit scientific criticisms of the status quo: "I believe there is pressure on scientists to be conservative".[27] Hansen is responsible for coining the term "The John Mercer Effect", meaning to play down your findings for fear of losing access to funding or of being considered alarmist.

Richard Alley, a world-leading Penn State University glaciologist, says that the most likely place to generate the worst-case scenario is Thwaites, warning that "even six feet of sea level rise by 2100 is not the worst-case scenario… We just don't know what the upper boundary is for how fast this can happen. We are dealing with an event that no human has ever witnessed before. We have no analog for this."[28]

Although the much larger East Antarctic Ice Sheet (EAIS) — with potential for a 50-metre sea-level rise if all ice were lost — has generally been considered more stable than WAIS, recent evidence suggests some outlet glaciers there are displaying similar dynamics to those on West Antarctica.

ABRUPT CHANGE IN THE ARCTIC

"The Arctic is screaming", says Mark Serreze, Arctic climate expert at the US National Snow and Ice Data Center.[29]

Arctic warming is racing ahead of the worst-case estimates, now heating four times faster than the global average,[30] and the region is undergoing abrupt climate change, understood as a transition of the climate system into a different mode on a time scale that is faster than the responsible forcing. In other words, it has passed a tipping point for rapid, system-level change. Researchers say that the Arctic "is currently experiencing an abrupt climate change event … climate models underestimate the abruptness of the recent changes observed in the Arctic (and) climate models underestimate this ongoing warming".[31]

In winter, the Arctic Ocean and the surrounding seas extending to the edges of Russia, Alaska, Canada and Greenland are covered by a thin skin of more than 14 million square kilometres of floating sea-ice, which is reduced in extent each summer by warmer conditions. Summer sea ice now covers only half the area it did in the 1980s, and because it is thinner, its volume is down 75%.[32] There is almost no multi-year ice left.

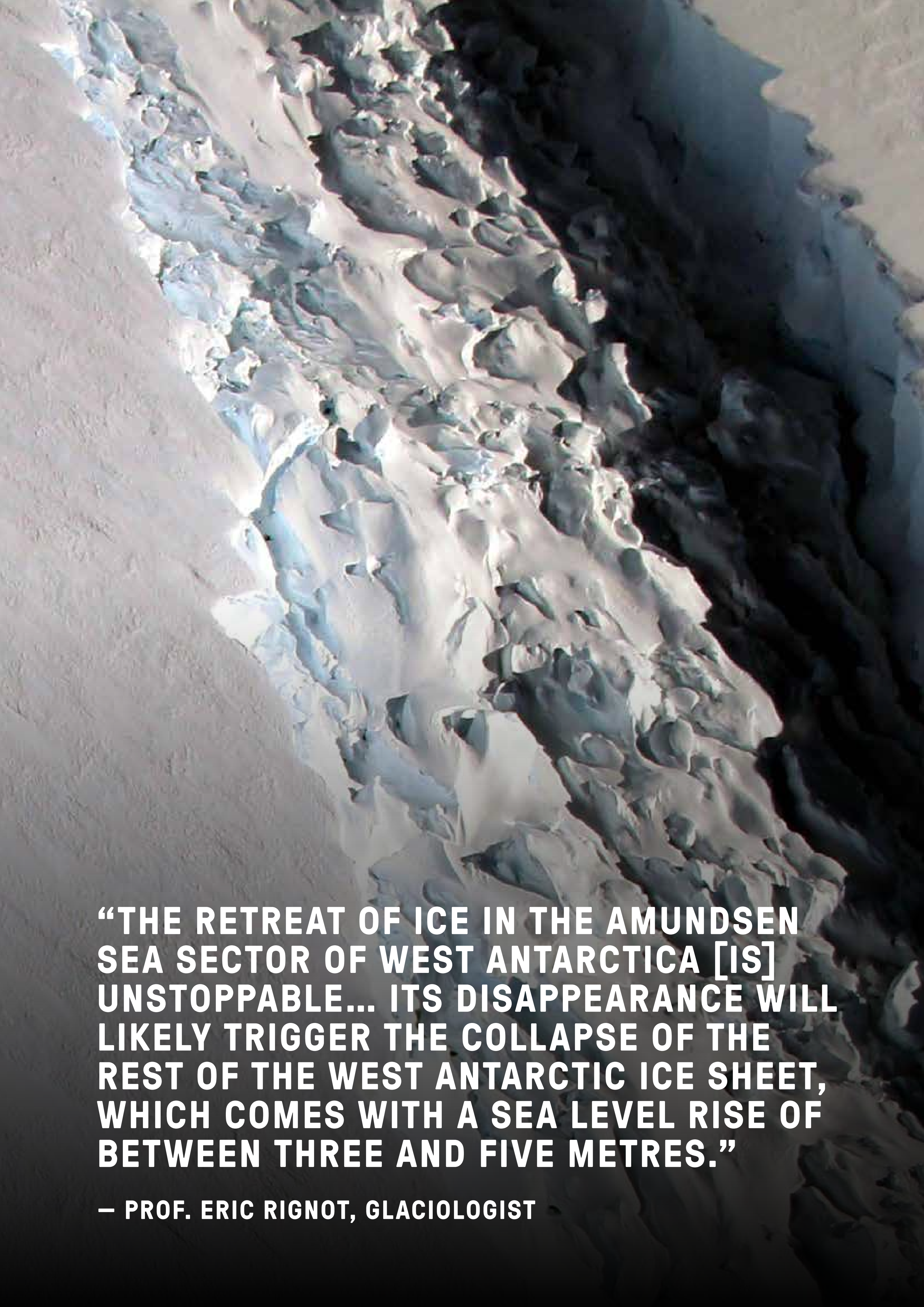
There is a close relationship between sea-ice changes and rapid contemporary Arctic and past Greenland warming,[33] an ominous signal about Greenland's future, and its impact on the AMOC (see Box page 14).

There is a strong positive feedback: as reflective sea ice in summer is replaced by dark, heat-absorbing open water, more energy is absorbed and the region heats, more ice is lost and the remaining ice is thinner and more fragile for the next summer melt. Another feedback is at work, too: the polar jet stream creates an atmospheric boundary between the Arctic and mid-latitude conditions, but the stream's destabilisation into a more meandering pattern caused by a hotter climate is now bringing big surges of heat into the Arctic. These have led to unprecedented heatwaves in Siberia and wildfires in Alaska.[35]

The Arctic is inexorably heading towards the day, within the next decade or so, when there will be no summer sea-ice (defined as less than ten percent of the area before the "big melt" commenced). This "blue water" event will lengthen to weeks and months if warming continues. There is uncertainty about the timing, "with some research suggesting that recent trends could lead to an ice-free summer Arctic as early as the 2020s and others suggesting 2030 or substantially later" depending on factors including future warming and natural variability.[36] "The chance that there will be any permanent sea ice left in the Arctic after 2022 is essentially zero… Can we lose 75-80% of permanent ice and recover? The answer is no," says Prof. James Anderson of Harvard University.[37]

Together with other feedbacks at work, the consequences of a summer ice-free Arctic are profound. The region's ecology would be unrecognisable, Greenland would be experiencing unstoppable and accelerating melting with severe consequences for the global ocean circulation system. More permafrost stores would be mobilised and the Boreal forests would suffer more severe dieback. The temperature differential between the Arctic and the tropics would be so reduced that basic weather, atmospheric circulation and precipitation patterns would be transformed. A climate-induced ozone hole may form. Impacts will affect the whole globe, from the Amazon rainforest to the West African and Indian monsoons, and more severe El Ninos.[38]

Arctic specialist Prof. Jason Box says that "if we don't get atmospheric carbon down and cool the Arctic, the climate physics and recent observations tell me we will probably trigger the release of these vast carbon stores, dooming our kids' to a hothouse Earth".[39]



“THE RETREAT OF ICE IN THE AMUNDSEN SEA SECTOR OF WEST ANTARCTICA [IS] UNSTOPPABLE… ITS DISAPPEARANCE WILL LIKELY TRIGGER THE COLLAPSE OF THE REST OF THE WEST ANTARCTIC ICE SHEET, WHICH COMES WITH A SEA LEVEL RISE OF BETWEEN THREE AND FIVE METRES.”

— PROF. ERIC RIGNOT, GLACIOLOGIST

GREENLAND BEYOND THE VIABILITY THRESHOLD

The Greenland Ice Sheet (GIS) contains enough ice to raise sea-levels by seven metres. There is strong evidence that GIS has passed a tipping point, is losing mass at accelerated rates in the 21st century,[40] melting seven times faster than it did in the 1990s, and that ice mass loss will continue to accelerate *for the current climate conditions*.

This is in part due to rapid Arctic warming. But a number of feedback mechanisms are driving these events, including:

- Positive melt-elevation feedback, a non-linear mechanism in which melting reduces the ice sheet height, exposing the ice surface to warmer temperatures, which further accelerates melting. Researchers say this process is likely to be responsible for the observed destabilization of GIS and is an "early-warning signal for a forthcoming critical transition" with "substantially enhanced melting in the near future".[41]
- 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 melting process," says Jason Box.[42]
- Enhanced rainfall: Rainfall makes GIS more prone to surface melt since it changes the surface reflectivity, and the melting reinforces itself: the rain melts snow, exposing the underlying darker ice, which absorbs more sunlight, increasing surface temperature, leading to more melting.[43]

Jason Box, Professor of Glaciology at the Geological Survey of Denmark and Greenland, says 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] means 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."[44]

[As an aside, many of the feedbacks and processes Box and others have described that are not accounted for in current Greenland models are also applicable for the Asian ice sheets: One-quarter of the Himalayan[45] and Tien Shan[46] ice sheets have already been lost.]
Ian Howat, Professor of Earth Sciences and distinguished university scholar at Ohio State, agrees with Box: "Glacier retreat has knocked the dynamics of the whole ice sheet into a constant state of loss... Even if the climate was to stay the same or even get a little colder, the ice sheet would still be losing mass." [47]
And a study published in 2020 found that GIS reached its tipping point 20 years ago, when widespread glacier retreat helped push the ice sheet from a balanced to an imbalanced state, and a "switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt", even if the oceans and atmosphere were to stop warming today.[48]

Norwegian and US scientists who took a close look at the ice age history of Greenland found that all it takes to trigger GIS melting away is a mean sea surface temperature higher than seven degrees Celsius. And the present mean sea surface temperature is already 7.7°C.[49]

Above-zero temperatures (and rainfall) are now being recorded at the summit of GIS,[50] leading to melting and rainfall at the highest elevations. The esteemed glaciologist Konrad Steffen, who in 2020 lost his life in a GIS crevasse, said in 2018: "Once we reach the point that melting occurs up to the highest point, Greenland [ice sheet] will disappear. Eventually we will have a global sea-level rise of five metres. This will maybe happen in 50 to 100 years… There will be a migration of 300–500 million people away from the coast, and that will be quite a big unrest." [51]

There is a significant chance of a sea-ice free Arctic in the next decade or so. "Could the Greenland ice sheet survive if the Arctic were ice-free in summer and fall?", asked researchers in 2007. Their answer:

"It has been argued that not only is ice sheet survival unlikely, but its disintegration would be a wet process that can proceed rapidly. Thus an ice-free Arctic Ocean, because it may hasten the melting of Greenland, may have implications for global sea level, as well as the regional environment, making Arctic climate change centrally relevant to the definition of dangerous human interference".[52]

Ice sheet loss on Greenland will be slower than for West Antarctica because it is driven "from above" on the surface, and not "from below" by warmer subsurface ocean temperatures as is the case for WAIS.

FORESTS, FALTERING LAND CARBON STORES AND THE AMAZON

The plant-based terrestrial biosphere may be understood as including the world's land-based plants, soils, derived dead organic matter, such as litter, and soil organic matter.

Plant photosynthesis uses CO_2 and water to produce sugar (glucose) and oxygen. Around 30% of the additional CO_2 produced by human actions has been drawn down from the atmosphere (mitigated) by increased plant photosynthesis. This adds to the land-based sink of stored carbon. But plants also respire, for example at night and in winter, by converting oxygen and stored glucose back into water and CO_2.

As the planet continues to warm, a point of warming is reached — the "thermal maximum for photosynthesis" — after which a combination of the rate of photosynthesis decreasing, and the rate of respiration increasing, results in the net flux of CO_2 from the atmosphere decreasing.

Together with more severe droughts and wildfires that also add to plant-based CO_2 emissions, the total amount of carbon stored in the terrestrial biosphere (the land sink) then starts to fall. This may be understood as a tipping point, a threshold beyond which large change is initiated in the terrestrial biosphere.

In ground-breaking research published in January 2021, Katharyn Duffy and colleagues mapped the relationship between increasing temperatures and carbon uptake 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 photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040." [53]

When those hot periods become the norm — as they will within a decade or two, because further warming of half a degree or more is already in the system — a tipping point will have been reached (with just the current level of greenhouse gases enough to trigger that event).

Christopher Schwalm, an ecologist and earth system modeller at the Woodwell Climate Research Center, says the findings mark a tipping point at which "the land system will act to accelerate climate change rather than slow it down". He said that "for my money, the results are conservative, because forest die-offs are not factored into this", but he was "surprised that this tipping point would happen so soon, maybe in 15 to 25 years, and not at the end of the century." [54]

Some ecosystems are more vulnerable than others, especially rainforests that are also under pressure from land-clearing for agriculture. A particular concern is the Amazon, which currently stores more than 120 billion tonnes of carbon. Lower precipitation, deforestation, drought and increasing wildfires could turn the Amazon rainforest to savanna. The Amazon carbon sink declined by a third between 2005 to 2015, when compared to the 1990s, mostly a result of increased tree mortality.[55]

In 2018 scientists concluded that "severity of the droughts of 2005, 2010 and 2015-16 could well represent the first flickers of [an] ecological tipping point" and that "the whole system is oscillating" to non-forest ecosystems in eastern, southern and central Amazonia." [56] Another study, in 2020, found the recent climatic instability in both Amazonia and the Andes and the drought-induced and fire-induced tree mortality "are aspects of critical slowing down; both possibly portending an imminent tipping point." [57]

In fact, Brazil's Amazon basin forest emitted more CO_2 than it has absorbed between 2010 and 2019: it gave off 16.6 billion tonnes of CO_2, while drawing down only 13.9 billion tonnes.[58] "We half-expected it, but it is the first time that we have figures showing that the Brazilian Amazon has flipped, and is now a net emitter," said study co-author Jean-Pierre Wigneron.[59] Another study concluded that southeastern Amazonia, in particular, is acting as a net carbon source (total carbon flux minus fire emissions) to the atmosphere.[60]

As well, a 2021 study concluded that current warming from non-CO_2 agents (especially methane and nitrous oxide) in the Amazon Basin largely offsets — and most likely exceeds — the climate service provided by atmospheric CO_2 uptake.[61]

CASCADES: HOW SYSTEM CHANGES CONNECT

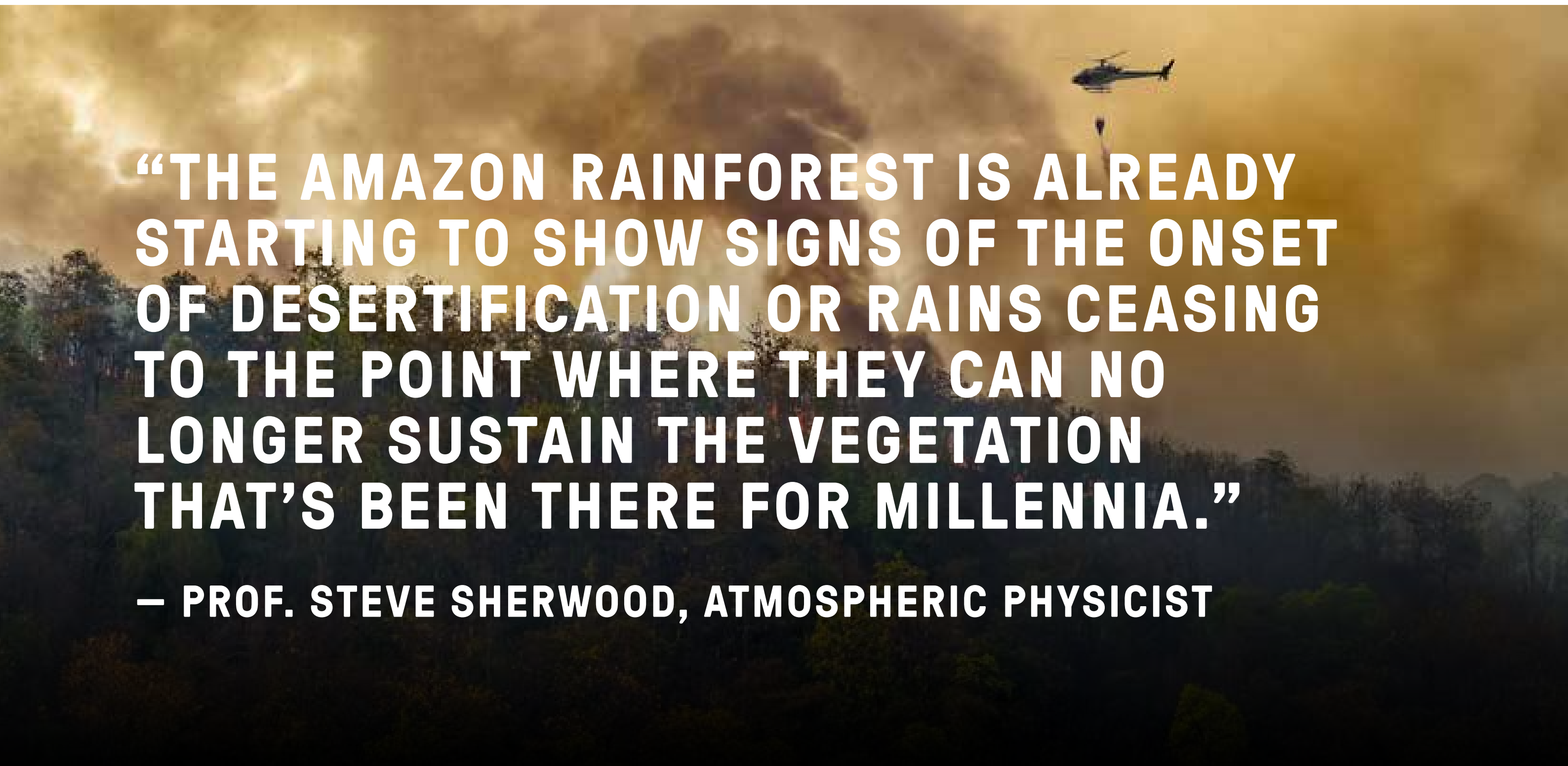
Contributing to the Amazon problem are rainfall changes driven by climate impacts on the Atlantic Meridional Overturning Circulation (AMOC) — often colloquially known as the "Gulf Stream" — which has been weakening for several centuries, and has slowed 15% since the mid-20th century.[62] The rate of change is accelerating, with climate models projecting further slow down.

The near-term loss of summer Arctic sea ice is driving an accelerating rate of ice-mass loss from Greenland, with the resultant increasing freshwater injection from Greenland into the north Atlantic contributing to the AMOC slowdown. An AMOC slowdown would reduce regional warming a little, especially in Europe, but would also lead to a reduction of ocean CO_2 uptake, and thus an acceleration of global-scale warming.[63] AMOC weakening can have a significant impact on the terrestrial primary productivity and carbon storage of the American Tropics, including changes in the seasonal cycle of precipitation over Amazonia.[64]

Niklas Boers of the Potsdam Institute for Climate Impact Research reported in 2021 that he had found "an almost complete loss of stability over the last century" of AMOC currents, and detected "significant early-warning signals" of an AMOC collapse that would have "severe impacts on the global climate system and further multi-stable Earth system components".[65]

Some scientists say the future impact of changes in Greenland on AMOC and ocean circulation more generally are being underestimated. Former NASA climate chief James Hansen wrote in December 2021 that:

> "On the scientific front, several colleagues and I assert that IPCC has underestimated the sensitivity of climate to growing freshwater injection from melting ice. One potential consequence – if we continue with business-as-usual emissions – is the shutdown of the overturning North Atlantic and Southern Ocean circulations by midcentury, each of which will contribute to acceleration of mass loss from the Antarctic ice sheet, with the likelihood of sea level rise of several metres within the lifetime of children born today".[66]



"THE AMAZON RAINFOREST IS ALREADY STARTING TO SHOW SIGNS OF THE ONSET OF DESERTIFICATION OR RAINS CEASING TO THE POINT WHERE THEY CAN NO LONGER SUSTAIN THE VEGETATION THAT'S BEEN THERE FOR MILLENNIA."

— PROF. STEVE SHERWOOD, ATMOSPHERIC PHYSICIST

PERMAFROST BEYOND THE MODELS

Permafrost is permanently frozen ground. It covers one-quarter of the land mass of the northern hemisphere, and contains 1.5 trillion tonnes of carbon, twice the amount currently in the atmosphere and triple the amount emitted by human activity since 1850. Permafrost buried beneath the Arctic Ocean holds 60 billion tons of methane (in structures known as methane clathrates) and 560 billion tons of organic carbon.[75]

Permafrost is releasing significant amounts of greenhouse gases, and feedbacks are under way, but the dynamics are not yet well enough understood to be able to judge whether tipping points have been reached or not. As previously noted, University of NSW researchers point out that: “We do not know exactly how close we are to a tipping point, or even whether we have already passed it… There are tipping points that while not yet triggered may already be fully committed to.”

As permafrost thaws, soil microbes awaken and feast on the warming biomass, creating heat as they do so: a positive feedback that drives more defrosting. Russian permafrost scientist Trofim Maximov, describes the other feedback: thawing permafrost releases greenhouse gases which cause warmer temperatures, melting the permafrost further: “It’s a natural process… which means that, unlike purely anthropogenic processes, once it starts, you can’t really stop it.”[76]

A 2018 study estimated that stabilisation of the climate at 2°C may eventually result in release of 225–345 gigatonnes (GtC) of thawed permafrost carbon.[77] That is equivalent to two-to-three decades of human emissions at the current rate. Some scientists consider that 1.5°C appears to be something of a “tipping point” for extensive permafrost thaw.[78]

The US government’s NOAA produces an annual Arctic Report Card. In 2019, it concluded that permafrost ecosystems could be releasing as much as 1.1 to 2.2 billion tons of CO_2 per year. The *Washington Post* quoted Prof. Ted Schuur:

‘These observations signify that the feedback to accelerating climate change may already be underway… Together [the studies] really paint the picture [that] we’ve turned this corner for Arctic carbon… Together they complement each other nicely and really in my mind are a smoking gun for this change already taking place’.[79]

Like other cryosphere systems, permafrost emissions are not well incorporated into climate models, especially emissions from deep permafrost, a problem exacerbated by evidence of abrupt thawing. Unusually warm summers, such as the record-breaking 2020 heatwave in Siberia and Svalbard, are happening more often, causing Arctic permafrost to thaw in some northern regions almost a century earlier than some climate models projected.[80] Subsea permafrost is not included in models.

Abrupt thaw could shift the entire northern hemisphere peatland carbon sink into a net source of warming, dominated by methane, lasting several centuries.[81] Arctic wildfires rapidly expand the layer of permafrost subject to thawing, and these remote, uncontrolled blazes are projected to increase 130–350% by mid-century, releasing more and more permafrost carbon.[82]

Evidence is emerging that sub-sea methane clathrates are starting to be mobilised over a large area of the continental slope off the East Siberian coast,[83] but there is not yet evidence on which to assess the system dynamics of the process.

Prof. Merritt Turetsky says that “permafrost is thawing much more quickly than models have predicted, with unknown consequences for greenhouse-gas release. Across the Arctic and Boreal regions, permafrost is collapsing suddenly as pockets of ice within it melt. Instead of a few centimetres of soil thawing each year, several metres of soil can become destabilized within days or weeks… Around 20% of frozen lands have features that increase the likelihood of abrupt thawing… the impacts of thawing permafrost on Earth’s climate could be twice that expected from current models.”[84]

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.[85]

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”.[86]

In conclusion: are permafrost and methane clathrates the “carbon bomb” that could drive the “Hothouse Earth” scenario? Yes. Do we know that the feedbacks have already driven these systems to a tipping point? No. But when risks are existential, focus must be given to the high-end possibilities, and what needs to be done to prevent them being realised.

“THE SAFE LEVEL OF ATMOSPHERIC CARBON DIOXIDE FOR CORAL REEFS IS ~320 PARTS PER MILLION... SETS THE SAFE LIMIT FOR A HEALTHY PLANET DURING A TIME OF ABRUPT GREENHOUSE-DRIVEN CLIMATE CHANGE.”

— PROF. CHARLIE VERON, BIOLOGIST

A DEATH SPIRAL FOR CORAL REEFS

Ecosystems, including coral reefs, mangroves and kelp forests in Australia, are degrading fast as the world's sixth mass extinction gathers pace.

Coral polyps are invertebrates similar to minute jellyfish, which build limestone structures, and live in a symbiotic relationship with algae-like unicellular zooxanthellae that reside within the coral structure, and give it colour. The coral provides the algae with a protected environment and compounds they need for photosynthesis. In return, zooxanthellae supply the coral with oxygen, glucose, glycerol, and amino acids, which are the products of photosynthesis. Corals survive within a narrow water temperature band, and suffer heat stress and expel zooxanthellae if the ocean temperature gets too high. Bleaching events vary in intensity; in the extreme case, all zooxanthellae are expelled and the living colony will appear totally white (hence "bleaching"). As elevated sea temperatures persist, coral mortality rates increase: corals may recover, if there are any zooxanthellae left in their tissues but, if not. death appears to be inevitable.

The bottom line: If severe bleaching events occur regularly at shorter than 10–15 year intervals, then reefs face a death spiral of coral mortality followed by inadequate recovery periods: "The time between recurrent events is increasingly too short to allow a full recovery of mature coral assemblages, which generally takes from 10 to 15 years for the fastest growing species and far longer for the full complement of life histories and morphologies of older assemblages."[67]

And that is what is happening now. Along Australia's Great Barrier Reef, the frequency of mass bleaching is increasing, with events occurring in 1998, 2002, 2016, 2017, 2020 and 2022. The 2016-17 events severely bleached half the reef, whose extent has been reduced by three-quarters over the last 40 years. Coral reproduction on the Great Barrier Reef has fallen 89% after repeated recent bleachings.[68] Multiple lines of evidence suggest the current physical conditions will cause decreasing extent and ecosystem collapse along the Great Barrier Reef at the current level of warming:

- Melbourne-based researchers showed in 2017 that the hotter water conditions that drove the severe bleaching in 2016 will occur on average one year in three at 1.2°C, and two years in every three at 1.5°C.[69]
- In 2021, researchers concluded that at 1.5°C, severe bleaching events would occur on average three times per decade.[70]

Given recovery times are 10-plus years, even warming in the 1.2–1.5°C range means a spiral of decreasing extent. Some corals adapted to hotter conditions will survive, but the reef as an ecosystem will be unrecognisable compared to fifty years ago.

And it is not just the Great Barrier Reef. Prof. Terry Hughes and colleagues looked at 100 reefs globally and found that the average interval between bleaching events is now less than half what it was before: "Such narrow recovery windows *do not allow for full recovery.* Furthermore, warming events such as El Niño are warmer than previously, as are general ocean conditions. Such changes are likely to make it *more and more difficult for reefs to recover* between stressful events" (emphasis added).[71]

New research published on 1 February 2022 was unequivocal about a 1.5°C outcome for corals: "Climate refugia are locations that maintain suitable environmental conditions for a resident species even when surrounding areas become inhospitable… We show that climate change will overwhelm current local-scale refugia, with declines in global thermal refugia from 84% of global coral reef pixels in the present-day climate to 0.2% at 1.5℃, and 0% at 2.0℃ of global warming… We confirm that warming of 1.5℃ relative to pre-industrial levels will be catastrophic for coral reefs".[72]

Dr Mark Eakin, coordinator of Coral Reef Watch at the US National Oceanic and Atmospheric Administration (NOAA), says rising ocean temperatures could have pushed the world's tropical coral reefs over a tipping point: "The real concern is with this much bleaching without tropical forcing. This may be a sign we've now tipped over to near-annual bleaching in many locations."[73]

And what would be safe for reefs? Dr Charlie Veron — who has discovered, described and identified about a third of all known coral species — addressed the Royal Society in London in 2009, saying that: "The safe level of atmospheric CO_2 for coral reefs is ~320 ppm. This identifies a bench-mark level for contemporary marine ecosystems. More than any other available measure, it sets the safe limit for a healthy planet during a time of abrupt greenhouse-driven climate change."[74]

SUMMING UP: FASTER THAN FORECAST, CASCADES LOOM

Reflecting on the evidence presented above, a number of conclusions may be drawn:

1. **At just 1.2°C of global average warming, tipping points have been passed for several large Earth systems.** These include Arctic sea ice, the Greenland Ice Sheet, the Amundsen Sea glaciers in West Antarctica, the eastern Amazonian rainforest, and the world's coral systems. The world will warm to 1.5°C by around 2030,[87] with additional warming well beyond 1.5°C in the system after that. Yet even at the current level of warming, these systems will continue to move to qualitatively different states. In most cases, strong positive feedbacks are driving abrupt change. At higher levels of warming, the rate of change will quicken. The meme that "we have eight years to avoid 1.5°C and tipping points" should be deleted from the climate advocacy vocabulary. It is simply wrong: 1.5°C will be reached around 2030 regardless of the emissions path, and some tipping points are already here.

2. **System-level change is happening faster than forecast.** In each case surveyed above, abrupt change is happening earlier and/or faster than projected only two decades ago. The 2007 Arctic sea-ice collapse was "100 years ahead of schedule"; in 2014 the tipping point for Amundsen Sea glaciers was one that "none of us thought would pass so quickly". It used to be said that the guardrail for coral reefs was warming under 2°C, then it was 1.5°C; it is now clear that it is under 0.5°C. In 1995, the IPCC projected "little change in the extent of the Greenland and Antarctic ice sheets… over the next 50-100 years". The 2001 IPCC report suggested that the Greenland and the West Antarctic ice sheets would not lose significant mass by 2100. Both have now passed their tipping points. The effect of the permafrost carbon feedback has not been included in the IPCC scenarios, including the 2014 report. And on it goes.

3. **Climate models don't incorporate key processes and are not reliable.** 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,[88] such as the stalling of the Gulf Stream,[89] polar ice melt[90] and the uptick in extreme weather events. Jason Box has described in detail the feedbacks on Greenland not represented in models. Thus Earth system and Integrated Assessment Model projections, and their use in determining carbon budgets, are not reliable.[91] It is important that observations, semi-empirical models, expert elicitations, and lessons from past climates are given more weight in the light of current model deficiencies.

4. **The Earth climate system is undergoing abrupt change.** It is not just that individual elements of the climate system are tipping and/or changing rapidly. They also affect each other. The Arctic is warming four times faster than the global average, so summer sea-ice is diminishing fast, adding a further forcing to Greenland's instability. It is inconceivable that Greenland could remain stable in Arctic summer blue-water conditions. Greenland melt-water injection into the north Atlantic is one factor slowing the AMOC, which in turn is negatively affecting precipitation over Amazonia and impacting the diminution of its carbon stores. Arctic warming may be a factor in destabilising the polar Jet Stream into a more "wavy" pattern, bringing record-breaking heat into the Arctic and triggering huge fires, with impacts on the mobilisation of permafrost carbon stores. Jet Steam destabilisation combined with global warming is also bringing new extremes over Europe, Asia and North America, including unprecedented cold, rains and floods. In an expert elicitation process conducted by Chatham House for its *Climate Change Risk Assessment Report 2021*, the physical and social cascading risks that participants identified as the greatest concern were "the interconnections between shifting weather patterns, resulting in changes to ecosystems and the rise of pests and diseases. Combined with heatwaves and drought, these impacts will likely drive unprecedented crop failure, food insecurity and migration."[92]

5. **Cascades and accelerated warming may trigger Hothouse conditions.** These chains of events are consistent with the cascade of system changes that may drive Earth past the "Hothouse Earth" threshold. This is not to say that this scenario is already locked into the system, but scientists have warned that it may become active in the 1.5–2°C threshold,[93] and that is where we are heading now, likely at an accelerated rate of warming over the next two decades. Current models, reported in the 2021 IPCC report, show around 0.3°C warming between 2020 and 2030, and more than 2°C by mid-century for the medium-emissions scenario. The next 25 years are projected to warm at a rate of 0.25–0.35°C per decade;[94] 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.[95] Even with greater emission-reduction ambition than at Glasgow, warming will likely exceed 2°C sometime in the 2040s. Short-lived atmospheric sulfate aerosols are a by-product of burning fossil fuel and have a cooling effect which has been hiding 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.[96] This appears poorly appreciated by many climate action advocates whose strategy is built around decarbonisation only, rather than the "three levers" of decarbonisation, drawdown and active cooling.

6. **Risks have been underestimated.** The risks are systemic, but "quantifying the probability and severity of systemic risks is not possible due to their complex nature".[97] Because abrupt system change is happening faster than forecast, we are ill-prepared for what may happen. Ice-sheet loss and rising sea levels are a delayed response to warming. Australian scientists from the University of New South Wales report that: "An equilibrium climate under *current temperatures* would have a sea level several metres higher than what we have today (likely 5–10 metres higher). We also know that an equilibrium climate under *current carbon dioxide* concentrations would have a sea level 5–25 metres higher" (emphasis added).[98] Is this widely understood? Due to model limitations, the increasing risk is that we will not know exactly how the climate crisis will unfold until it's too late.[99] Is there a risk that the Hothouse scenario will be initiated? Scientists have answered "yes".[100] What actions would be required to mitigate this outcome, or the risk it may soon be triggered, depending on human actions over the next decade? These questions are barely being asked, let alone answered, yet the consequences of not having a sound response may be existential for human civilisation.

7. **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 in 2021 and the forecasts for 2022-24.[101] 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.[102] 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.

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