Climate tipping points – too risky to bet against

The growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions

Timothy M. Lenton, Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen & Hans Joachim Schellnhuber

Politicians, economists and even some natural scientists have tended to treat tipping points[1] - such as the loss of the Amazon rainforest or the West Antarctic ice sheet - as high-impact, but highly uncertain and low-probability events. However, scientific evidence is accumulating that Earth system tipping points may be closer than previously thought, and interconnected across different biophysical systems, potentially committing the world to long-term irreversible changes.

Here we summarise evidence on the threat of crossing tipping points, identify knowledge gaps, and suggest how these should be plugged. We explore the impacts of such changes, how quickly they may unfold, and whether we still have any control over them.

We argue the consideration of tipping points helps define that we are in a climate emergency and strengthens this year's chorus of calls – from schoolchildren to the world's scientists, cities to countries – for urgent climate action.

The Intergovernmental Panel on Climate Change (IPCC) introduced the idea of tipping points two decades ago. These 'large-scale discontinuities' in the climate system were then considered likely only if global warming exceeded 5°C. Now information summarised in two recent IPCC Special Reports[2,3] points to the crossing of tipping points even at 1-2°C of warming (see: Too close for comfort).

Despite the Paris Agreement's goal to limit warming to well below 2 °C, current national pledges to reduce emissions, if implemented, are likely to result in at least 3 °C of global warming. Some economists working with cost-benefit climate-economy models have previously suggested 3 °C warming as optimal climate policy. However, such models assume that climate tipping points are high impact, but very low probability events. If instead tipping points already have higher probability, this aligns the 'optimal policy' recommendations of simple cost-benefit climate-economy models[4] with the recent IPCC report[2] to limiting warming to 1.5°C – requiring an emergency response.

Ice tipping

We think that several cryosphere tipping points appear dangerously close, but mitigating greenhouse gas emissions could still slow down the inevitable accumulation of impacts and help us adapt.

Research in the last decade has shown that the Amundsen Sea Embayment of West Antarctica may have passed a tipping point[3] – in which the 'grounding line' where ice, ocean and bedrock meet is retreating irreversibly. A model study shows[5] that when this sector collapses, it could destabilise the rest of the West Antarctic ice sheet, like toppling dominoes – leading to about 3m of sea-level rise during the coming centuries to millennia. Paleo-evidence shows that such widespread collapse of the West Antarctic ice sheet has occurred repeatedly in past inter-glacial intervals.

New data show part of the East Antarctic ice sheet – the Wilkes basin – may be undergoing the same marine ice sheet instability[3]. Modelling work suggests that it could add another 3-4m to sea-level on timescales beyond a century.

The Greenland ice sheet is melting at an accelerating rate[3] and could add a further 7m to sea-level over thousands of years, if it passes a threshold– beyond which, as the ice sheet melts, its elevation lowers, exposing the surface to ever warmer air. Models suggest the Greenland ice sheet could be already be doomed at 1.5°C of warming[3], which could be as soon as 2030.

Thus, future generations may already be committed to the order of 10m sea-level rise over thousands of years[3]. However, the timescale over which tipping unfolds – and sea-level rises – is still under our control, because the rate of meltdown depends on the magnitude of warming above the tipping point. At 1.5°C global warming, it could take ten thousand years to unfold[3], but above 2°C the response could take less than a thousand years[6]. Only recently a marine ice cliff instability was identified that could further accelerate marine ice sheet loss, but lack of observational constraints make its contribution uncertain. Researchers need more observational data to establish if ice sheet tipping is underway, and improved models constrained by past and present data to resolve how soon and fast the ice sheets could go.

Even if ice sheet tipping is underway, there remains a strong mitigation incentive to slow sea-level rise, which will aid adaptation including eventual resettlement of large low-lying population centres.

A further key impetus to limit warming to 1.5°C, is that some tipping points could be triggered earlier at low levels of global warming. Although initially overlooked, the last generation of IPCC models projected a cluster of abrupt shifts[7] at 1.5-2°C. Several involve sea-ice, which is already shrinking rapidly in the Arctic such that the region has a 10-35% chance[3] of being largely ice free in summer at 2°C.

Biosphere tipping

Climate change and other human activities risk triggering biosphere tipping points, across a range of ecosystems and scales (see: Change underway).

Ocean heatwaves have led to mass coral bleaching and loss of half of the shallow-water corals on the Great Barrier Reef. A staggering 99% of tropical corals are projected[2] to be lost by 2°C, owing to interactions between warming, ocean acidification and pollution. This would represent a profound loss of marine biodiversity and human livelihoods.

In addition to undermining our life-support system, biosphere tipping points can also trigger abrupt carbon release back to the atmosphere. This can amplify climate change and abruptly reduce remaining carbon emission budgets to limit warming to 1.5°C.

Deforestation and climate change are destabilizing the Amazon, the world's largest rainforest, and home to one in ten known species. Estimates of where an Amazon tipping point could lie range[8] from 40% to just 20% of forest cover loss. About 17% has already been lost since 1970, with the rate of deforestation clearly depending non-linearly on policy actions. To narrow down where the tipping point lies requires models that include deforestation and climate change as interacting drivers and fire and climate feedbacks as interacting tipping mechanisms across scales.

With the Arctic warming at least twice as fast as the global average, the boreal forest in the subarctic is vulnerable to tipping. Already warming temperatures have triggered a population explosion of bark beetles and an abrupt increase in fires causing North American boreal forest dieback, with some regions already observed to have switched from a carbon sink to a source[9]. Permafrost across the Arctic is irreversibly thawing and releasing CO_2 and methane – a more potent yet shorter-lived greenhouse gas.

Researchers need to better understand these observed changes in major ecosystems at 1°C as well as where future tipping points might lie. Existing carbon stores and potential CO_2 and methane releases need better quantification.

Even without potential biosphere tipping points, the world's remaining emission budget for a 50:50 chance of saying within 1.5°C is only about 500 $GtCO_2$. Permafrost emissions could take an estimated[10] 20% (100 $GtCO_2$) off this budget, and this does not consider deep permafrost or undersea methane hydrates. If forest tipping points are near, Amazon dieback could release[11] another 90 $GtCO_2$, and boreal forests a further[11] 110 $GtCO_2$. With emissions still >40 $GtCO_2$ yr^{-1}, the remaining budget could be all but erased already.

Global tipping

In our view, the clearest source of emergency would be if we were approaching a global tipping point to a new, less habitable, 'hothouse' climate state[11]. This could happen if tipping points interact with sufficient strength to trigger a tipping cascade[11]. Interactions could happen via ocean and atmosphere circulation or via feedbacks that increase greenhouse gas levels and global temperature. Alternatively, strong cloud feedbacks could cause global tipping[12,13].

We argue that cascading effects between tipping elements may be a common feature. Recent research analysing 30 types of regime shift, spanning the physical climate and ecological systems – from West Antarctic ice sheet collapse to switching from rainforest to savanna – indicated that crossing tipping points in one system can increase the risk of crossing tipping points in other systems. Such links were found for 45% of possible interactions[14].

We suggest that specific examples of interacting tipping elements are starting to be observed. For example, Arctic sea-ice loss is amplifying regional warming and Arctic warming and Greenland melting are driving an influx of freshwater into the North Atlantic. This may have contributed to a recent 15% slowdown[15] of the Atlantic Meridional Overturning Circulation (AMOC)[3]. Rapid melt of the Greenland ice sheet and further slowdown of the AMOC could tip the West African monsoon, triggering drought in the Sahel**.** AMOC slowdown could also dry the Amazon, disrupt the East Asian monsoon, and cause heat to build-up in the Southern Ocean with potential to accelerate Antarctic ice loss.

The paleo-record shows global tipping, such as the entry into ice age cycles 2.6 Ma and their switch in amplitude and frequency around 1 Ma, which models are only just capable of simulating. Sub-global tipping occurred repeatedly within and at the end of the last ice age (the Dansgaard-Oeschger and Heinrich events). Although not directly applicable to the present interglacial, this highlights that the Earth system has been unstable across multiple timescales beforehand, under relatively weak forcing caused by changes in the Earth's orbit. Now we are strongly forcing the system; with atmospheric CO_2 concentration and global temperature increasing at rates an order of magnitude faster than during the most recent deglaciation.

CO_2 is already at levels last seen ~4 Ma in the Pliocene, and rapidly heading towards levels last seen ~50 Ma in the Eocene, when temperatures were up to 14°C higher than preindustrial. It is challenging for climate models to simulate such past 'hothouse' Earth states. One possible explanation is that they have been missing a key tipping point: A recent cloud-resolving model suggests that the abrupt breakup of stratocumulus cloud decks above ~1200ppm CO_2 may have resulted in around 8°C of global warming[12].

Some early results from the latest climate models – run for the IPCC's sixth assessment report (AR6) due in 2021 – indicate a much larger climate response to doubling of atmospheric CO_2 than previous models. Early analysis links this to an altered balance of cloud feedbacks in the models. In particular, a new satellite observational constraint on the ice crystal content of clouds weakens a crucial negative feedback in the models, increasing their climate sensitivity[13]. Many more results are pending and further investigation is clearly required, but in our view these early results might suggest that a global tipping point is possible**.**

To address these issues, we need models that capture a richer suite of couplings and feedbacks in the Earth system, and we need to improve both present and past data constraints on climate models. Improving models' ability to capture known past abrupt climate changes and 'hothouse' climate states should increase confidence in their ability to capture potential future abrupt climate changes and 'hothouse' climate states.

Some may respond that the possibility of global tipping remains highly speculative. However, given its huge impact and irreversible nature, any serious risk assessment must consider the evidence concerning this risk, however limited our understanding may still be. To err on the unsafe side is not a responsible option.

If damaging tipping cascades can occur and a global tipping cannot be ruled out, then this is an existential threat to civilization and no amount of economic cost-benefit analysis is going to help us. Instead we need to change our approach to the climate problem.

Act now

We think that the evidence from tipping points alone suggests we are in a state of planetary emergency, where both the risk and urgency of the situation are acute (see: Defining emergency).

We argue that the intervention time left to prevent tipping may already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is at best 30 years. Hence we may 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 – may still be somewhat under our control.

The stability and resilience of our planet is in peril, and international action – not just words – has to reflect this.

Defining emergency

We define emergency (E) as the product of *risk* and *urgency*. Risk (R) is defined by insurers as probability (p) times damage (D). Urgency (U) is defined in emergency situations as reaction time to an alert (τ) divided by intervention time left to avoid a bad outcome (T). Thus:

$E = R \times U = p \times D \times \tau / T$.

The situation is an emergency if both risk and urgency are high. If reaction time is longer than the intervention time left ($\tau/T>1$) we have lost control.

Timothy M. Lenton is director of the Global Systems Institute, University of Exeter, UK. **Johan Rockström** is director of the Potsdam Institute for Climate Impact Research, Germany. **Owen Gaffney** is global sustainability analyst, Potsdam Institute for Climate Impact Research, Germany and Stockholm Resilience Centre, Sweden. **Stefan Rahmstorf** is professor, Potsdam University and co-chair of Earth system analysis, Potsdam Institute for Climate Impact Research, Germany. **Katherine Richardson** is professor, University of Copenhagen, Denmark. **Will Steffen** is emeritus professor, Australian National University, Australia. **Hans-Joachim Schellnhuber** is founding director, Potsdam Institute for Climate Impact Research, Germany.

e-mail: t.m.lenton@exeter.ac.uk

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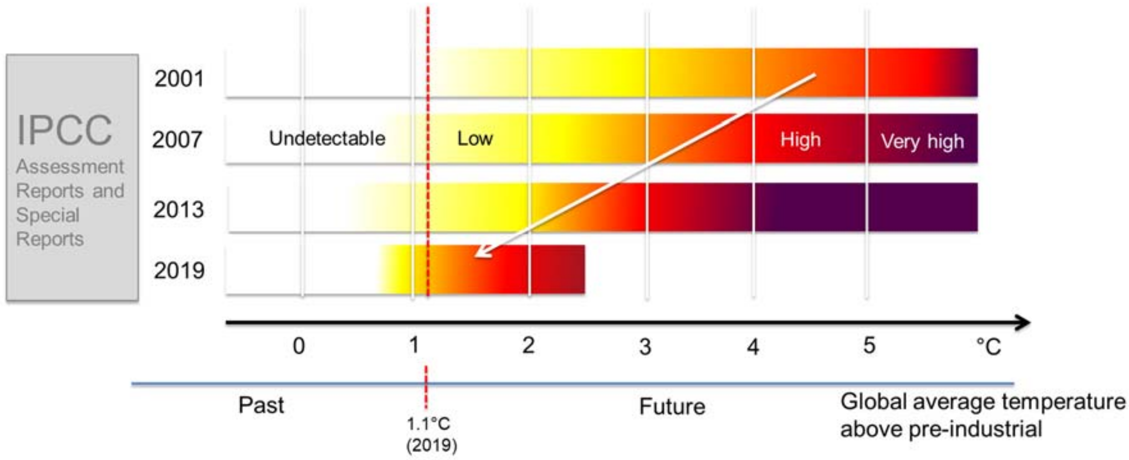
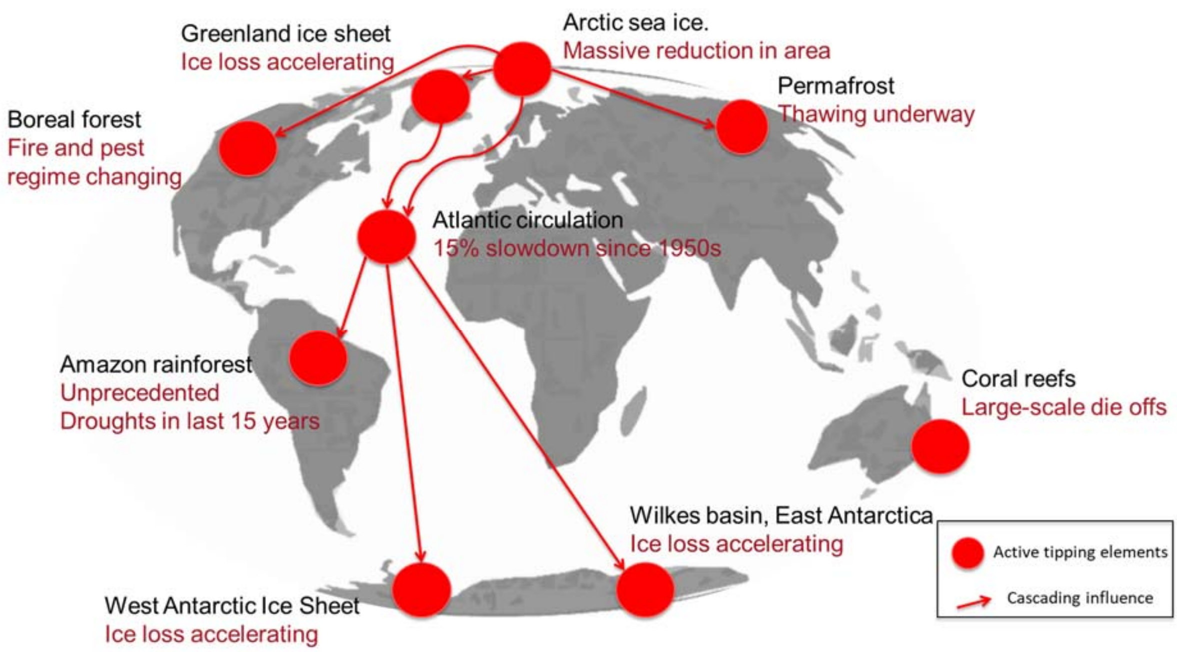
Figures



Too close for comfort. Each subsequent report from the Intergovernmental Panel on Climate Change revises downwards the temperature at which "large-scale discontinuities" in the climate system become a high risk. Meanwhile global average temperature continues rising.



Change underway. Several tipping elements in the climate system now show greater changes than were recognised just a decade ago[1] and new tipping elements have also been identified.