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Foreword

Steering away from trouble

We all know deep down that we are not acting fast enough – collectively – to tackle climate change. Maybe we are telling ourselves that it will not be that bad after all. That the problems will come for someone else, somewhere else, in the future. That we can carry on as we are and act later if things start turning out to be worse than we thought.

Perhaps that was how the captain of the RMS *Titanic* was thinking late in the evening of 14 April 1912, when despite having received six separate warnings of icebergs from nearby ships that day, he continued to charge into the dark at 22 knots – just a couple of knots short of the ship's maximum speed.

The problem is that in a changing climate, just as onboard the *Titanic*, there could be irreversible tipping points ahead that have devastating consequences. For example, a collapse of the Atlantic Meridional Overturning Circulation would commit the UK to glacial winters. In one climate model that crosses this tipping point, the average decade sees a winter in which sea ice covers most of the North Sea and surrounds Scotland. As icy winds blast across that frozen surface, the temperature in London plummets to −20C and in Edinburgh to −30C.

If we wait until we see such an 'iceberg' dead ahead and then try to act, it will be too late – just as it was on the *Titanic*. The climate 'ship' will not sink as fast: the circulation of the ocean is a sluggish beast. But as the late Wally Broecker, notable geochemist, put it: 'We are poking it with sticks'.

Faced with the risk of tipping points, we need to act before tipping occurs. Every fraction of a degree of global warming takes us further into the danger zone. This has just been tragically demonstrated with the worldwide dieback of over 80 per cent of tropical coral reefs.

Our only viable, collective option is to stop emitting the greenhouse gases that cause warming as fast as we can. The good news is that we have everything we need to accelerate ourselves out of trouble; and there is a trick that we have been missing: there are positive tipping points that we can all play a part in activating. The more we adopt clean technologies, the more affordable, attractive and accessible they become for others to adopt. And the more of us who change behaviour, the more people we influence to join us.

That is what will persuade those on the 'bridge' to change course.

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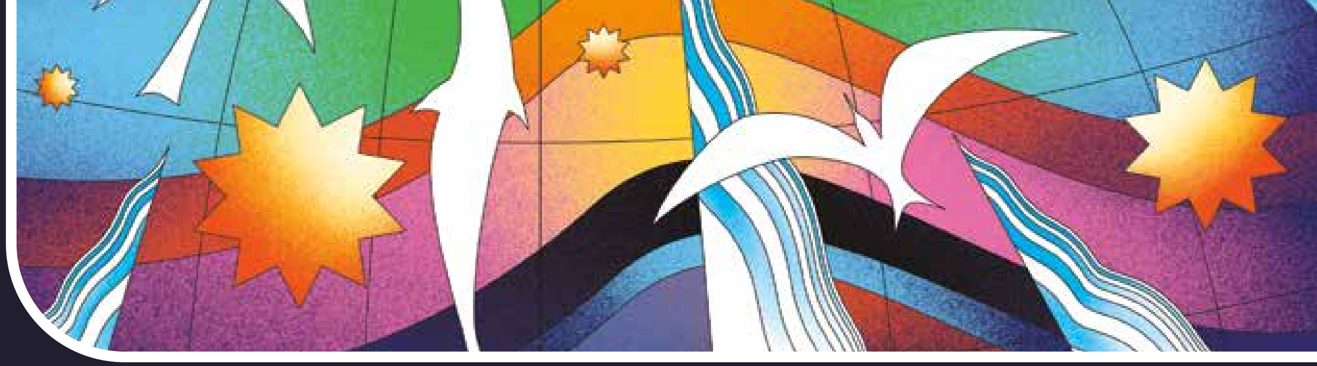
Tim Lenton OBE is Professor of Climate Change and Earth System Science at the University of Exeter, and author of *Positive Tipping Points: How to Fix the Climate Crisis.*[1] He is a world-renowned climate scientist with over 25 years in research focused on climate dynamics and associated tipping points.



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Cover design: Scott Balmer is an illustrator based in Scotland. With his unique psychedelic art style, Scott has produced illustrations for *Wired*, *The Transmitter*, *Science Focus*, *The Guardian*, *NY Times* and *Wizards of the Coast.*

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environmental SCIENTIST explores key issues in environmental science research and practice, featuring original articles by professionals, academics, and experts from across the sector.

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Tipping points: the peril and the promise

Steven Smith lays out the complexities and paradoxes of climate tipping points and the catalysts for action.

A tipping point is one of those rare scientific ideas that is intuitively understood. We have all balanced on the hind legs of a chair, leaned back farther than it was possible to recover, and viscerally had that feeling of unstoppable change from one stable 'system' (a chair that returns to its upright position) to another (a chair that tips onto its back). The term is now becoming a familiar part of how we discuss environmental issues, and its precise meaning matters more than ever.[1,2] The definition set out by Tim Lenton and colleagues in 2008 remains the clearest one: 'A tipping point is a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system'.[3] Change can become self-sustaining once a threshold is crossed. The process continues without further external input.

This issue of *environmental SCIENTIST* is organised around a tension within that single idea. The same dynamics that make damaging climate tipping points so dangerous also describe how rapid, beneficial change can take hold in our economies and societies. The articles that follow consider both, and they ask readers to hold two propositions together: that in the physical environment the world is close to dangerous thresholds that we must not cross; and that crossing thresholds of a very different kind, in technology, markets and behaviour, may be the most credible route to avoiding the danger.[4,5]

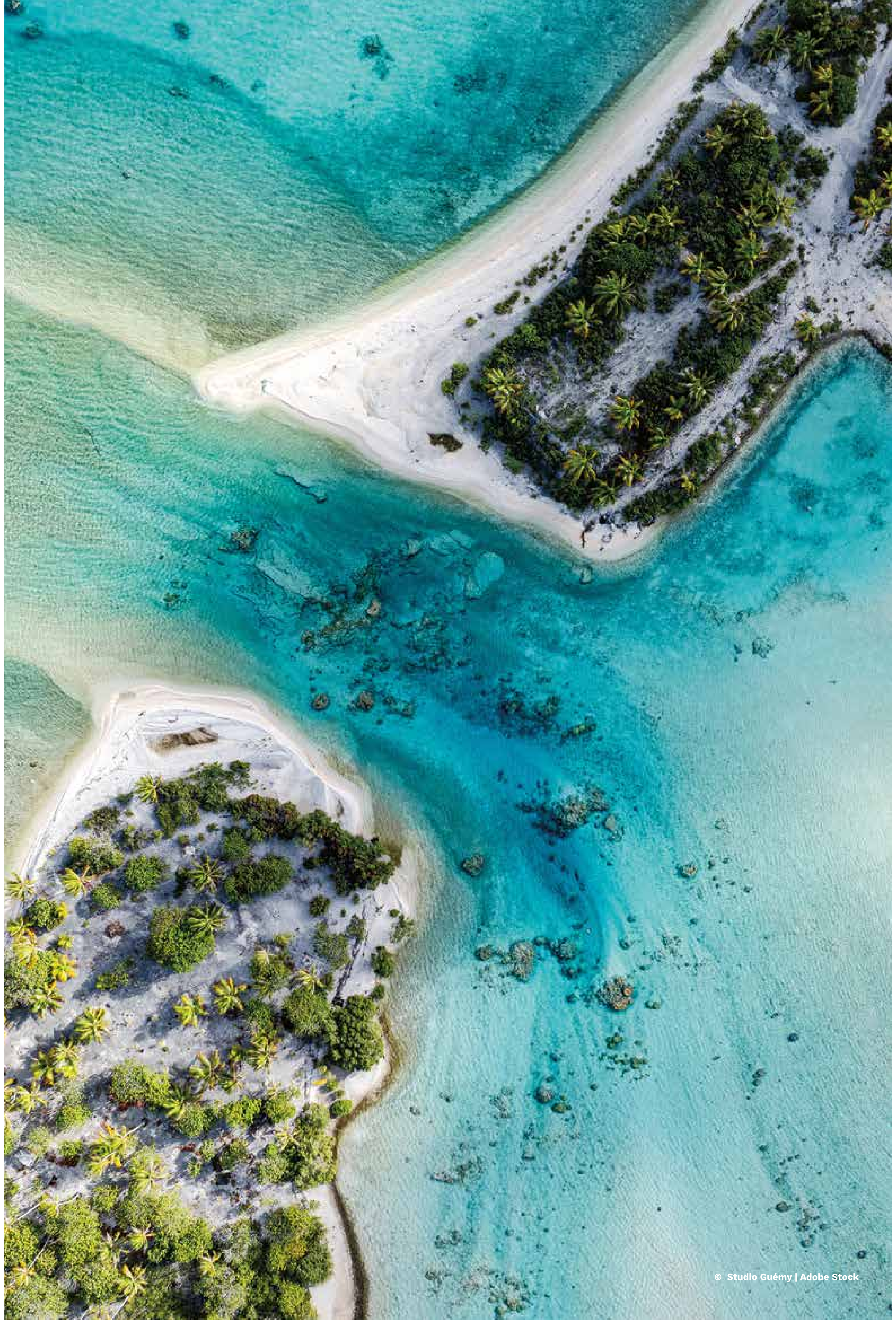
BOX 1. WHAT IS A TIPPING POINT?

A tipping point is reached when a system crosses a threshold beyond which change becomes self-sustaining. A ball nudged partway up the side of a valley rolls back; pushed over the rim, it accelerates into a new valley of its own accord. Negative tipping points that can affect the fate of ice sheets, ocean currents and rainforests behave in this way and are usually irreversible in terms of human timescales. Positive tipping points follow the same logic in reverse: once a cleaner technology or behaviour becomes cheaper, better and easier to access than the unsustainable one it replaces, adoption can become self-reinforcing and accelerate of its own accord.

THE PROXIMITY OF RISK

Over the past few decades, negative Earth system tipping points were treated as low-probability, high-impact risks somewhere beyond 2C of warming. As David Armstrong McKay's primer in this issue sets out, that is no longer the case. The number of recognised climate tipping elements has grown from nine to 16 to 25, and several are now assessed as capable of tipping within the range of warming the world is already experiencing.[6] The average global temperature is now around 1.4C above pre-industrial levels, and the best estimate of the threshold of the Greenland ice sheet is approximately 1.5C.[7,8] The widespread dieback of warm-water coral reefs, on which the food and livelihoods of hundreds of millions of people depend, is already underway.[6]

The articles that follow give this proximity tangible form. Inès Otosaka examines how the melting rate of the Greenland and Antarctic ice sheets, which between them hold enough frozen water to raise global sea levels by some 65 m over centuries to millennia, has accelerated from 88 billion tonnes a year in the 1990s to nearly 400 billion tonnes a year in the 2010s. Parts of West Antarctica may already have passed the point of no return.



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Hogan and colleagues describe the effort to measure, at the boundary where warm ocean water meets the ice, the small-scale physics of melting that current sea-level projections still leave out. Nicole Laureanti and colleagues consider the Atlantic Meridional Overturning Circulation (AMOC), the vast oceanic conveyor of heat that gives north-western Europe its temperate climate. They argue that the risk of collapse this century may be greater than the most recent Intergovernmental Panel on Climate Change assessment, while stressing that uncertainties remain. A collapse could drive January temperatures in parts of Europe down by more than 10C, raise sea levels along the US East Coast and disrupt the monsoons on which billions of people depend.

Carlos Nobre, who first published on the Amazon tipping point in 1990, describes a rainforest whose collapse to a savanna state – if deforestation and warming combine to cross the threshold – could release hundreds of billions of tonnes of carbon, turning one of the planet's great carbon sinks into a source.

A weakening AMOC, a melting Greenland and a stressed Amazon are not separate threats. They are linked. Crossing one threshold can raise the likelihood of crossing another. As Armstrong McKay observes, every further fraction of a degree of warming makes such outcomes more likely.

ADAPTATION, FAIRNESS AND GOVERNANCE

Sarah Redicker notes that 2024 was the first calendar year in which global temperatures exceeded 1.5C above pre-industrial levels. The 1.5C limit, which 195 countries and the EU agreed should not be crossed, became, at least briefly, a reality. A single record year is not the same as the long-term average to which the Paris Agreement limit refers, but we are now likely to exceed 1.5C as a 20-year average at around 2030.[9] Action on climate change, Redicker argues, can no longer rest on prevention alone; it must also address adaptation to change that can no longer be prevented, and the question of who is left to cope.

That question is, at its heart, one of fairness. The burdens of a tipping world fall most heavily on

those least responsible for creating it, and the international mechanisms intended to share them remain pitifully small beside the scale of the need: the loss and damage fund agreed at COP28 attracted initial pledges far smaller than the annual costs facing developing countries.

Erin Sikorsky carries the analysis into national security. She argues that tipping points will not merely add to familiar threats but reorganise the conditions that security planning has long taken for granted – from the reliability of harvests to the viability of coastal infrastructure. Planning that is built on the assumption of a stable environment, she warns, has no historical precedent to fall back on once that assumption fails.

Manjana Milkoreit provides the connecting argument: the institutions available to us were designed for problems that are gradual, reversible and bounded by borders. They are poorly suited to emerging tipping point risks that are the opposite: non-linear, irreversible and global. Since holding global warming to 1.5C without temporary overshoot is no longer realistic, she argues, the practical task becomes limiting how far and for how long that overshoot extends. The key obstacles in her analysis are the slowness of governance to adapt and a deep failure of imagination.

We need to start thinking differently, and quickly, because we are entering a new climate reality of systemic risk. If the business adage 'you can't manage what you don't measure' is true, then 'you can't govern what you don't consider' is doubly so.

James Dyke takes up the question that follows once we accept the inevitability of overshooting 1.5C: what do we do next? Relying on the Earth's natural capacity to sequester enough carbon to reduce global temperatures to a safer operating space of 1C would take thousands of years. That leaves the geoengineering approaches that have become increasingly central to climate policy: carbon dioxide removal and solar radiation modification.

▲ **Southern dieback of boreal forest is another Earth system tipping point at risk. © Uwe Bergwitz | Adobe Stock**

Dyke explains that the risks of impermanent carbon storage, the unavoidable laws of thermodynamics and the prohibitive amount of energy required make it highly unlikely that carbon dioxide removal technologies will play a leading role in limiting warming to 1C. Solar radiation modification, whose best-researched method is sulphate aerosol injection, carries enormous risks of its own – from tens of thousands of annual deaths due to the pollution caused to the impact of disrupting the monsoon rains on which billions of people depend. The most robust and just response, he argues, is to rebuild climate policy around a rapid fossil fuel phase-out while preparing communities for the deterioration already underway.

TIPPING THE OTHER WAY

Being in a new climate reality of systemic risk gives positive tipping points added importance. Were the damaging thresholds still safely distant, then gradual and incremental progress might be sufficient. On the evidence assembled here, they are not. The situation calls for rapid, radical change that is self-reinforcing.

Cormac Lynch shows how the dynamic operates in the energy system. A positive tipping point occurs when a low-carbon technology becomes more affordable, accessible and attractive than the incumbent one, prompting a self-reinforcing shift. Heat pumps are already several times more efficient than fossil-fuelled heating, yet the way we price electricity – loading it with taxes and levies while gas sets the marginal price – kills that advantage.

Rebalancing those costs is the kind of modest policy intervention that could trigger a much larger transformation. Tanvir Ahmad offers a human illustration from displaced communities in Pakistan, where the distribution of solar home systems has done far more than provide light: more than nine in 10 of the women surveyed reported feeling safer after dark, children could study into the evening, and households were freed from the fumes and emissions of kerosene. A solution, as he writes, does not need to be large to be systemically important.

These examples demonstrate that the self-reinforcing dynamics we fear in the ice and ocean can become a source of hope when turned deliberately to sustainable technologies and behaviours, and that they can move more quickly than conventional forecasting tends to assume.

> **"Justice is not a constraint on the urgency of the transition but a condition of its success."**

SPEED WITH JUSTICE

One qualification runs through this issue and deserves to be emphasised, because it is easily lost amid the talk of speed and urgency: speed is necessary, but it is not sufficient. A transition to a sustainable future that is rapid but unjust or that strands communities, widens inequality or is imposed from above, is unlikely to endure. The evidence collected here, from Redicker's account of the adaptation gap to Ahmad's stories of dignity and safety, points to the same conclusion: durable change is rooted in fairness and shared benefit and carries people with it. Justice is not a constraint on the urgency of the transition but a condition of its success.

That is the balance this issue attempts to hold. The risks are real and the relevant thresholds are closer than much policy still assumes; yet the same dynamics that make those risks so acute also indicate a way forward – deliberately creating the conditions in which cleaner, fairer, better systems begin to sustain themselves.

Steven R. Smith is a Research Fellow at the Global Systems Institute and Green Futures Solutions at the University of Exeter. Steve is one of the lead authors of the *Global Tipping Points* reports (2023 and 2025) whose research interests span the social, economic and political dimensions of the transition to a sustainable future.

s.r.smith@exeter.ac.uk

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Over the edge: a climate tipping points primer

David Armstrong McKay outlines climate tipping points, how they interact with one another and the challenges we face when thresholds are reached.

A core finding of modern climate science is the tight relationship between global warming and the total emissions of carbon dioxide (CO_2). Since 1850, humans have released around 2,400 billion tonnes of CO_2 into the atmosphere, with global temperature in turn increasing by around 1.4C today.[1,2] Plotted on a graph, and smoothing out natural variations we see from year to year, the two are in near lockstep – just one of many strands of evidence in support of the human-enhanced greenhouse effect. It is also clear this relationship is what we call linear – meaning that each tonne of CO_2 emitted causes similar warming to the one before – and all theory and models point to this continuing into the future.

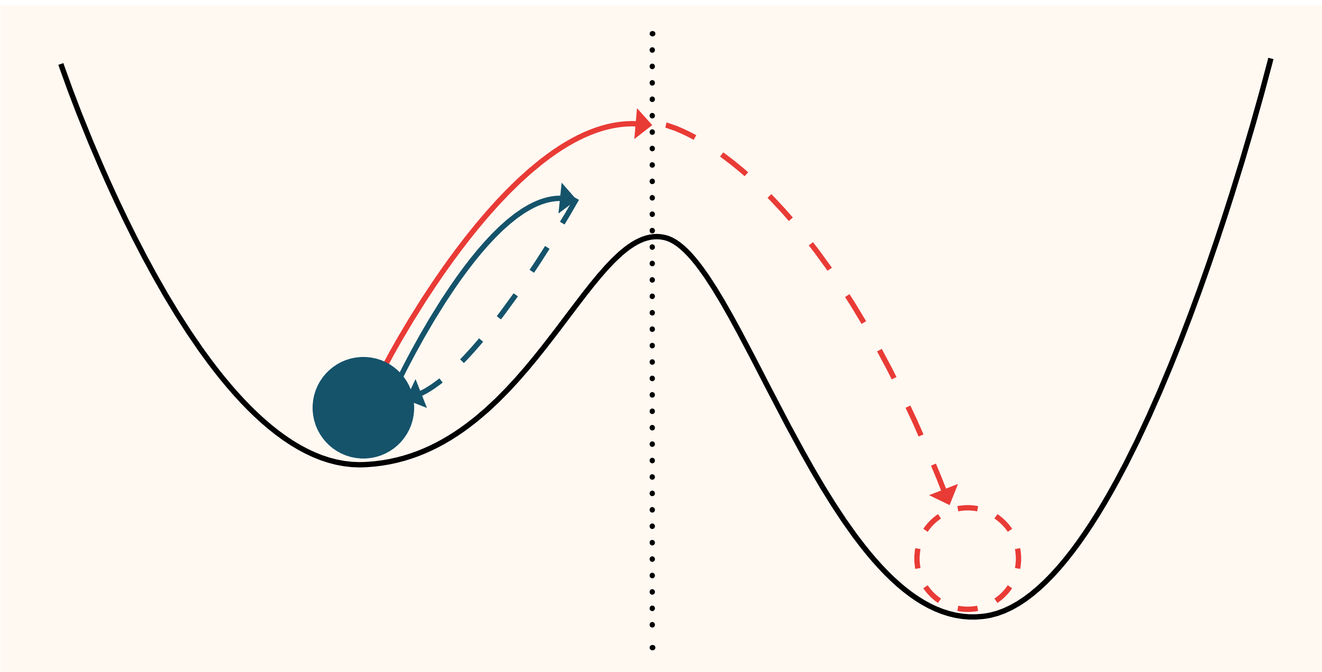
CLIMATE SURPRISES

The linearity of global warming is clear, but we also have evidence that not all of the climate system always behaves so linearly. While evidence for global warming has accumulated since the 1960s, palaeoclimatologists (researchers of ancient climate change) also began to find evidence of surprising past climate shifts.[3] Ice cores from Greenland showed how the end of the last Ice Age glacial (i.e. cooler period) was far more abrupt than geological theory expected, and the glacial itself featured even more rapid but temporary temperature swings, associated with shifting ocean currents. Ocean sediment cores enabled researchers to see even further back, showing how gradual cooling over the past 50 million years was punctuated by abrupt warming and cooling shifts. Nascent climate models helped make sense of this behaviour, showing how the climate system also features non-linear dynamics, allowing for our otherwise linear expectations to be interrupted by what became known as climate surprises.

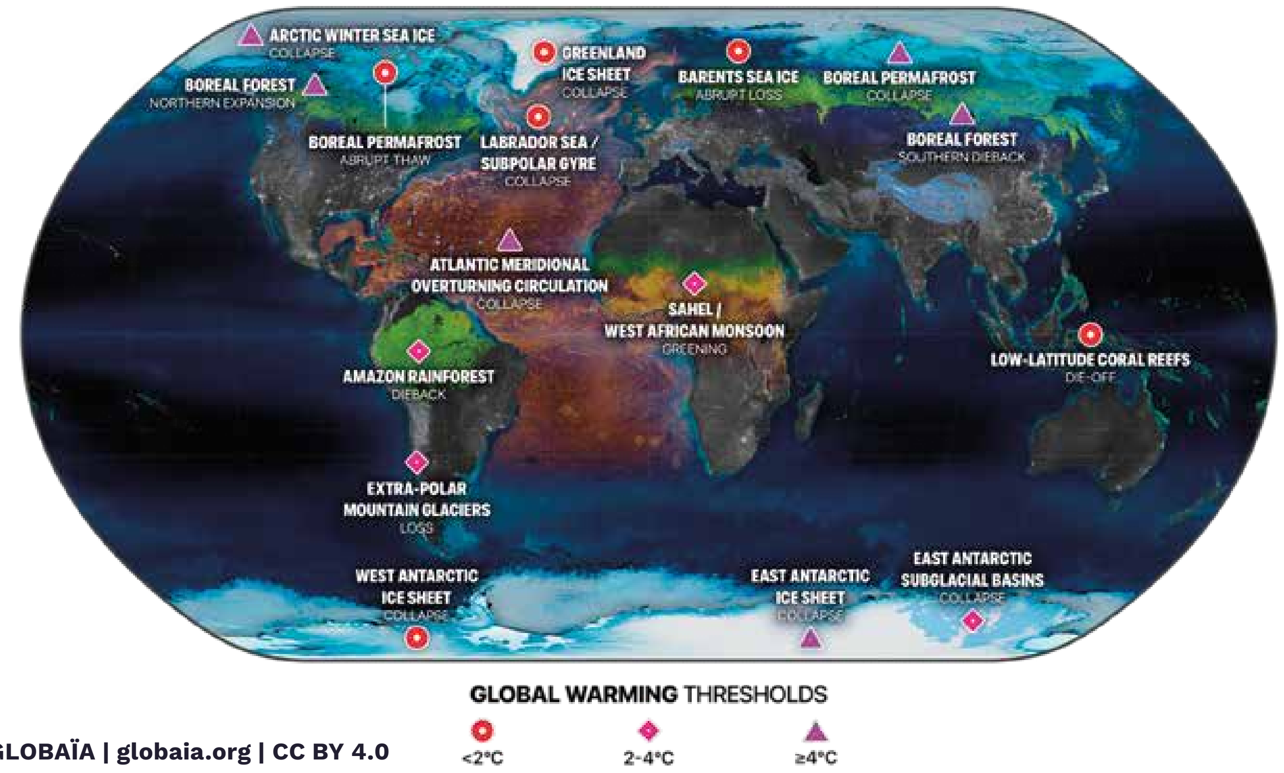
One such climate surprise is a tipping point. Originally a sociological term, it was popularised by Malcolm Gladwell's book *The Tipping Point*.[4] By 2004, some climate scientists began to adopt the term, at first as a useful metaphor to communicate the possibility of climate surprises in general. In 2008 a group led by Tim Lenton developed a more specific definition in a now-seminal paper.[5]

They defined climate tipping points as 'a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system'. Key here, and in follow-up research, is that crossing this threshold leads to a self-sustaining shift in that system's state – for example, from closed forest to open savanna, or from ice sheet to isolated ice caps – that is effectively irreversible, even if warming were to stop and reverse.

This shift is driven by positive feedbacks (which can drive feedback loops), with the initial driver amplified by the system's response, and under certain circumstances becoming self-sustaining (see **Figure 1**). In this illustrative example, the ball (representing the state of a system) starts out on the left-hand valley, where it is fairly stable. If it is pushed to the right – by warming, for example – but if the pushing stops before reaching the hilltop, the ball will roll back to its initial, resilient, state. However, if it crosses the threshold, the ball will keep rolling until it reaches a new stable state, even if the pushing were to stop shortly after the threshold.



▲ **Figure 1. An analogy for tipping dynamics. (Source: Based on Armstrong McKay, 2024[3])**



▲ **Figure 2. Sixteen proposed climate tipping elements with their best-estimate global warming thresholds. (Armstrong McKay *et al.*, 2022[6])**

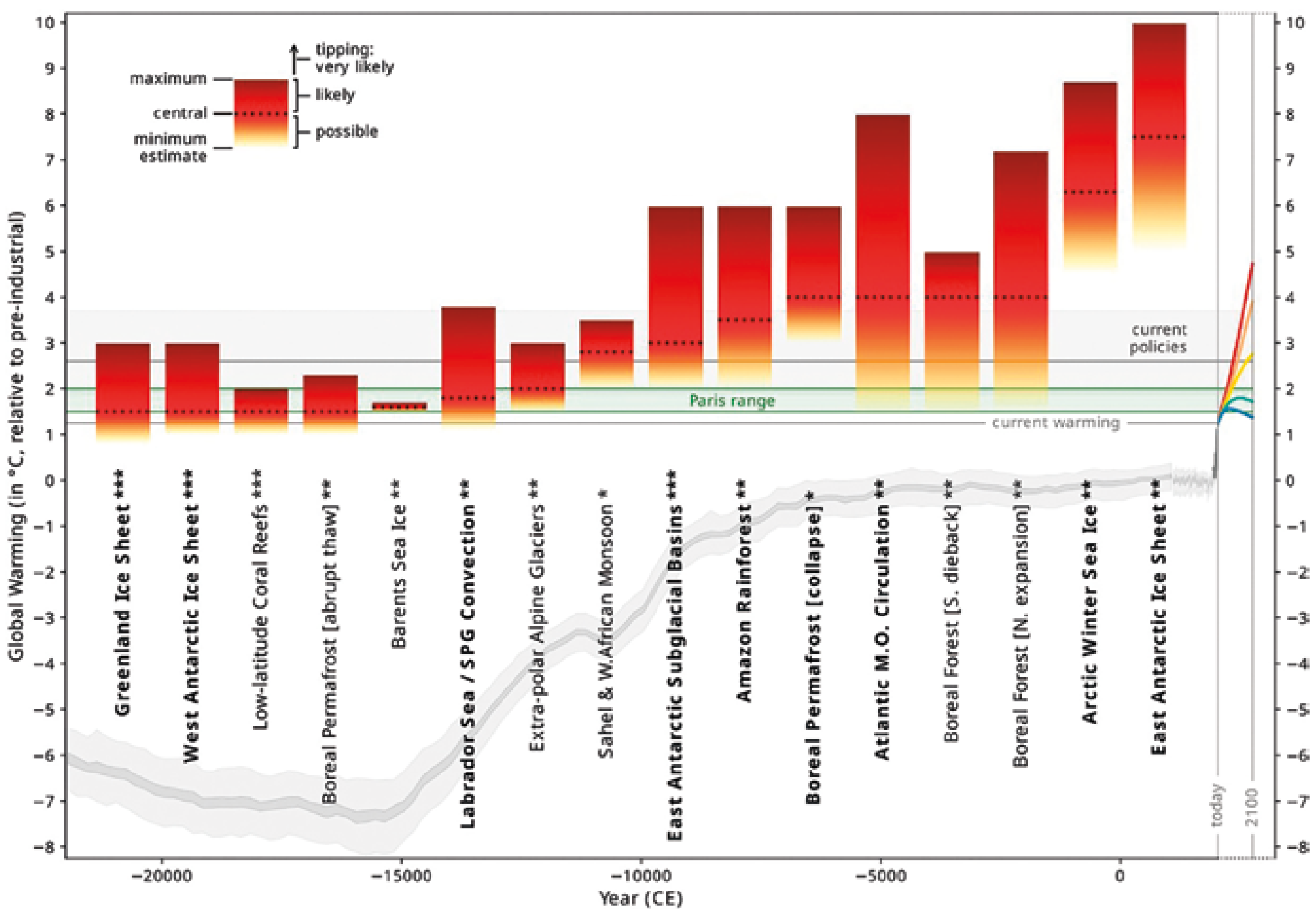
Nine parts of the climate system – termed tipping elements – were initially identified as potentially featuring tipping points that could be triggered by human activity this century. Since then, many more systems (such as warm-water coral reefs and ocean convection in the North Atlantic subpolar gyre) have joined the list, while others such as Arctic sea ice have been dropped as new evidence emerged (with models showing no clear threshold beyond which feedbacks lock in sea ice loss). A major reassessment came in 2022, following a systematic analysis of published evidence from across geological records, climate models and observations, and updated by the *Global Tipping Points* reports in 2023 and 2025.[6,7,8] Together, these assessments identify multiple major elements, which if tipped would have substantial impacts on people and nature (see **Figure 2**).

The estimated ranges of global warming at which tipping points could occur for each tipping element are shown as 'burning embers' (see **Figure 3**). The chart shows the minimum-level tipping thought possible at the bottom of each burning ember; the central 'best' estimate beyond which tipping is thought likely is marked by the dotted line; and the maximum level is at the top of each ember. Also shown are the confidence level in each element having tipping dynamics (by the number of asterisks after the name); the global warming levels for current, Paris Agreement range and estimated current policy trajectory; and the reconstructed past and future global temperatures – the latter coloured in accordance with the emissions scenarios used by the Intergovernmental Panel on Climate Change (from blue for very low to red for very high emissions).

CRYOSPHERE TIPPING POINTS

The first major category of climate tipping points can be found in the Earth's cryosphere – the frozen parts of the planet.

Ice sheets are some of the best-known possible tipping elements, with clear potential for tipping dynamics and holding many metres worth of sea level rise.



▲ **Figure 3. The 'burning embers' diagram of tipping ranges. (Source: Armstrong McKay, 2024[3]; Armstrong McKay *et al.*, 2022[6]) (CC-BY-NC 4.0)**

▲ **AMOC collapse could lead to a Siberian climate for the UK. © evdokimari | Adobe Stock**

Melting of the Greenland ice sheet, for example, could become self-sustaining due to the melt-elevation feedback: as it melts, it loses height, dropping its cold top into warmer, lower altitudes, amplifying melt. Studies indicate that beyond a threshold between 0.8C and 3.4C (with a best estimate of 1.5C) this could result in continued ice sheet melt even if warming stopped or reversed. This means that a Greenland ice sheet collapse is already possible, locking in up to 7 m of sea level rise, although is not yet likely unless warming remains above Paris Agreement levels by the end of the century.

At the other end of the planet, there is also evidence that the West Antarctic ice sheet – holding another 5 m worth of sea level rise – also has a threshold beyond which large-scale collapse is locked in. In this case, the key vulnerability is that the ice sheet base sits in a basin deep beneath sea level, with warming ocean water causing its grounding line (i.e. where the ice meets bedrock) to recede. It is estimated that somewhere between 1C and 3C, most likely at 1.5C or more, grounding lines will have retreated enough for this receding to become self-sustaining across most of the ice sheet. As with Greenland, full ice sheet collapse would take thousands of years, which means that the billion or so people living within 10 m of sea level rise across the planet do not face near-term inundation. However, if triggered, ice sheet collapse would accelerate sea level rise within the next few decades, threatening coastal cities and ecosystems with extreme flooding events far sooner than expected.

Another key cryosphere tipping element is permafrost. This includes all ground frozen for two years or more and underlies around 15 per cent of land in the northern hemisphere. This freezing prevents organic matter from decaying, resulting in the storage of up to 1,500 billion tonnes of carbon – around twice as much as in the atmosphere. However, warming is driving some permafrost to thaw, resulting in this organic matter decaying and increasingly releasing CO_2 and methane.

While the potential for wide-scale tipping is unclear, localised abrupt thaw involves self-sustaining tipping dynamics; it will be an increasingly powerful additional driver of warming on top of human emissions, as well as a disruptor of boreal landscapes, infrastructure and the livelihoods of Indigenous people and local communities who depend on herding, hunting or farming.

CIRCULATION TIPPING POINTS

The next category of climate tipping points lies in the circulation currents of the ocean and atmosphere.

Perhaps the most famous of these is the Atlantic Meridional Overturning Circulation, or AMOC. This is a system of currents bringing warm water northwards in the Atlantic, before it cools, becomes saltier and dense enough to sink off Greenland, driving ocean convection. Observations suggest the AMOC has begun to weaken, with models indicating that warming waters and increasing meltwater can disrupt the key convection process by making surface waters less salty and dense. Most models suggest this will be a gradual, linear decline with warming, but they are not able to re-create some of the more abrupt AMOC collapses that geological evidence indicates have happened in the past. An increasing number of complex models though are able to simulate AMOC collapse; however, due to missing processes and complex dynamics, the point at which it might occur is highly uncertain – estimates range from as low as 1.4C to as high as 8C, and collapse may depend on exactly where meltwater is concentrated.

AMOC collapse would not be as rapid or sensational as in Hollywood films; it would occur over many decades but would still have dramatic implications. Not only would Europe cool and dry – with Siberian-like winters and dry summers, for example, making arable farming all but impossible in the UK – but it would also drive large monsoon shifts in the tropics, disrupting agriculture and ecosystems over many continents.

Other ocean circulation systems may also have a tipping point. Convection in the subpolar gyre in the North Atlantic could collapse sooner and faster than the rest of the AMOC – shown to occur as early as the 2040s in around 40 per cent of relevant models – taking only a decade and having similar but less-intense impacts. Meltwater from Antarctica could also trigger convection collapse in the Southern Ocean but so far is less well-studied.

In the atmosphere, the biggest tipping-related effect is through the monsoons. For most, climate change is expected to strengthen rather than weaker them, with warm air holding more moisture. Interactions with vegetation could still lead to tipping, however, with the West African monsoon potentially leading to a greener Sahel, for example. In contrast, air pollution could potentially lead to a shift towards a weaker South Asian monsoon by regionally darkening the atmosphere and weakening the air pressure gradient that brings moisture from the Indian Ocean – although this is still uncertain.

BIOSPHERE TIPPING POINTS

The final set of climate tipping points is within the Earth's biosphere – the planet's ecosystems and biomes.

The Amazon rainforest, in particular, has attracted concern for its potential for tipping behaviour. Forest is being lost from the double threat of climate change – which is leading to more severe droughts and greater wildfire risks – and direct degradation and deforestation due to growing pressures from agriculture, infrastructure and mining. A key concern, though, is that there could be thresholds, both in warming and deforestation levels, beyond which this forest loss would begin to cascade across a wider area.

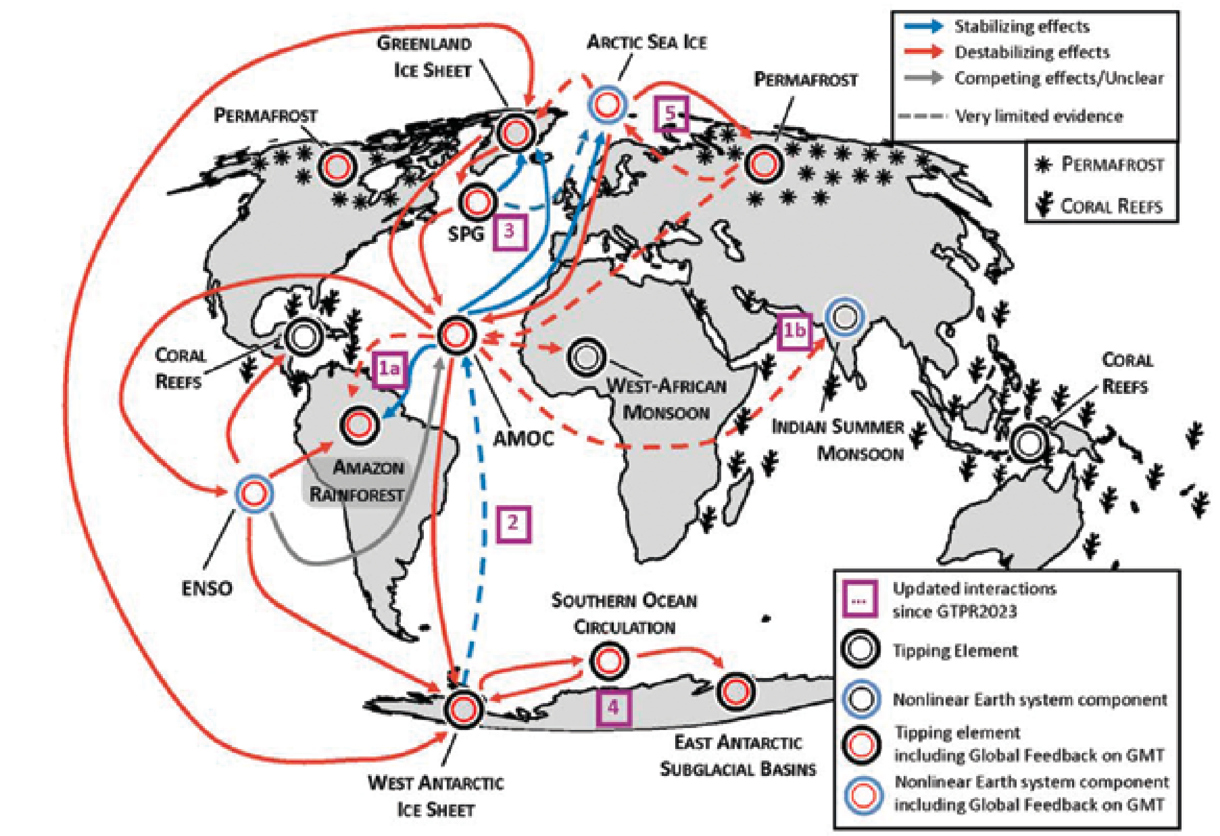
This could happen because the Amazon rainforest itself helps to expand the area where there is enough precipitation to sustain rainforest by recycling rainfall through evaporation and transpiration back into the atmosphere and carrying it downwind to drier areas. But if enough forest is lost, these drier areas (currently making up around 40 per cent of the Amazon) would not receive enough of this recycled rain, leading to rainforest dieback. Estimates for when this could happen are uncertain: from climate change alone, it could happen between 2C and 6C of warming; for deforestation, a precautionary threshold of 20 per cent forest loss (versus around 15–18 per cent today) has been proposed; and warming and deforestation together make more than 1.5C risky. Amazon dieback effects would include substantial habitat loss in Earth's most biodiverse land biome and regional amplification of warming and drying not only in the Amazon but down to the southern cone of South America.

Another key biome at risk of tipping is warm-water coral reef. Coral reefs consist of millions of small reef-building animals living in symbiosis with photosynthesising algae, providing food in return for shelter. However, when stressed, such as by a severe marine heatwave, corals can expel the symbiotic algae that feed them, becoming pale and starved – a process known as coral bleaching. This can happen naturally, but climate change is making heatwaves more extreme and more frequent. Eventually, bleaching becomes too frequent to recover from each time, leading to increasing mortality; beyond a coral-loss threshold, the reef ecosystem collapses. This is a localised process that happens differently in each reef, but by 1.5C, widespread reef mortality is expected around the world and may already be inevitable if warming remains above around 1.2C for long. This would lead to substantial biodiversity loss in one of Earth's richest biomes – with around a quarter of marine species connected in part of their life cycle to coral reefs – and affect around half a billion people's livelihoods linked to reefs through fisheries, coastal protection and tourism.

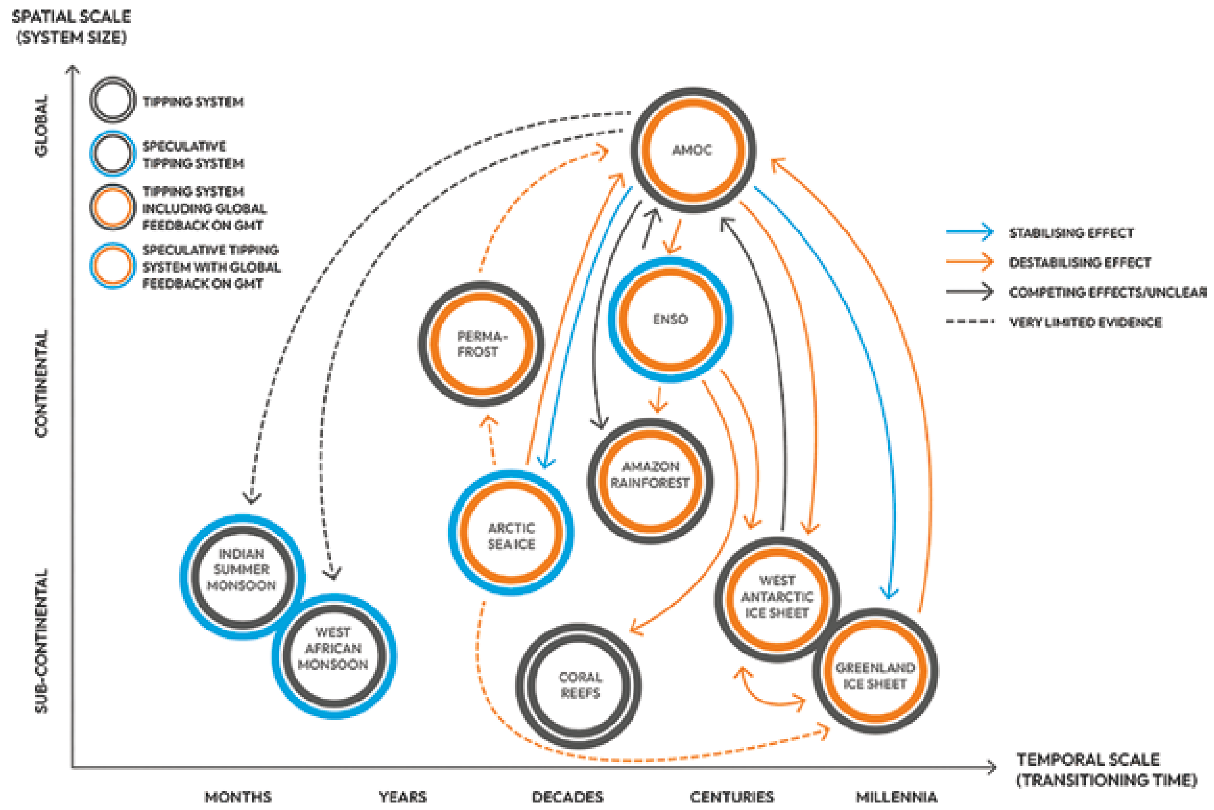
Many other parts of the biosphere could also see local- to regional-scale tipping points due to climate change and other human pressures, including in boreal forests, savannahs, mangroves and fisheries. However, unlike many cryosphere or circulation systems, the likelihood for climate-induced tipping can be reduced by also

▲ **The Hadejia River meandering through the Sahel, Nigeria. © Aerial View | Adobe Stock**

▲ **Mother and child walking through monsoon showers. © sugitas | Adobe Stock**



▲ **Figure 4. Interactions between tipping elements. (Source: Lenton *et al.*, 2023[7]) (CC BY-NC-ND 4.0)**



▲ **Figure 5. Interactions between tipping systems across scales in space and time. (Source: Lenton *et al.*, 2023[7]) (CC BY-NC-ND 4.0)**

tackling other human-driven pressures, including habitat loss and pollution. In the Amazon, for example, deforestation lowers the warming threshold for widespread dieback, but halting deforestation and restoring forest (via natural regeneration or agroforestry) in key areas can help maintain the moisture-recycling feedbacks that sustain much of it.

THE OUTLOOK

Scientists have assessed these systems as being capable of tipping given sufficient global warming or other human drivers. One tipping point occurring is also expected to, in most cases, make other tipping points more likely – in the worst case leading to a tipping cascade of one triggering another, and so on (see **Figure 4** and **Figure 5**).[10]

However, deep uncertainty remains on their timings, interactions and impacts. Some scientists have critiqued the usefulness of tipping points as a concept, highlighting variable definitions, misinterpretations around impacts being instantaneous or leading to runaway warming, and encouraging potentially 'doomist' or alarmist reactions in response.[3,11] It is true that tipping points can be presented in an overly simplistic and fatalistic way, and more care should be taken to discuss them in a nuanced way.

There is considerable evidence though that various parts of the climate system can undergo substantial self-sustaining state shifts because of human activities, with serious implications for the welfare of humans and other species. While further research is needed to reduce some of the uncertainties, we can be sure that every further fraction of a degree of warming makes climate surprises like tipping points more likely, underlining the need for urgent emissions cuts and climate adaptation. ES

Dr David Armstrong McKay is a Lecturer in Geography, Climate Change and Society at the University of Sussex. His research focuses on the non-linear dynamics of the Earth system, from climate tipping points to ecological resilience and food system sustainability, and he is an active science communicator on these topics.

davidarmstrongmckay.com
climatetippingpoints.info
mstdn.social/@davidamckay
@davidamckay.bsky.social

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The Amazon is close to its tipping point

Bea Gilbert speaks to world-renowned scientist Carlos Nobre about his extensive research on the degradation of the Amazon rainforest and its significance as a climate tipping point.

▼ **Road crossing the Brazilian Pantanal wetlands. © puntel | Adobe Stock**

BEA GILBERT (BG): What has changed during the decades you have been studying the Amazon?

CARLOS NOBRE (CN): I've been doing research in the Amazon for 43 years, so I know the risks involved with this tipping point. But now we also have a tremendous risk of tipping points in three other biomes in Brazil: the tropical savanna (the Cerrado), the western flooded area (Pantanal) and the steppe savanna in north-east Brazil (Caatinga, the semiarid biome).

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Along with two colleagues from the University of Maryland, we were the first scientists to publish on the Amazon's tipping point potential in 1991.[1] I spent a year in Maryland in 1988–9 doing the research, and this was the first time we realised that even when deforestation in the Amazon stops, the forest will never regrow if the tipping point is reached. In these papers, we stated that up to 50 per cent of the Amazon would never recover because, with deforestation, the dry season would become much longer – around six months long – and would not be able to maintain a tropical forest environment.

Of course, in 1990, this wasn't called a tipping point: scientists only began to use the tipping points framework in 2008–9. We know now that there is a synergistic interaction between global warming and deforestation in the Amazon, and that we are going to exceed the tipping point when deforestation reaches 20–25 per cent, and global warming reaches 2C.

Nature has just published a new study, and one of the authors is my former PhD student and now a top scientist.[2] Her name is Marina Hirota, at the Federal University of Southern University of Santa Catarina in Florianópolis, Brazil. The authors have done beautiful work. They did the same calculation that I did 10 years ago, but the more recent one shows that the risks are even greater: the tipping point happens when deforestation reaches 22–28 per cent, but global warming will only need to be 1.5–1.8C. Science shows very clearly we are going to reach 1.5C global warming by 2030.

Now the Amazon is very close to its tipping point, because deforestation is at 17–18 per cent. According to new studies, reaching 22 per cent deforestation and global warming of 1.5C is a tremendous risk. Back in 1999, I led important research called the Large-Scale Biosphere–Atmosphere Interaction experiment in the Amazon. The study showed that in the southern Amazon – more than 2 million square kilometres from the Atlantic Ocean to Bolivia – the dry season is increasing by one week per decade. Today, it's four to five weeks longer in comparison to the last 40–45 years, and up to 20 per cent drier.

Tree mortality is also increasing in this area. In one study I worked on with a colleague, Luciana Gatti, we calculated the carbon dioxide markers at four sites in the Amazon: in the south-east, north-east, south-west and north-west. Once a month, aircraft took measurements of carbon dioxide and carbon monoxide. Biomes, especially tropical forest, remove a tremendous amount of carbon dioxide. Out of all carbon dioxide that we create through fossil fuel burning, deforestation and agriculture, so much of it is removed by the forest and by the ocean. Now the Amazon is losing that capacity, and this was shown in our study. In the south-eastern Amazon, we have found that the forest has become a carbon source, and degradation is increasing significantly. So the Amazon is very close to its tipping point. If we continue with global warming and deforestation we are definitely going to reach this tipping point by 2040.

BG: What are the risks if the tipping point is triggered?

CN: There are many, many risks. Up to 77 per cent of the Amazon will self-degrade.[2] The Amazon stores more than 150 billion tons of carbon; and this is carbon removal that's happened over millions of years. If the Amazon self-degrades, by 2100, 200–250 billion tons of carbon dioxide will be released. If that happens, it will be impossible to maintain global warming at 1.5C. There is a tremendous risk for the planet if we exceed 1.5C: melting permafrost could then release a further over 200 billion tons of greenhouse gases by 2100. So these two tipping points alone – the melting of the permafrost and the degradation of the Amazon – will release more than 400 billion tons of greenhouse gases. The temperature will then reach 3–4C of warming.

And this is just one critical area. The other is biodiversity. The Amazon has the highest biodiversity of any ecosystem on the planet: it is home to about 13 per cent of all flora and fauna species known to science.

We also know that degraded tropical forest presents a large risk of epidemics and pandemics. In 2024, two epidemics emerged from the Amazon and spread: the Mayaro virus disease and Oropouche fever (sometimes called sloth fever). Oropouche is transmitted by an insect that exists all over Brazil, and one study suggests that millions of Brazilians have already been infected in recent decades. Studies have shown that in the Amazon there are many zoonoses that could become epidemics.

▲ Carlos Nobre in 2012. © Ministério da Ciência, Tecnologia e Inovação. (CC BY-2.0)

The third major risk is to another ecosystem service. The Amazon rainforest is very efficient at recycling water: rainfall goes into the soil, the root system brings the water up to the leaves, and transpiration causes it to go into the atmosphere where it forms clouds and subsequently becomes rainfall. About 40 per cent of the rainfall in the Amazon depends on this water recycling.[3] The Amazon exports a lot of water vapour to ecosystems to the south of the Amazon tropical savanna, and further south still to the Atlantic rainforest. About 50 per cent of the rain in the tropical savanna south of the Amazon depends on these moisture fluctuations: in the west, it's called the aerial river, but in Brazil we call them flying rivers.

If we cross the tipping point in the Amazon, it will reduce the aerial rivers and a lot of the tropical savanna to the south of the Amazon will become a semiarid biome like in north-east Brazil, and we'll lose most of its biodiversity. It will also degrade a lot of the Atlantic rainforest that is in southern Brazil, Uruguay, Paraguay and northern Argentina.

BG: What are the biggest contributing factors to the destruction of the Amazon?

CN: Global warming. Brazil produces about 3–4 per cent of global emissions, but the impacts of global warming are particularly felt in the Amazon. Not only through the increase in temperature. Before global warming, we used to have one severe drought every 20 years. The forest had adapted to that, because it would then have 20 years to regrow following the droughts and wildfires. But now, in the last 20 years, we have had five very severe droughts: in 2005, 2010, 2015–16 and 2023–4, the latter being a record-breaking drought.

Historically, fires were caused by lightning strikes, but now many are human-made. Unfortunately, soy crop farmers and cattle ranchers still use fire to regenerate pasture, and sometimes they lose control and the fire moves into the forest. But between 2023 and 2024 there was a record number of fires across the Amazon, and more than ever were due to organised crime: more than 95 per cent of these fires were human-made. This shows that there is tremendous risk posed by the synergistic interactions between global warming and human-made drivers, in particular during a severe drought.

BG: We have spoken about how the habitat and ecosystems might change. How will vulnerable communities and people who depend on the Amazon – such as Indigenous groups – be affected?

CN: Indigenous peoples arrived in the Amazon about 13,000–14,000 years ago, and they have always maintained the forest. Indigenous science has developed over thousands of years: people domesticated hundreds of species, they developed agroforestry systems, and created the production of a lot of fruits, vegetables, medicinal plants and oils, all while maintaining the forest.

But unfortunately, in the 1970s most Amazonian countries started deforesting and bringing cattle in to graze, followed by soy crop farming. This puts Indigenous people under tremendous risk. Brazil's current government is trying to demarcate many new Indigenous territories, but the risks remain high due to organised crime and land grabbing: criminal groups grab public land, deforest it, put down pasture, bring in cattle, then sell them in the legal cattle ranch markets.

Another significant illegal activity is gold mining. Organised crime carries out a lot of illegal gold mining, using mercury to separate the gold that is collected from near to and in the river. That mercury spreads in the water, then is absorbed by fish. The Amazon population mostly eats fish, so they have high levels of bioaccumulated mercury, which is very dangerous for their health. In the largest Indigenous territory in the world – a 90,000-square-kilometre area inhabited by the Yanomami Indigenous group – there were more than 20,000 illegal gold mines at one point, and the mercury level was very high. A lot of people died.

BG: How have governments, particularly governments across South America, responded

to the Amazon approaching its tipping point? Is there any prospect of real legislative change when it comes to defending the rainforest?

CN: In August of 2023 there was an important summit meeting in Belem, Brazil, the same city where COP30 was held. Most Amazonian countries, except French Guyana (because this is sometimes considered European) signed documents saying they would move towards zero deforestation. Deforestation rates started to drop from 2023. There was about a 50 per cent reduction in deforestation in 2025, compared to 2022. The first four months of 2026 in the Brazilian Amazon have seen the lowest deforestation rate in history, and it might be this year that we finally reach more than a 60 per cent reduction.

However, when the rate of deforestation dropped in 2023, organised crime gangs started using fire: they would set fires and then leave. Stationary satellites take about one and a half to two hours to detect a fire, and only when the area on fire reaches 30–40 square metres in size. While there was a record-breaking number of forest fires in 2023–4, the good news is that there was a reduction in the second half of 2025, as Amazonian governments have started combating this crime. This was also because 2025 was a normal rainfall year, unlike 2023–4's record-breaking drought. There was a drought for four months this year and we haven't seen many fires so far.

Brazil is starting an important plan to restore 24 million hectares by 2050 (with 6 million hectares by 2030) all over southern Brazilian Amazon. It's seeking a lot of international funding: US$40 billion in total, with $10 billion by 2030. Colombia is also moving towards restoration. To keep global warming to around 1.5C, we have to enact large-scale restoration as a nature-based solution.

I'm a co-chair of the Science Panel for the Amazon, and at COP28 we launched what we call a socio-bioeconomy of healthy standing forest and flowing rivers.[4] Essentially, this tells us how to revert to the same socio-bioeconomy that Indigenous people developed over thousands of years. Of the four nature-based solutions, large-scale restoration of the socio-bioeconomy is third. The fourth is valuing Indigenous Peoples' and local communities' knowledge – really learning from them, because they have been living so well for thousands of years in the Amazon. ES

Carlos Nobre is an internationally recognised meteorologist and climate scientist who has published research on the climate impacts of the Amazon rainforest over four decades. Carlos was one of the first researchers in the 1990s to sound the alarm on the devastating impacts of Amazonian deforestation on global warming. He has worked at Brazil's National Institute for Space Research and now works at the University of São Paulo and is Co-Chair of the Science Panel for the Amazon.

www.sp-amazon.org

▲ **A wildfire rages across the Brazilian Amazon. © Brarymi | Adobe Stock**

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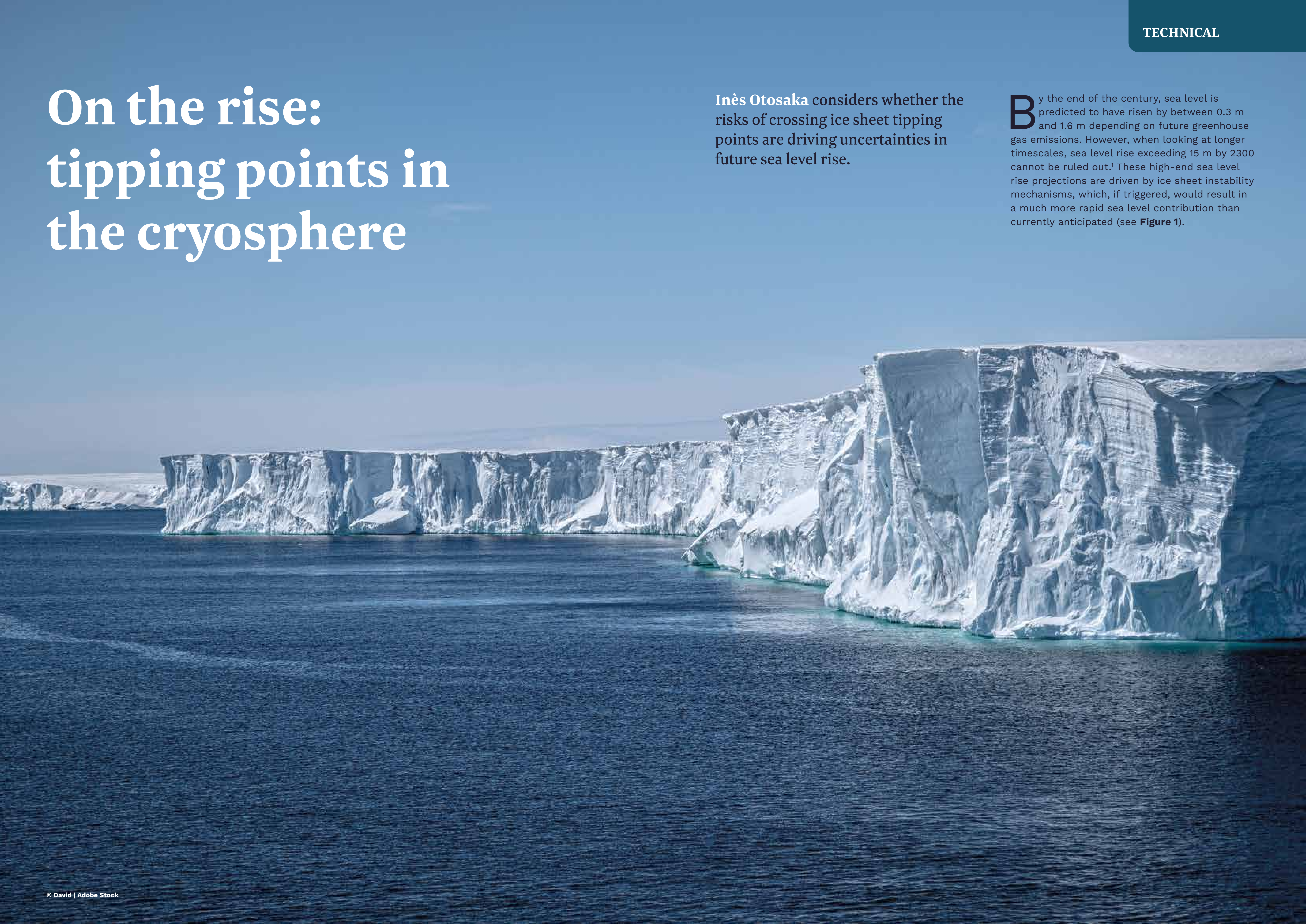
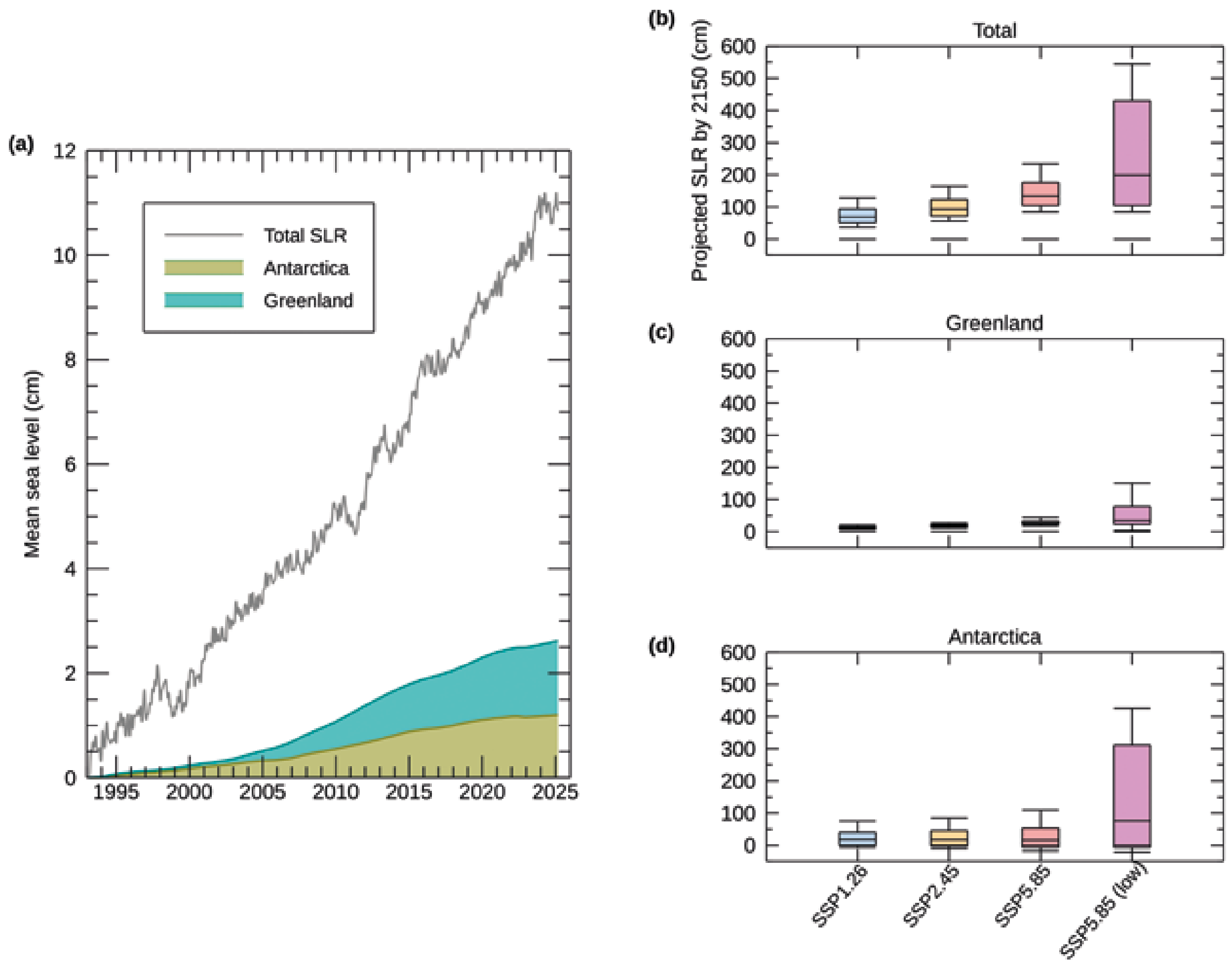
On the rise: tipping points in the cryosphere

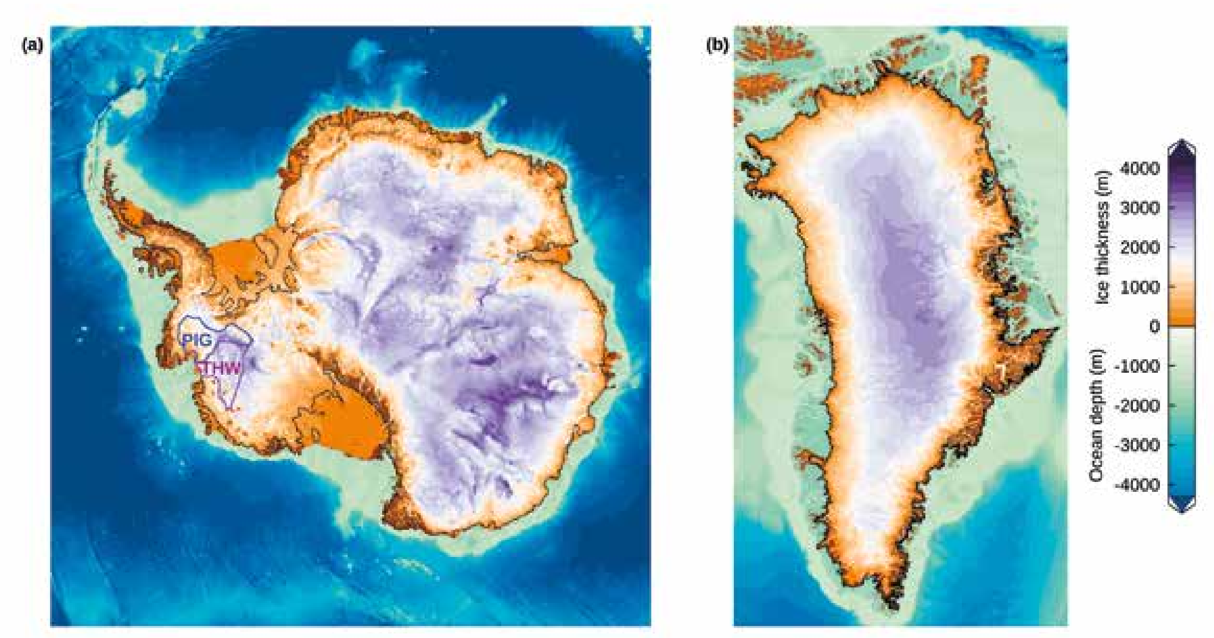
Inès Otosaka considers whether the risks of crossing ice sheet tipping points are driving uncertainties in future sea level rise.

By the end of the century, sea level is predicted to have risen by between 0.3 m and 1.6 m depending on future greenhouse gas emissions. However, when looking at longer timescales, sea level rise exceeding 15 m by 2300 cannot be ruled out.[1] These high-end sea level rise projections are driven by ice sheet instability mechanisms, which, if triggered, would result in a much more rapid sea level contribution than currently anticipated (see **Figure 1**).





▲ **Figure 1. (a) Observed and (b) projected total sea level rise (SLR) and respective contributions from the (c) Greenland and (d) Antarctic ice sheets. (Source: Created by the author based on Fox-Kemper *et al.*, 2021;[1] AVISO, 2026;[2] and Otosaka *et al.*, 2023[3])**



▲ **Figure 2. Thickness of the (a) Antarctic and (b) Greenland ice sheets and surrounding ocean bathymetry. The black outline indicates the boundary between floating and grounding ice (i.e. the grounding line). The locations of Pine Island (PIG) and Thwaites (THW) glaciers, two of the fastest-flowing glaciers in Antarctica, are shown by the blue and purple outlines respectively. (Source: Created by the author based on Morlighem *et al.*, 2020;[4] and Morlighem *et al.*, 2017[5])**

This figure shows the projected sea level rise by 2150 for total sea level rise, as well as Greenland and Antarctica ice-sheet-related sea level rise under different climate warming scenarios. Scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively, are of low, intermediate and very high greenhouse gas emissions. The final scenario – SSP5-8.5 (low) – incorporates some additional low-likelihood, high-impact ice sheet processes.

The Greenland and Antarctic ice sheets store enough frozen water to raise sea levels by 65m (see **Figure 2**). While these huge bodies of ice were previously thought to change very slowly over millennia, satellite data have revealed that the pace of ice-sheet-mass loss has accelerated since the 1990s, rising from 88 gigatonnes of ice per year (Gt/yr) to 391 Gt/yr in the 2010s.[3]

As a result, the ice sheets are now a major contributor to global sea level rise, accounting for around a fourth of all sea level rise, and are projected to become the main driver of future sea level rise, outpacing contributions from mountain glaciers and ocean thermal expansion (ocean water expanding and taking up more space as it warms).

Yet projecting the ice sheets' future contribution to sea level rise is no easy task, especially because of the possibility of tipping points being crossed. Crossing tipping points would result in a non-linear response of the ice sheets in which a small increase in ocean or atmospheric warming leads to a very large and abrupt change in the ice sheets, potentially resulting in an irreversible retreat of large glacier sectors of Antarctica and Greenland.

ICE SHEET INSTABILITY MECHANISMS

The ice sheets gain mass through snowfall accumulation and lose it through melting under the action of the atmosphere and oceans. On the one hand, warming air temperatures lead to melting at the surface of the ice sheet, resulting in meltwater run-off. On the other hand, ice that is transported via ice streams and glaciers under the effect of gravity from the interior of the ice sheet to the ocean melts at the ice–ocean interface or can break off to form icebergs. In Greenland, ice has been lost under the combined effect of ocean and atmospheric warming, while in Antarctica – where 75 per cent of the continent is fringed by large floating platforms of ice called ice shelves – oceanic processes have driven most of the mass loss to date. When ice losses exceed snowfall accumulation, the ice sheets contribute to raising the global mean sea level.

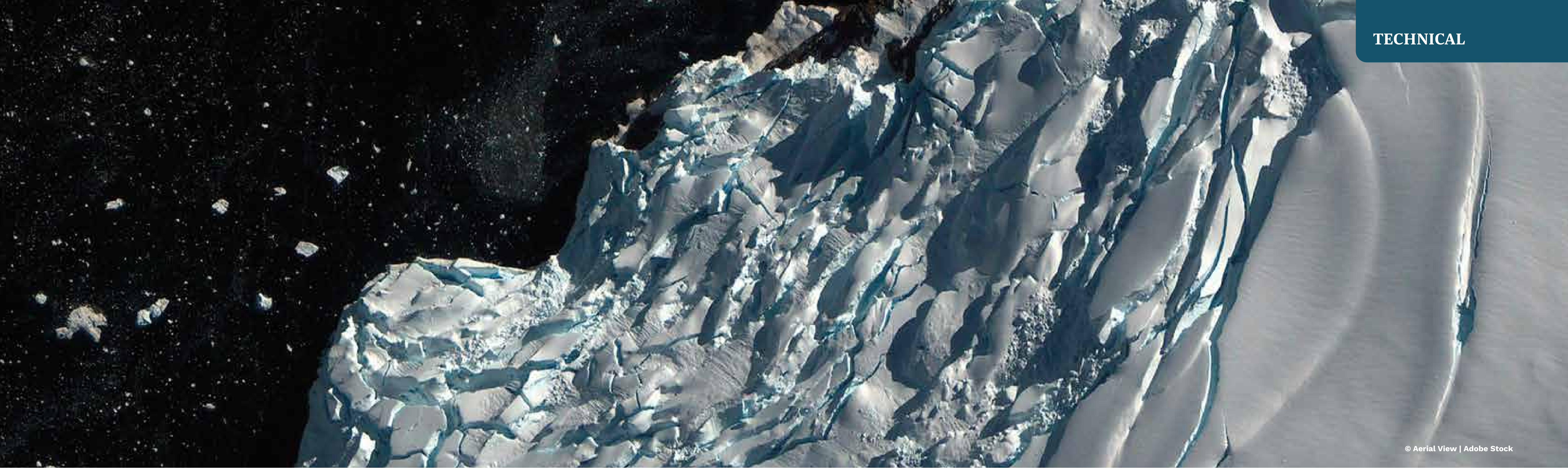


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TABLE 1. SUMMARY OF THE THREE MAIN ICE SHEET INSTABILITY MECHANISMS

MECHANISM	REGION MOST VULNERABLE	PRECURSOR SIGNS
Surface elevation melt instability	Greenland	Elevation decrease, surface melt increase, melt ponds forming further inland
Marine ice sheet instability	West Antarctica	Rapid grounding line retreat, reduced ice shelf buttressing, increased ice discharge
Marine ice cliff instability	West Antarctica, Antarctic peninsula	Crevasses propagation, melt pond formation on ice shelves

There are three main instability mechanisms that can be triggered and lead to accelerated ice losses and a partial collapse of parts of the Greenland and Antarctic ice sheets: surface elevation melt instability, marine ice sheet instability and marine ice cliff instability (see **Table 1**).

Surface elevation melt instability
In Greenland, where surface melt has increased in recent years, a self-reinforcing feedback loop can be triggered in which surface elevation of the ice sheet decreases because of warming air temperature; this results in further increased surface melt because the elevation of the ice is now lower and therefore exposed to warmer air temperatures.

Marine ice sheet instability
In Antarctica, regions where the ice sheet is grounded below sea level and deepens inland can be subjected to marine ice sheet instability. In the absence of ice shelves or when ice shelves do not provide sufficient buttressing (resistive forces that help slow down inland ice discharge), a retreat of the grounding line (the boundary between grounded and floating ice) leads to an increase in ice discharge to the ocean (as the ice thickness increases inland). This in turn leads to a further retreat of the ice sheet in a self-reinforcing loop.[6]

Marine ice cliff instability
A third instability mechanism has been theorised, in which a collapse of tall ice cliffs (approximately 100 m) triggered by ice-shelf collapse induce a rapid and sustained retreat of the ice sheet as further, taller ice cliffs, also prone to failure, become exposed behind.[7]

SIGNS FROM SATELLITE OBSERVATIONS

Satellite measurements are an essential tool to gaining a deeper understanding of both the recent past and present evolution of irreversible change in the polar ice sheets, and for detecting early warning signals of tipping points being crossed. Importantly, it is now possible to measure changes in the ice sheet elevation, flow and grounding line location – the vital signs of tipping – at fine spatial (typically between 100 m to a few kms) and temporal (typically at monthly intervals) scales and over several decades.

In the context of marine ice sheet instability, measurements of grounding line location and ice velocities are necessary to assess the stability of grounding line migration. To assess the possibility of the onset of marine ice cliff instability, it is critical to assess the integrity of ice shelves, which can be achieved by mapping their calving front (the sea-facing edge), thickness, melt rates, and extent of crevasses and damage over time. Finally, to examine the precursors of surface elevation melt instability, monitoring changes in the ice sheet surface elevation and surface mass balance, including surface melt extent and meltwater run-off of the ice sheets, is essential.

IDENTIFYING CRITICAL THRESHOLDS

While monitoring these parameters from space can undoubtedly provide useful information on the evolution of the Greenland and Antarctic ice sheets, it is necessary to complement these observations with targeted numerical model simulations to assess whether tipping has already occurred. Understanding the proximity and timing of tipping points under different climate warming scenarios is also important.

Ice sheet models have improved over the years and now include more sophisticated physical representations of key ice dynamics processes, and more work is currently being done – including coupling ice sheet models to ocean models to better represent ice–ocean interactions and to account for calving and damage processes. Models are useful to both understand the physical processes driving the observed changes and to investigate the stability of the ice sheets under different climate warming scenarios – therefore, offering the means to identify potential

thresholds beyond which we might not be able to regrow the ice sheets even if climate warming were reversed.

PROXIMITY TO TIPPING POINTS

Theory, satellite data and computer models have been instrumental in identifying these instability mechanisms. However, there remain large uncertainties on how close we might be to triggering those. It is suspected that marine ice sheet instability is already underway in West Antarctica, where satellite data have shown rapid retreat and thinning of the Pine Island and Thwaites glaciers, some of the fastest flowing in Antarctica.[8]

At the same time, simulations have also suggested that parts of West Antarctica are already at risk of substantial long-term ice loss even below 1C of global warming above pre-industrial levels and so may have already passed a tipping point.[9] Conversely, marine ice cliff instability has never been observed and is still a subject of debate within the scientific community. Some computer simulations show that following the start of a rapid marine ice cliff instability retreat, the ice also thins rapidly; this prevents further high cliff fronts to form, therefore avoiding the dramatic retreat predicted in the case of marine ice cliff instability.[10]

BOX 1. THE CRYOTIPPING PROJECT

In a new project funded by the European Space Agency, an international team of scientists is using satellite data and computer models to detect ice sheet instabilities in West Antarctica, focusing on Thwaites Glacier. The team is working on developing new methods for detecting ice sheet tipping points and will contrast evidence of ice sheet tipping over the past 10,000 years to the current pace of grounding line retreat observed by satellites and to that predicted by models over the next centuries. This project contributes to advancing our knowledge of the potential irreversible retreat of Thwaites Glacier and will assess how close we might be to crossing a tipping point.

FAR-REACHING CONSEQUENCES

While ice sheet instability mechanisms can be triggered over the next decades, their consequences unfold over centuries and millennia. Even if atmospheric and ocean warming were to be reversed in the future, the ice sheets will continue to respond to past changes and contribute to sea level rise, potentially with a committed multi-metre sea level rise.

Increasing ice sheet losses will affect coastal communities worldwide, with more frequent and widespread coastal inundations, erosion of the shoreline and infrastructure damage. In addition, tipping of the Greenland and West Antarctic ice sheets has the potential to initiate tipping cascades, triggering instabilities in other connected parts of the climate system. For instance, melting of the ice sheets would lead to an input of freshwater to the oceans with the potential to disrupt ocean currents. Melting of the Greenland ice sheet could disrupt the North Atlantic Meridional Overturning Circulation, and melting of the Antarctic ice sheet has the potential to weaken the Abyssal Overturning Circulation. The slowdown of these currents would reduce transfers of heat, oxygen, carbon and nutrients, adversely affecting marine ecosystems and causing changes in weather patterns across the globe. ES

Dr Inès Otosaka is Assistant Professor at Northumbria University and Co-Director of Science at the UK Centre for Polar Observation and Modelling. She is an expert in satellite observations of the cryosphere and is leading international projects funded by the European Space Agency on measuring ice sheet contributions to sea level rise and assessing the proximity and timing of tipping points in West Antarctica (CryoTipping).

✉ **ines.otosaka@northumbria.ac.uk**

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After 1.5C: preventing tipping points in a world of overshoot

Manjana Milkoreit considers how our understanding of and approach to governance must change if we are to successfully tackle this global challenge.

Tipping points are no longer a distant possibility. They are increasingly recognised in policy contexts – from international climate governance to national security debates around risks such as the collapse of the Atlantic Meridional Overturning Circulation (AMOC) – as processes that humans may trigger within the horizon of present-day decision-making. For the first time, political institutions must contend with the possibility of committing to large-scale and irreversible Earth system change within decades.

Yet governance systems remain poorly equipped to deal with this class of risk. Most environmental institutions are built to manage gradual change and reversible harms, but tipping dynamics involve non-linearity, irreversibility and deep uncertainty. All governance is structured around territorial boundaries – mostly state borders – and time horizons that do not fit the large scales of tipping elements and their dynamics. Tipping points can transform the environmental conditions on which societies depend and preventing them therefore requires more than stronger climate policy; it demands a different understanding of risk, agency and responsibility.

BEYOND GRADUAL CHANGE: THE RISKS

Tipping points refer to a certain type of change process: fundamental reorganisations of whole Earth systems. A rainforest may shift towards a grassland. An ice sheet may enter long-term retreat and disappear. Ocean circulations may shut down and alter regional climates for generations. These are not merely examples of climate stressors gradually intensifying; systems in their current form and with their existing functions are being lost.

That distinction matters because these systems provide the background conditions of social stability. They regulate water availability, shape growing conditions, stabilise coastlines and influence regional weather patterns. Their reorganisation can therefore remove, rather than simply stress, the environmental foundations on which economies and societies depend. System reorganisation, combined with irreversibility, acceleration and uncertainty over timing and impacts, raises the stakes for preventive action and precaution – governance efforts to avoid the crossing of tipping points.[1] Once thresholds are crossed, options narrow sharply and adaptation may become severely constrained.[2]

> **"Once thresholds are crossed, options narrow sharply and adaptation may become severely constrained."**

Tipping processes are not inevitable. Prevention is possible for all Earth systems where the tipping point has not yet been crossed. Furthermore, not all tipping points are equally close. Different tipping elements respond differently to human pressures, and not all will be lost if one is crossed.[3] That is why prevention and the ability to devise effective prevention strategies matter.

DYNAMICS THAT WEAKEN PREVENTION

While prevention is possible for most tipping elements – and urgent for a subset with tipping points between 1.5C and 2C of warming – a set of political dynamics related to the interpretation of tipping point risks appears to make prevention efforts challenging.[4,5] These dynamics do not reflect explicit choices against prevention but tend to steer strong preventive action further into the future.

The first dynamic relates to the under-specification of mitigation pathways in climate governance. Long-term goals such as temperature stabilisation to well below 2C or of net zero by mid-century are essential, but they intentionally leave open very different emissions pathways. Policy-making has largely focused on endpoints rather than the politically more sensitive question of how to reach them. In the context of tipping points, this is a critical limitation. Pathways that delay emissions reductions and rely more heavily on future carbon removal tend to produce higher peak warming and longer periods above critical thresholds, increasing tipping risks.[5-7] Prevention, therefore, requires greater specification of near-term emissions reductions and a shift towards front-loaded mitigation pathways that limit overshoot and rapidly return to 1.5C.

A second dynamic is a bias towards domestically controllable responses.[8] As tipping risks enter policy debates, adaptation and resilience are often emphasised as pragmatic responses. These are vital – but they are also more readily governed at national or local levels than the globally coordinated emissions reductions required to reduce tipping risks. In a context where international mitigation has proven difficult, this creates a structural pull towards responses that are easier to implement. Yet where tipping points involve large-scale system reorganisation, the scope for effective domestic adaptation may be fundamentally limited.

A third dynamic is the framing of technological intervention as risk insurance. As tipping points are increasingly understood to be abrupt and potentially irreversible, proposals such as solar radiation management (a set of large-scale technological climate interventions designed to reflect incoming sunlight back into space to reduce global warming, such as injecting aerosol particles in the atmosphere or brightening marine clouds) are often presented as a necessary back-up option.[9] This framing draws directly on elevated threat perceptions linked to tipping risks. Yet such approaches do not address the drivers of climate change, may not prevent several tipping processes (or may even accelerate others) and introduce significant new uncertainties and governance challenges. Framing them as insurance can also weaken incentives for the emissions reductions that remain the most reliable means of reducing tipping risks.

Taken together, these dynamics do not eliminate the possibility of prevention, but they do help to explain why it is not yet prioritised in the emerging discourse on tipping-point governance.

PREVENTIVE GOVERNANCE STRATEGIES

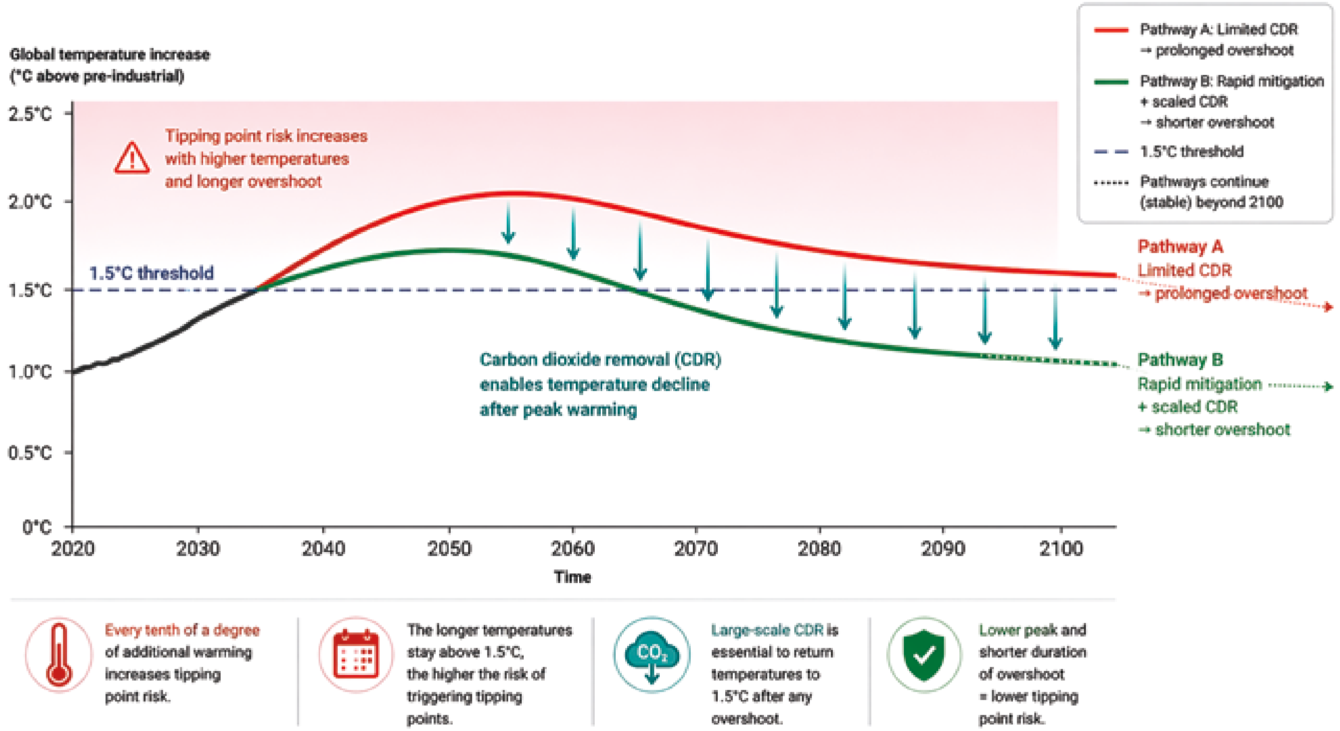
If tipping points represent a different class of risk, and the above-mentioned dynamics systematically steer governance away from prevention, addressing tipping risks requires more than an incremental strengthening of climate policy. It requires moving away from loosely specified long-term targets towards mitigation pathways that are explicitly designed to reduce tipping risks.

This begins with a recognition that limiting warming to 1.5C without overshoot is no longer feasible.[10] The policy challenge is therefore not whether overshoot occurs, but by how much – and for how long. Each additional one-tenth of a degree of warming, and each year it continues above 1.5C, increases the likelihood of triggering irreversible change. Translating long-term targets into front-loaded mitigation pathways that minimise peak warming and the duration of overshoot becomes the central task of prevention.

Rapid emissions reductions remain the most important lever. This includes accelerating the phase-out of fossil fuels and scaling up action on short-lived climate pollutants such as methane, which can reduce near-term warming.

At the same time, mitigation must be complemented by large-scale carbon dioxide removal (CDR). Returning temperatures to around 1.5C after overshoot will require the removal of several billion tonnes of carbon dioxide annually by mid-century.[11] CDR capacity can be created with a portfolio of approaches – ranging from nature-based solutions, such as afforestation

▲ A panel at COP30. © Kenny Garcia/Aljun Alvarez/hlcchampions | Wikimedia Commons | CC BY-4.0



▲ **Figure 1. Overshoot pathways and the role of carbon dioxide removal. (Source: IPCC AR6, 2022;[12] Rogelj *et al.*, 2018;[13] and Lenton et al., 2025[3])**

and ecosystem restoration, to engineered options, such as direct air capture and bioenergy with carbon capture and storage. Without such capacity, overshoot cannot be reversed, and tipping risks remain elevated. Different emission pathways create different tipping risks, because of different peak temperatures and overshoot duration (see **Figure 1**).

This makes CDR an immediate governance challenge. Governments should set explicit national CDR targets alongside emissions reduction goals, invest in infrastructure and early deployment, and ensure that removal is used to address residual emissions rather than to justify continued fossil fuel use.[14]

Given the relationship to global temperature, tipping-point prevention has direct implications for key climate governance frameworks, especially the Paris Agreement. For example, the next round of Nationally Determined Contributions should assess how national emissions trajectories and CDR capacities affect tipping risks. The second Global Stocktake should evaluate collective progress in reducing those risks – not only emissions gaps.

For tipping elements influenced by multiple drivers, prevention must extend beyond climate policy and climate governance institutions. The Amazon rainforest, for example, depends not only on global temperature but also on deforestation and land use. Preventing its destabilisation requires coordinated action across policy domains and scales, including global mitigation efforts, regional and national forest protection and restoration policies, and strengthening Indigenous stewardship. More broadly, this points to the need for polycentric governance: aligning actions across sectors and scales.

Preventing tipping points is therefore not a matter of setting new goals, but of changing how existing institutions operate, what they prioritise and how quickly they act.

IMAGINATION AS A PREVENTIVE FOUNDATION

Preventing Earth system tipping points is not only a problem of knowledge and capacity, but

▲ **Delegates applauding at COP30. © Kenny Garcia / Hlcchampions | Wikimedia Commons**

also one of imagination. Effective prevention requires the ability to anticipate non-linear, disruptive futures and to act on them in the present. Yet climate governance exhibits a persistent 'imagination gap': a failure to fully grasp the severity of tipping risks and to envision concrete pathways that will avoid them.[15]

The future is not an extension of the present. Tipping dynamics require imagining fundamentally different system trajectories – characterised by thresholds, rapid change and irreversible shifts. Without such futures in view, policies remain oriented towards gradualism and optimisation rather than risk avoidance.

Imagination also shapes political feasibility. Collective visions of possible and desirable futures guide decision-making, define what is considered achievable and motivate action. Where tipping-related futures are absent, poorly specified or dismissed as implausible, preventive action is delayed. Strengthening prevention, therefore, requires institutionalising practices that expand socio-climatic possibilities – integrating scientific knowledge about tipping dynamics with credible, concrete representations of both undesirable and avoidable futures. In practice, this includes integrating tipping dynamics into scenario development, stress-testing mitigation pathways against threshold risks and making high-impact futures more visible in policy processes.

CONCLUSION

Earth system tipping points compress time, amplify consequences and reduce the margin for error. They do not introduce a new climate objective but fundamentally alter what it means to achieve existing ones. In a world where some degree of temperature overshoot is now unavoidable, the task is no longer simply to limit warming but to minimise the depth and duration of exceeding 1.5C to prevent tipping dynamics in major Earth systems.

This shifts the focus of governance from long-term targets alone to the specification of pathways and timelines and to the credibility of near-term action. Preventing tipping risks requires decisions that are robust to non-linear change: front-loaded emissions reduction pathways, determined investments in carbon removal, and coordinated interventions across sectors and scales. Ultimately, tipping risks are less constrained by scientific uncertainty than by governance lag. Whether critical thresholds are crossed will depend on how quickly institutions translate existing knowledge into decisions that anticipate and avoid disruption rather than react to it. ES

Manjana Milkoreit is a Researcher at the University of Oslo, focusing on international climate change governance. She contributed to the *Global Tipping Points* reports in 2023 and 2025, leading on the sections on governance of Earth system tipping points.[3,16]

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Adapting to the inevitable: who bears the burden when tipping points are crossed?

Sarah Redicker examines the inequitable distribution of the consequences of breached tipping points.

◀ **A Goan fisherman repairing fishing nets. © shintartanya | Adobe Stock**

In 2024, the world crossed a threshold. For the first time in recorded human history, global average temperatures exceeded 1.5C above pre-industrial levels over a full calendar year.[1] The target enshrined in the Paris Agreement, long treated as the outer boundary of manageable climate change, had become a description of the present.

This does not mean the Paris Agreement has failed in every sense, or that emissions reductions no longer matter. Every fraction of a degree still counts. But it does mean that an honest conversation about climate change can no longer focus solely on prevention. Some consequences are no longer hypothetical, and climate dynamics have been disturbed in ways that will play out over centuries regardless of near-term emissions trajectories. Attention now turns towards what it will mean in terms of adapting when tipping points are already crossed, who is expected to carry that burden and whether the global systems meant to support adaptation are remotely equal to the task.

WHAT LOCKED IN MEANS IN PRACTICE

The language of climate tipping points can feel abstract. Thresholds, feedback loops, irreversibility: these are the terms of systems science and they describe processes. But the consequences of tipping points already being crossed are neither abstract nor evenly distributed.

Coral reef systems offer the most visible example. Reefs support the livelihoods of millions of coastal people who depend on fisheries and agriculture for food security and income, many living in low-income communities across Southeast Asia, the Pacific and the Caribbean. Mass bleaching events, once rare, are now recurring with insufficient recovery time between them in every tropical region with abundant coral reefs.[2] For fishing communities that have no alternative protein source and no financial buffer, this is not an ecological statistic but a livelihood crisis already underway.

Adapting to heat follows the same underlying logic, but with one important difference. Extreme heat is not itself a tipping element in the Earth system, but it is one of the main ways that a warming climate – and the tipping dynamics that warming can trigger – causes immediate harm to people. In cities across tropical South Asia and sub-Saharan Africa, in particular, extreme heat events are intensifying in both frequency and duration. Outdoor workers, who are disproportionately from lower-income groups, bear the greatest physiological risk. In rural agricultural regions, the compounding effects of heat and drought are reducing crop yields and shortening growing seasons in areas where subsistence farming remains the primary source of food and income. The communities least able to relocate, diversify their income or access cooling infrastructure are absorbing consequences they did not principally cause.

THE ADAPTATION GAP IS AN INEQUALITY GAP

Adaptation is not a single action: it exists on a spectrum, from incremental adjustments that allow communities to continue living broadly as they do to transformative responses that fundamentally alter how and where people live. This distinction matters, because access to different forms of adaptation is itself deeply unequal.

BOX 1. ADAPTATION IN ACTION: THE TERAI

In Nepal's tropical Terai lowlands, access to irrigation is the difference between planting once a year and planting three times. Tubewell irrigation, drawing on groundwater, allows farmers to cultivate through dry seasons and buffer against the increasingly erratic monsoon rainfall that climate change is bringing to the region (see **Figure 1**). The monsoon is itself a possible tipping element. Pollution, land-use change and warming are pushing it towards a more unstable pattern, with longer dry spells broken by heavier bursts of rain. For those with access to irrigation, it is not simply a productivity tool but the foundation of a viable rural livelihood under changing conditions.

But access is far from universal. Installing and maintaining a tubewell pump requires capital that many smallholder households do not have. Government support exists but is unevenly distributed and, within communities, existing inequalities in land tenure, social status and financial resources shape who benefits and who does not.

The result is a familiar pattern where those most exposed to climate risk are often least able to access the technology that would reduce it.

The deeper problem is that the water resource itself is under pressure. Groundwater levels across the Terai are falling, yet systematic monitoring of aquifer levels remains extremely limited. There is no long-term baseline, no shared data and no governance framework capable of managing extraction sustainably across communities. Farmers are making rational individual decisions to pump, while collectively drawing down on a resource that none of them can afford to lose.

This is adaptation at its sharpest dilemma: a working response to monsoon destabilisation, unequally distributed and built on a groundwater foundation that nobody is watching.

▲ **Figure 1. A proud farmer from Nepal's Madesh Province demonstrating the water flow through the communities' new tubewell pump. The pump secures the livelihood for 400 farming households. (Photo blurred to protect identity) (© Sarah Redicker)**

Measures such as sea walls and coastal protection as ice sheets melt and sea levels rise, or irrigation and water storage to cope with a less reliable monsoon deal with clear risks in a step-by-step way. These interventions have been highly effective, and many are already being deployed. But they require capital, technical expertise, functioning institutions and time. Countries and communities that have these resources can adapt incrementally. Those that do not, and those facing tipping points like coral reef collapse where incremental fixes eventually run out, must look to a broader range of responses.

Mobility sits across this spectrum. People move away from risk. Seasonal and circular migration has been a feature of rural livelihood strategies across South and Southeast Asia, sub-Saharan Africa and elsewhere for generations, long predating contemporary climate change. Households diversify their income by moving temporarily, maintaining their connection to land and community while reducing dependence on a single, increasingly variable source of income. In this sense, mobility is often an incremental adaptation, a familiar and practised response that is being extended and intensified as climate pressures grow, rather than a rupture from normal life.

At the more transformative end sits managed retreat and planned relocation, such as government-led programmes where infrastructure and housing are deliberately moved out of hazard zones for whole communities. Such schemes are widespread and growing – for example, in Ghana, Bangladesh and India in response to coastal erosion and flood risk.[3] These schemes raise complex questions about consent, community cohesion and the adequacy of support for those who move. For example, the Ramyapatna relocation settlement in Odisha, India, that was built for households displaced by Cyclone Phailin in 2013, now stands largely abandoned. Residents have returned to their original coastal settlement because proximity to the sea remains essential for fishing livelihoods. Managed retreat can protect lives and assets, but its implementation has been uneven, and the line between a genuinely supported choice and a managed necessity is not always clear.

The pattern running through these examples, from Terai farmers to relocated Odisha communities, is not simply a coincidence of geography. It is the central moral and political problem of climate adaptation. The burden is being borne by those least responsible for creating it, and the resources to address that burden are not flowing at anything close to the necessary scale.

THE GOVERNANCE GAP

The international community has not been idle. The Paris Agreement established the Global Goal on Adaptation, national adaptation plans provide a framework for countries to identify their priorities and needs, and the landmark agreement on loss and damage at COP27 in 2022 represented a long-overdue acknowledgement that some climate impacts are beyond adaptation entirely.

The gap between architecture and reality is, however, substantial. The loss and damage fund, formally operationalised at COP28 in Dubai, United Arab Emirates, received initial pledges of around US$700 million. However, the estimated annual cost of climate-related loss and damage in developing countries is estimated to be around $200–400 billion annually.[4] The fund is not yet a solution – it is a symbol of direction, and an underfunded one.

Climate finance more broadly tells a similar story. The long-standing pledge by wealthy nations to mobilise $100 billion per year for climate action

▼ **The Narayani River, Chitwan National Park, Nepal. © Ingo Bartussek | Adobe Stock**

▲ **Water supply tanks at Melkadida refugee camp, Dollo Aldo, Somali region. © Stanley Dullea | Adobe Stock**

in developing countries, a commitment made in 2009, was only met for the first time in 2022, more than a decade late. The bulk of that finance has historically flowed towards mitigation rather than adaptation, despite the communities most in need contributing the least to the emissions requiring mitigation in the first place.

Adaptation remains chronically underfunded relative to assessed need. The United Nations Environment Programme estimates that adaptation finance needs in developing countries will reach over $310 billion per year by 2035, making current flows 12 times insufficient.[5] Meanwhile, foreign aid is falling globally, directly threatening climate adaptation commitments. The geopolitical backdrop makes this harder still. The USA, the world's largest historical emitter, withdrew from the Paris Agreement on the second Trump administration's first day in January 2025, simultaneously revoking its International Climate Finance plan and withdrawing from the Just Energy Transition Partnership.

The multilateral cooperation that effective global adaptation finance requires is under strain. The current geopolitical climate, characterised by rising nationalism, contested multilateral institutions and the withdrawal of several major donor countries from international climate commitments, makes sustained and scaled adaptation finance harder to secure and harder to guarantee.

ADAPTATION IN AN UNEQUAL WORLD

The conversation about climate tipping points has been dominated by the question of whether they can be avoided. That question has not disappeared, and emissions reductions remain essential: every fraction of a degree of further warming narrows the space for adaptation further. But the honest conversation that the current moment demands must also reckon with what is already unavoidable.

Adaptation is being navigated, unevenly and often invisibly, by farming households diversifying their livelihoods, by coastal communities making decisions about whether to stay or move, by governments implementing relocation programmes and by local authorities building infrastructure their national budgets can barely sustain.

What adequate adaptation requires is not a mystery. It requires climate finance flowing at a scale commensurate with assessed need, rather than at a fraction of it. It requires that the communities most exposed to climate risk are centred in the design of adaptation policy, rather than consulted at its margins. It requires governance frameworks that treat mobility as a legitimate and supported adaptation strategy, rather than as a failure to be managed. And it requires a level of sustained multilateral commitment that the current geopolitical moment makes genuinely difficult to sustain, yet no less necessary.

The focus of discussions is not whether adaptation is needed, but who will be supported to do it, on whose terms and with what resources. Those are political questions as much as scientific ones, and they deserve the same urgency. ES

Sarah Redicker is a Postdoctoral Research Associate at the University of Exeter. As an interdisciplinary environmental social scientist, her research focuses on sustainable rural development under climate change, examining how adaptation is shaped by identity, power and equity. Her work spans household resilience, climate-induced mobility, and water and communal resource governance.

✉ **s.redicker@exeter.ac.uk**

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Tabitha Halliday – Student
Hilary Hao – Decarbonisation Specialist
Iona Hartley – Assistant Geo-environmental Consultant
Georgina Hermitage – Environmental Protection Officer
Isobelle Jackson – Geo-environmental Consultant
Jessica Knox – Environmental Consultant
Lauren Martin – Project Engineer
Phoebe McAlpine – Environmental Project Support
Lola McAuley – Assistant Consultant
Alex McDonald – Environmental Consultant
Emily Moore – Graduate Air Quality Consultant
Muddassir Mukadam – MSc Planning Student
Kimberly O'Connor – Environmental & Sustainability Consultant
Gisoo Pasha Moghaddam – Senior Process Engineer
Isobel Pearce – Environmental Impact Assessment Consultant
Callum Roberts – Geo-environmental Engineer
Madelyn Robertson – Environmental Compliance Officer
Fiona Robson – Geo-environmental Engineer
Hugh Shackleton – Graduate
Matthew Smith – Air Quality Consultant
Eloise Sykes – Senior Environmental Advisor
Sandra Talledo – Creative Director
Nathan Tsang – Environmental Advisor
Callum Whitehead – Assistant Project Manager – EIA
Lauren Williams – Graduate Environmental Technician
Katie Wills – Sustainability & Environmental Management Consltant
Finlay Wilson – Graduate Environmental Consultant

Af AFFILIATE

Christopher Bailey – Acoustics Consultant
Jennifer Gilmour – Graduate
Rebecca Hutt – PhD Student
Aleksandra Kieronska – Laboratory Technician
Abdullah Al Mamun – Environmental Graduate
Amy Sainsbury – Graduate
Maud Sanciaume – Senior Policy Officer – Minerals & Waste
Karl Shaw – Graduate
Ollie Walker – Student
Adepeju Eunice Willoughby – Student
Natalia Zamudio – Student

Unlocking positive energy tipping points: the impact of electricity prices

Cormac Lynch assesses the economics of the electricity market and the long-term benefits of changes we can make today.

Achieving national and global decarbonisation targets will require economies to be transformed rather than tweaked incrementally. Fossil fuels need to be rapidly phased out and replaced by low- or zero-carbon alternatives. While many uncertainties remain in this transformation, in many emission-intensive sectors the pathway to decarbonisation is becoming clearer. Sales of electric cars continue to rise rapidly, heat pumps are already a cheap form of heating in some countries and even electric trucks are starting to gain a foothold in the market. Globally, however, the pace of decarbonisation must accelerate if we are to avoid the most dangerous climate and environmental impacts.


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Triggering positive tipping points could be a highly effective way for governments, businesses and consumers to make this happen. Achieving a positive tipping point requires new, low-carbon technology to become more affordable, accessible and attractive than incumbent technology.[1] This new technology can accelerate decarbonisation by allowing small policy interventions to induce large, self-reinforcing transitions. Identifying and activating such tipping points could enhance the cost-effectiveness of climate policy.

Governments have several policy levers to hand to trigger positive tipping points, including subsidies, taxes and regulation. Electricity pricing is also crucial, since electrification is the most straightforward way to decarbonise many sectors. Yet in many countries, current electricity pricing structures act as a hindrance rather than an enabler of tipping points, despite the significant co-benefits that electrification can deliver to economies.

ECONOMIC ARGUMENT FOR ELECTRIFICATION

With increasing geopolitical tension and fragmentation, ensuring security of energy supply has become a priority for many governments. The Russian invasion of Ukraine in 2022 caused global energy prices to increase by 20 per cent, contributing to some of the highest inflation levels seen in almost four decades in Organisation for Economic Co-operation and Development countries.[2] The current war in Iran has so far led to average diesel prices to increase by over 30 per cent.[3] If fossil fuel importer countries were able to decouple their transport, power and heating systems from fossil fuels and replace them with clean domestic resources, it would shield both consumers and governments from the most severe costs of global price spikes while also reducing greenhouse gas emissions.

Recent macroeconomic modelling work has also shown that the low-carbon transition can generate substantial economic opportunities. Because of the uneven distribution of fossil fuel deposits, most countries are net fossil fuel importers.[4] For some countries, the cost of imports can be sizeable; for example, the cost of India's fossil fuel imports in 2022 was 5 per cent of its annual gross domestic product.[5] Through increasing the share of electric vehicles, heat pumps and other low-carbon technologies, there is an opportunity for countries to improve their trade balances to free up resources that can be spent domestically instead.[6] This is dependent on the extent to which countries can onshore the supply chains of new technologies.

Reducing reliance on fossil fuels also brings significant environmental and health benefits by improving air quality. Additionally, research modelling has shown that the lower energy and mobility costs made possible by low-carbon technologies can create productivity gains as sector-specific transitions cause an economy-wide wave of investment.[7] This research forms part of a growing number of studies that challenge the narrative that the low-carbon transition is more costly than a future that maintains the status quo.

THE BARRIER OF ELECTRICITY PRICES

Across Europe, high electricity prices have been identified as a key barrier to the uptake of low-carbon technologies. In 2024, the UK's Climate Change Committee, an independent advisory body to the Government, made reducing electricity prices its key recommendation to increase the speed of decarbonisation.[8]

Despite the strong economic and geopolitical case for electrification and the urgent need to cut emissions, high electricity prices remain a major barrier to reaching positive tipping points. Low-carbon technologies typically involve higher upfront costs, which are then offset by lower operational costs as they are usually more efficient than fossil fuel alternatives. High electricity prices can erode


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▲ **A solar farm in Schleswig-Holstein, Germany. © Michael | Adobe Stock**

this advantage, reducing the attractiveness and competitiveness of clean technologies. This issue is particularly salient in the case of the heat pump transition and the associated spark gap (see **Box 1**).

BOX 1. THE SPARK GAP

Heat pumps are often characterised by high upfront costs relative to gas boilers but have substantially lower running costs because they are three to four times more efficient than fossil-based heating systems. However, in some countries, households cannot realise these potential economic benefits because of the relative price of electricity and gas. This price difference is commonly referred to as the spark gap, with higher values indicating a higher relative price of electricity compared to gas. A wider spark gap reduces the relative attractiveness of heat pumps compared to gas boilers. Reducing this gap has been identified by industry experts as a key factor in accelerating the adoption of heat pumps.

While there are several drivers of a wide spark gap, two of the most frequently identified are: (1) high taxes and levies applied to electricity prices; and (2) the coupling of electricity prices to gas through marginal pricing in electricity markets. For many countries, household electricity prices include a range of policy costs, levies and network charges that are not applied (or are applied to a lesser extent) to gas. In Germany, for instance, 32 per cent of the average electricity price in 2025 accounted for taxes and levies.[9]

In addition, electricity wholesale prices are often set through marginal pricing, where gas power frequently dictates the price. As a result, the rapidly increasing share of low-cost renewables, often the cheapest form of electricity generation, does not fully translate into lower retail electricity prices.[8] This also means that global gas price spikes, like the one seen in 2022, are passed on to electricity prices. This helps to sustain a high spark gap even in increasingly low-carbon electricity systems.

LOWER PRICES FOR POSITIVE TIPPING POINTS

Beyond the heat pump transition, lower electricity prices would also improve the attractiveness of several low-carbon technologies, including electric vehicles. While electric cars are either at or rapidly approaching cost parity with internal combustion engine vehicles, heavy-duty electric trucks remain further from the cost tipping point.[9,10] In the freight sector, operational expenditure is often dominated by fuel costs, meaning that electricity costs will likely be key to enabling positive tipping points.

It must be acknowledged, however, that lowering electricity prices is not straightforward. Efforts are ongoing in a number of countries, including in Germany, where many taxes and levies have already been removed.[12] Meanwhile, the UK's Review of Electricity Market Arrangements seeks to modernise pricing for a high-renewables grid.

One way in which positive tipping points could be enabled is through the rebalancing of taxes and levies across energy carriers. In many countries, electricity prices include a disproportionate share of policy costs, which are not equivalently applied to fossil fuels. Shifting these costs away from electricity can improve its relative affordability against not only gas but also transport fuels.

The extent to which electricity prices are driven by gas through marginal pricing should also be addressed as a priority given that this leaves households exposed to future fossil fuel price shocks, even when the grid is dominated by low-cost wind and solar. This can be achieved through mechanisms such as long-term contracts, including contracts-for-difference, which stabilise prices and shield consumers from short-term spikes.

The opportunities that can be realised by triggering positive energy tipping points go beyond climate objectives, particularly in an increasingly fragmented and unstable world. While the ingredients for affordable electricity are already present in most places thanks to cheap and abundant renewable power, existing market design and policy choices often inhibit the full potential of electrification. It should be noted that other challenges for electrification persist, especially around access to finance in developing economies, improving grid stability and reducing potential trade challenges resulting from the geographic concentration of some renewable supply chains. While these should not be downplayed, unlocking positive tipping points through cheaper, cleaner electricity is central to driving rapid emissions reductions, strengthening economic resilience, and avoiding the worst impacts of climate change and broader ecological degradation. ES

Cormac Lynch is Transition Economics Impact Fellow at Green Futures Solutions, University of Exeter. His research focuses on the macroeconomic impacts of the low-carbon transition and how climate policies can be designed in a way that maximises emissions reductions and builds more resilient economies.

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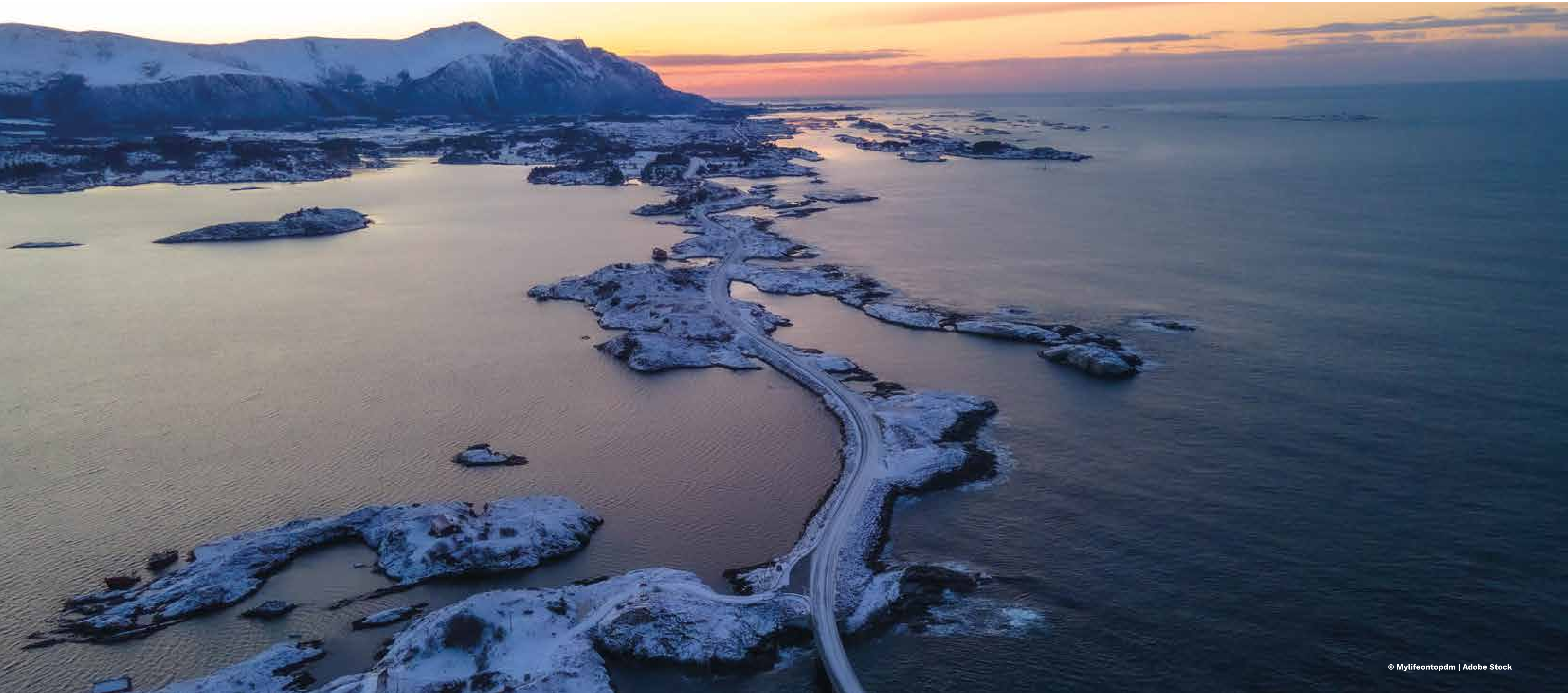
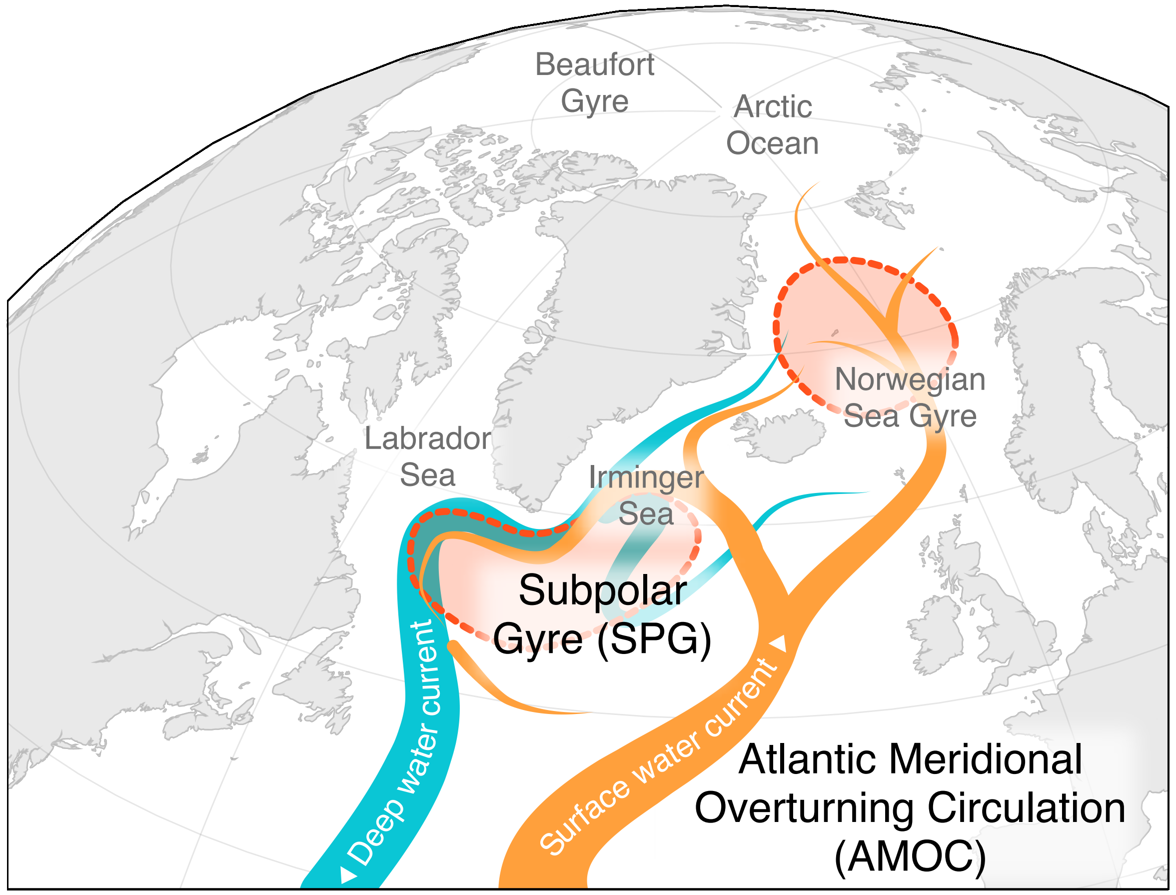
The Atlantic Meridional Overturning Circulation at a tipping point: evidence and global consequences

Nicole Laureanti, **Karoline Ramin**, **Willem Huiskamp** and **Bijan Fallah** outline the possible wide-ranging changes of this vital system and their effect on our daily lives.

The Atlantic Meridional Overturning Circulation (AMOC) is responsible for redistributing heat from the tropics and the southern hemisphere to the northern high latitudes. It represents a series of warm, saline surface currents that flow into the subpolar North Atlantic, balanced by a deep, cold return flow (see **Figure 1**).





▲ **Figure 1. Overview of the major oceanic circulation systems in the North Atlantic. (Source: Loriani *et al.*, 2025[1]) (CC BY-4.0)**

Upon reaching the subpolar North Atlantic and Nordic seas, these surface waters (orange pathways) lose heat to the atmosphere and cool, becoming denser than the underlying water masses and sinking into the ocean interior, driving the convection areas (orange shaded areas): to begin their southward return (blue pathways), see **Figure 1**. The AMOC connects the Atlantic Ocean to a global network of currents that continuously transport energy, water, nutrients and carbon, maintaining a highly resilient transport that prevents extreme cold in the subpolar North Atlantic and continental Europe.

Despite the AMOC system's resilience, climate change can alter it. Global warming increases surface temperatures and freshwater availability in the North Atlantic. The combination of increased rainfall and ice-sheet melt in Greenland, along with surface warming, reduces the density of surface waters. This stabilises the stratification of the water column, which inhibits the critical sinking of water masses in the subpolar seas. Consequently, the northward flow of the AMOC weakens, delivering less salt to the region and further reducing density. This self-reinforcing mechanism risks forcing the AMOC to a point of no return over the coming decades, rushing it towards collapse or shutdown within decades or centuries. This qualifies the AMOC as a tipping element: a component of the Earth's system that has the potential to dramatically shift once pushed past a specific threshold by human-caused warming through self-perpetuating feedback.[2,3]

CONSEQUENCES OF A SYSTEM SHUTDOWN

Our future climate can be shaped by variations in AMOC strength. Potential consequences would include a modified (in particular, colder) climate over Europe and even an amplification of greenhouse gas emissions due to the triggering of significant amounts of carbon dioxide release in the Southern Ocean.[4–8]

The main impacts of an AMOC slowdown stem from changes in precipitation and temperature patterns. Shifts in the Intertropical Convergence Zone pathways are found due to the AMOC slowdown, but they could also lead to a major rearranging of global monsoon systems in regions where more than half of the world's population lives.[4,9] In South America, studies indicate that AMOC slowdown can also be a precursor to changes in the mean state of the climate and to climate extremes.[10] In addition, a general cooling of the North Atlantic is often associated with AMOC collapse, leading to major impacts on Europe's climate.[4–7] The slowdown of the AMOC increases summer precipitation in southern Europe while increasing winter storm tracks in the North Atlantic.[5] Even under scenarios where high emissions were constantly released to atmosphere, an AMOC shutdown state can reduce minimum January temperatures in Europe by more than 10C compared to an intact state.[7]

Global marine ecosystems can also be endangered due to an AMOC slowdown.[11,12] Primary productivity is driven largely by current pathways and the nutrients they carry. By altering this transport, AMOC slowdown can modify the temperature and nutrient availability in the ocean, potentially leading to a decline in phytoplankton biomass. Sea levels along the US East Coast can also rise more quickly if the AMOC weakens, as evidenced by the 2009–10 jump in sea level north of New York City, mainly related to a 30 per cent slowdown in the AMOC.[13–16]

Other research has explored the impact of AMOC collapse on food supplies across different sectors.[5,17,18] For the UK, the collapse of the ocean currents could result in agricultural resource scarcity an order of magnitude larger than the impacts of climate change without an AMOC collapse.[5,19]

As a large-scale system of currents, the AMOC is strongly connected to other Earth system components and, upon change, might destabilise or stabilise them, potentially initiating a tipping cascade.[20] Specifically, by altering heat and precipitation distributions in the Earth system, the AMOC slowdown can drive modulations in the Intertropical Convergence Zone, leading to extended impacts on atmospheric circulation features.[1,9]

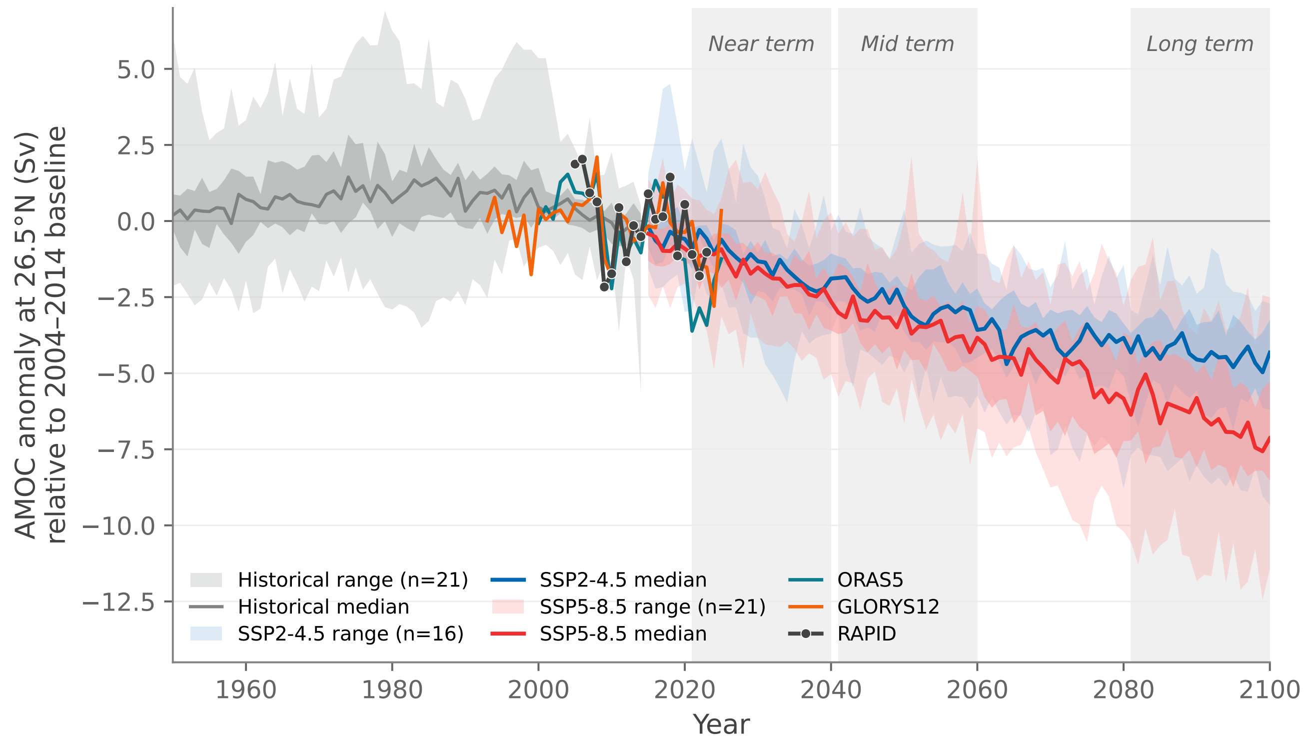
The tipping cascades relationship between the AMOC and the Amazon rainforest, for example, suggests that the collapse of the AMOC can drive dieback in different parts of the Amazon.[21-23] A weakened AMOC could stabilise the southern and eastern Amazon by shifting the Intertropical Convergence Zone southward, increasing vital dry-season precipitation in these sectors.[22,23] However, this same mechanism intensifies the vulnerability of northern Amazonian territories by inducing significant drying and prolonging dry seasons. This pattern is supported by paleo-evidence, which shows that past AMOC slowdowns increased southern and decreased northern moisture. These precipitation shifts can offset drying from global warming, thereby stabilising the southern forest by delaying or preventing critical moisture loss.[21,22,24] Although this seems to be a direct link, studies also need to consider the intrinsic resilience of the Amazon, which can amplify or reduce its residual variability, depending on moisture recycling mechanisms.[25]

EVIDENCE OF SYSTEM CHANGES

Studies suggest that the AMOC weakened or even fully collapsed in the early Holocene, 8,200 years ago, and there is a broad consensus that the AMOC has been slowing down and will continue to do so even under conservative future emission scenarios.[26-28]

The evidence for a current slowdown is drawn from relatively short measurements of AMOC transport from the RAPID array, a source of AMOC strength measurements that began in 2004; however, proxies also extend the evidence over time, indicating that current days show the weakest state of the AMOC, with a weakening of 15 per cent since the mid-21st century.[29,30] In addition, more resources from climate projections led to agreement on the potential risk of AMOC slowdown or even shutdown in this century.[31-33] This understanding has progressed since the last assessment by the Intergovernmental Panel on Climate Change, which suggested that a full shutdown of the AMOC was unlikely in the 21st century, based on Coupled Model Intercomparison Project (CMIP) simulations.[34] More recent studies of the models indicate that projections – after accounting for bias removal to reduce their uncertainty – reveal a 51 per cent weakening by 2100, and even more likely after 2100.[31,32]

The contrast between the temporal coverage of CMIP simulations and observations is clear (see **Figure 2**).



▲ **Figure 2. Atlantic Meridional Overturning Circulation transport strength change (Sv) comparison with different data sources. (Source: Created by the authors)**

From 1950–2100, the AMOC behaviour is shown for the CMIP6 multi-model median (in grey, based on 21 models) during the historical period and for the SSP2-4.5 scenario (blue, 16 models), and for the SSP5-8.5 scenario (red, 21 models). Overlaid from 2000–4, highlighted in the figure is the time series from two ocean reanalyses: ORAS5 (from 2000 onwards, in light blue) and GLORYS12 (in orange); and RAPID array observations (in black).[35-37] The spread of the models is higher than that of the observation and reanalysis products, but the 25–75th percentile range (darker shadows in the background) shows consistent behaviour with the current climate despite the large interannual variability. Thus, this nonetheless suggests that the AMOC state may be either weakening or on the pathway to destabilisation, as the models indicate.

As close as the observations are to the projections, there is still great uncertainty in the climate models. To determine the weakened state of the AMOC, in addition to greenhouse gas emissions, the models can be forced by adding freshwater discharges to the simulations.[5,7,38] Freshwater discharges are used to compensate for the sea ice and freshwater budget biases and other effects of ice sheet melting, which may be poorly represented in CMIP simulations.[39-42]

The risk of overlooking the freshwater budget in climate simulations, an important destabilising factor in the AMOC, suggests that a more realistic approach to CMIP runs would be to couple ice sheet dynamics to Earth system models.[6,39,41,43] To expand understanding of these factors and model variations across the Earth system, the Tipping Points Modelling Intercomparison Project (TIPMIP) was proposed. It has been indicated that the overturning weakens quasi-linearly with global temperature tendencies in one model.[20] However, the unbalanced freshwater discharges may influence this behaviour and a new series of experiments was specifically designed for the ocean domain of TIPMIP to distinguish the behaviour of different models in response to various possibilities of freshwater release in the North Atlantic.[43,44] Further outcomes currently in production are expected to provide additional information on the weakening of this system.

Understanding the future stability of the AMOC is more than a scientific curiosity; it is a prerequisite for global policy in a warming world.[45] Crossing the AMOC tipping point could expose billions of people to agricultural collapse across Africa, Asia and South America due to severe disruptions in monsoon systems, and in Europe due to intense cooling. For marine ecosystems and coastal communities, this could mean accelerated sea level rise and biogeochemical changes. Furthermore, scientific knowledge should continue to explore not only the AMOC tipping dynamics but also which regions face irreversible changes and how quickly mitigation could reduce these risks once a tipping process is underway. ES

Nicole Laureanti is a Postdoctoral Researcher at Potsdam Institute for Climate Impact Research (PIK), with a PhD in meteorology and experience in physical oceanography. She is currently developing AMOC research as part of the TIPMIP.
@itlaurena.bsky.social

Karoline Ramin is a Doctoral Researcher at PIK in the TIPMIP, working on data from Earth system models. Her research focuses on AMOC interactions and committed impacts from tipping systems.

Willem Huiskamp is a Senior Scientist at PIK with a background in paleoclimate and oceanography. His work focuses on the large-scale changes of the physical and biogeochemical systems of the ocean.

Bijan Fallah is a Senior Staff Scientist at PIK. With a PhD in meteorology and 15 years' experience in atmospheric science, his research focuses on Earth system analysis and paleoclimate data assimilation. He specialises in the reconstruction of the AMOC using particle filter implementations and ensemble-based modelling.

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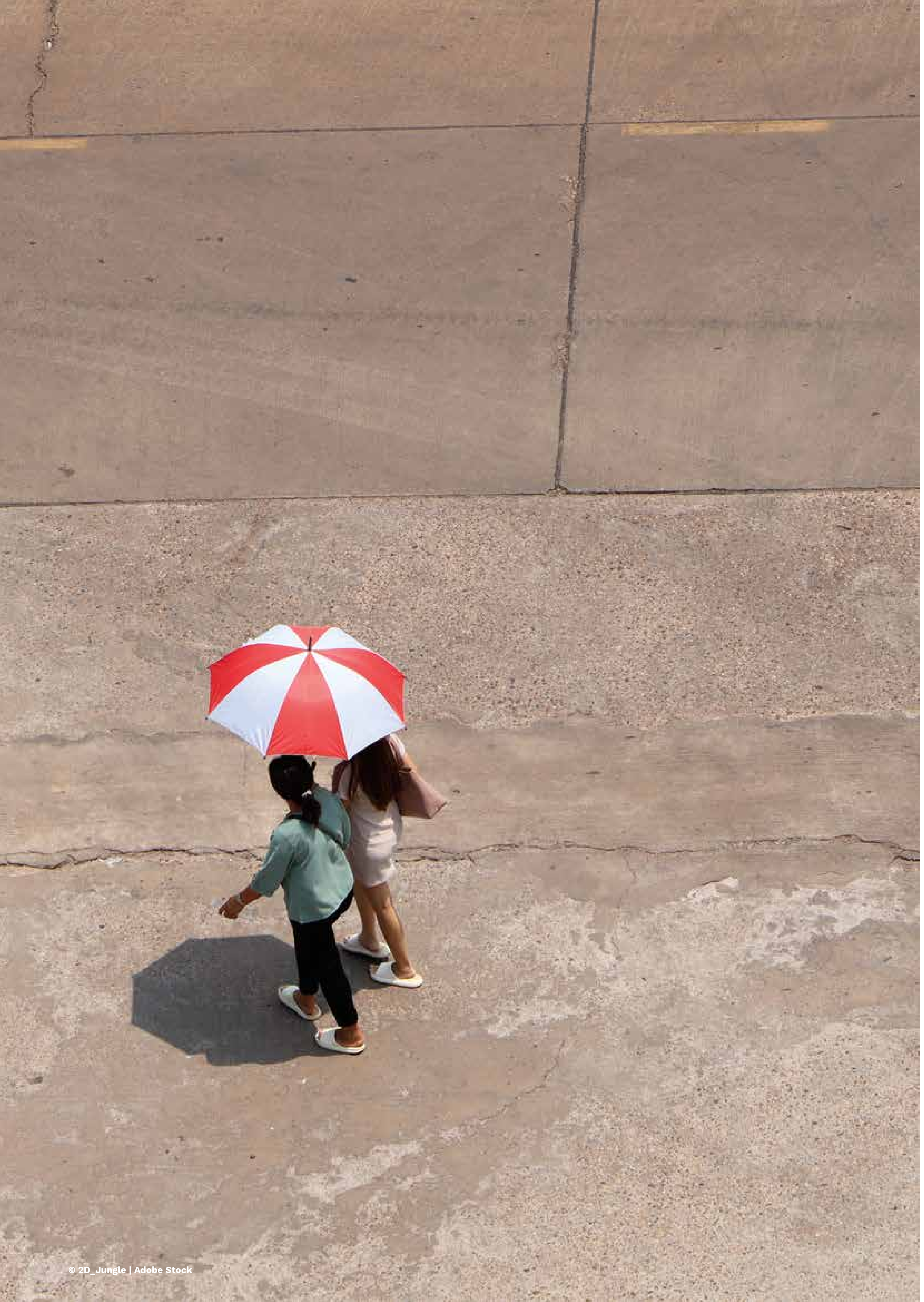

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When overshoot becomes inevitable: what next?

James Dyke considers some of the solutions proposed to manage climate overshoot.

Determining what constitutes dangerous climate change is an unavoidably subjective exercise. After decades of international negotiations, in 2015 the international community settled on 'well below 2C' as the point beyond which climate change must not progress. This was formalised in the Paris Agreement and adopted at COP21 on 12 December 2015.[1] Later, it was refined as 1.5C, in part because of the increasing acknowledgement that while 2C may be manageable in wealthy, industrialised nations, warming beyond 1.5C would represent an existential risk to many low-lying island nations that would be underwater due to sea level rise. This highlights the large differences in vulnerabilities to climate change, as well as the continuing chasm when it comes to which nations are most responsible for the climate crisis.

The rapidly developing science of tipping points is refining what is considered safe, with increasing evidence that above 1C lurk potentially rapid and irreversible changes to the Earth system that could have catastrophic consequences.[2] Given that we are about to breach 1.5C of warming, the only way we would be able to reduce some tipping point risks would be to reduce the amount of warming itself.

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The good news is that if we rapidly phased out fossil fuels while simultaneously decarbonising our food systems, the Earth's natural biogeochemical cycling processes would remove all the extra carbon we have put into the atmosphere and temperatures would fall. The bad news is that the removal process will take about 100,000 years.[3]

"If a week is a long time in politics, then a hundred millennia is an eternity."

CAN WE AVOID OR REVERSE TIPPING POINTS?

If a week is a long time in politics, then a hundred millennia is an eternity. If we hope to keep warming to anywhere around 1C – and so try to reduce the chance of activating tipping points – then we need to deliberately interfere with the climate system. The term used to describe this is geoengineering and it could be advanced via two routes.[4] One is carbon dioxide removal (CDR), which captures a wide range of techniques that would accelerate the removal of carbon dioxide from the atmosphere. The second is solar radiation modification (SRM), which covers a suite of proposals that would alter the Earth's energy balance, such that more energy leaves than enters and so warming would reduce.

While some of these ideas sound like science fiction – like launching mirrors twice the surface area of India into space to block energy from the sun – the notion of geoengineering has become central to all climate policy that seeks to limit warming to not just 1C but arguably any amount up to and beyond 3C. That is because geoengineering has become a key component of overshoot (i.e. where warming is going to exceed safe levels) with future technologies being proposed as a way to lower warming.

This overshoot approach can be understood as the evolution of net zero.

Back in 2015, limiting warming to well below 2C would have required a rapid phase-out of fossil fuels. Given that this pace of decarbonisation would have significantly disrupted political and economic systems, researchers working on climate policies instead proposed an approach in which the pace of decarbonisation could be moderated by accompanying it with carbon capture and removal. The argument at the time was that so-called hard-to-decarbonise sectors, such as aviation and steel manufacturing, could continue to emit carbon dioxide as long as an equal amount was removed from the atmosphere. If what goes down equals what goes up, then we would reach net zero, the point at which humanity's climate forcing stops.

In some respects, defining exactly which sectors are hard to decarbonise is moot, because such a net zero approach depends on there being credible plans to permanently remove carbon from the atmosphere. Unfortunately, rather than pegging net zero policies to carbon removal capabilities, the effective promise of future carbon removal facilitated a 'burn now, pay later' approach that has seen carbon dioxide emissions continue to increase over the past decade, with 2025 posting record-breaking levels.[5,6]

CARBON DIOXIDE REMOVAL

Today, annual carbon dioxide equivalent emissions stand at approximately 42 billion tonnes a year.[6] CDR capacity is estimated at just over 2 billion tonnes a year, with over 99 per cent of this being deemed nature-based, in that the carbon is removed largely via reforestation and afforestation.[7] The fundamental limitation with such approaches is that while the carbon has been removed from the atmosphere, it has not been removed from the biosphere. Trees die and when they decay the carbon they removed during

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their growth is respired back into the air. Tree mortality in certain regions is forecast to increase as a consequence of hotter and drier conditions driven by climate change.

New research concludes that regions of the Amazon rainforest may undergo tipping towards dieback at below 2C of warming.[8] There have already been instances of large wildfires releasing carbon from forests that were being used to offset carbon emissions.[9] For it to play a useful role, CDR has to permanently store captured carbon by converting the gas into minerals. This is promised to be achieved via engineered removals such as direct air capture (DAC), which strips carbon dioxide out of the air using chemical sorbents and stores it within the Earth's crust, such as in depleted oil and gas fields. There, the gas will slowly form carbonaceous rocks and so will reside, essentially, forever. This solves both the permanence and land-use problems, because while hundreds of millions of hectares could be required for nature-based CDR, the footprint of DAC is orders of magnitude smaller.[10] Unfortunately its energy footprint is potentially vast.

Atmospheric carbon dioxide concentrations are measured in parts per million. Removing this very dilute gas from the air, compressing and then storing it underground is essentially reducing the entropy that was increased when the highly carbon-dense fossil fuels were burnt in the first place. This means there are unavoidable thermodynamic limits to how efficient this enterprise could be. Issues of efficiency could be dealt with by significantly increasing the energy available. However, scaling up current DAC technologies to gigaton scale could require a substantial fraction of global electricity generation; such generation is urgently needed to decarbonise transport and other sectors.[11] In practical terms, CDR currently has a very small role to play in limiting warming to 1C.

It is here that SRM is offered as a potential climate-saviour technology.

SOLAR RADIATION MODIFICATION

SRM could be progressed in two ways: firstly, by decreasing the total amount of shortwave radiation entering the Earth from the sun; and secondly, by increasing the total amount of longwave radiation that leaves the Earth for space. Most current SRM research and funding focuses on the first route, with sulphate aerosol injection (SAI) generating most interest.

Geological processes already do this. Volcanoes are natural sources of aerosols. Large eruptions can inject millions of tons of dust and sulphate compounds high into the atmosphere where they will reside for around a year before being precipitated out. The eruption of Mount Pinatubo in 1991 in the Philippines is often cited as the inspiration for SRM research because its sulphurous ejecta dropped the global average temperature by around 0.5C for nearly two years.[12]

Yet the first proposals for SAI as a means to offset human-caused warming can be traced back to the 1970s.[13] In that respect it is not a new idea. What is relatively recent is the increasing argument that it should not only be researched but actively deployed because it may play a vital role in averting particular tipping points, such as Amazon dieback or collapse of the Atlantic Meridional Overturning Circulation.

If one considers warming beyond 1.5C to represent unacceptable risks, and if CDR remains very limited, and if emissions continue to rise, then the only option would be to deploy SAI, as it is currently the best-researched SRM technology. It is hard to say what exactly SAI's readiness level is. In principle, all the technologies exist: a fleet of several hundred wide-bodied jets could be repurposed into sulphur tankers that could deliver the required dose at sufficient altitude to have an almost immediate cooling effect. But this is not without risks and inadvertent consequences, which can be just as concerning as those of breaching tipping points.[14] Tens of thousands of people may die from air pollution each year as a result of injecting several million tons of sulphurous compounds into the atmosphere.[15] While this is significant, most SAI research is motivated to try to understand the global and regional climatic consequences.

For example, there are reasons to conclude that injection at high latitudes has the potential to disrupt regional climate dynamics in lower latitudes. This could include the movement in space and time of vital seasonal rains.

▲ **Pilot carbon capture facility at Ferrybridge gas and multi-fuel power station, Yorkshire. © Chris Chambers | Adobe Stock**


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Research indicates that the Southeast Asian monsoon could be delayed, or its intensity significantly reduced.[16] This opens up the potential for further climate inequities, not to mention a significant complication of climate change diplomacy. Thus far, the international community has struggled to decide how the existing carbon budget for 1.5C of warming should be best allocated. How it is to manage individual nation states deploying SAI at a time of increasing climate-related loss and damage, forced migration and economic impacts has yet to be seriously considered.

What this means is that prospects of returning warming to 1C anytime this century must be currently assessed as being extremely small. The most robust and just response to the climate change challenge is to fundamentally rethink climate policy so that it can do the job of producing a rapid fossil fuel phase-out. Crucially, policy-makers will also need to consider how best to respond to existing climate impacts while preparing communities for the likely serious deterioration of environmental conditions for the rest of this century and beyond.

This is a frightening prospect. It is understandable that some may wish to take refuge in the promise of future technological solutions. But this moment demands a sober appraisal of the science and technologies that are available today. The amount of warming humans have produced since the Industrial Revolution is a surprisingly simple sum of cumulative emissions. Simply put, past actions have fixed our present climate. The amount of future warming is still very much up to us. ES

Dr James Dyke, DPhil, is an Associate Professor in Earth Systems Science, Director of the Environmental Intelligence Centre for Doctoral Training and Assistant Director of the Global Systems Institute, University of Exeter. He is a Fellow of European Geophysical Union, the Earth League, the Higher Education Academy and the Royal Society of Arts. James has written for *The Guardian, The Independent, The i Paper, The Washington Post, The Boston Globe,* and Bloomberg. His book *Fire, Storm and Flood: The Violence of Climate Change* was published in 2021.[17]

hello@jamesgdyke.info
www.jamesgdyke.info

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Breach: climate tipping points and cascading security risks

Erin Sikorsky considers the national security implications of crossing climate thresholds.

Changes to Earth's biome are coming faster and at lower temperatures than previously assessed. Such changes will profoundly reshape food security, migration patterns, coastal habitability and broader resource availability in the decades to come. These dynamics in turn affect national security, including through sharpening geopolitical competition, undermining state stability and threatening critical infrastructure. At the same time, existing national security challenges can hinder the ability of countries to address tipping point risks, or in some cases accelerate the likelihood of crossing tipping point thresholds.

In some ways, the security community is well placed to navigate the unique characteristics of tipping points given that it regularly deals with uncertainty in assessing a variety of parameters – notably, adversaries' plans and intentions, the irreversibility of some types of weapons, and cascading, compound risks in highly dynamic conflict environments. The challenge for the security community comes less in the form of the characteristics of such tipping points, and more through the substance itself; security planners are used to holding the climate and environment constant in their analysis – an unstated underlying assumption.

Building risk assessment capabilities and analytical cultures that help security planners challenge these assumptions will be critical to navigating the fallout from these tipping point changes in the years to come.

BEYOND THE THREAT MULTIPLIER

Overall, key characteristics of tipping points include irreversibility, non-linearity, deep uncertainty and the potential for cascading failures. The latter is particularly important: tipping points are connected and can affect one another. These characteristics represent a qualitative addition to conventional climate security analysis, which has largely focused on a threat multiplier framework.

This approach, first popularised by US defence analysts in the late 00s, examines how climate change intersects with existing security threats and priorities, capturing the phenomenon of incremental climate stressors layered on top of existing fragilities.[1] For example, climate-change-driven drought or land degradation can contribute to resource stress in areas of high national security interest already facing instability, conflict and extremism, such as Somalia, Sudan or Yemen. This framing has helped engage defence and security planners in integrating climate change into their work.

However, the threat multiplier framework carries the embedded assumptions that climate change impacts are gradual and bounded. Given the complex and irreversible nature of tipping points, if and when they are crossed will reshape countries' national interests, capacity and resource availability, creating new and different threats. In other words, crossing key climate tipping points will create risks that not only compound existing security challenges but outpace and outshine them. The analytical question changes from 'How does climate change make current security threats worse?' to 'What happens when the underlying system reorganises into a state for which there is no historical analogue?'

NATIONAL SECURITY CONSEQUENCES

The national security implications of crossing tipping point thresholds can be categorised across three overlapping pathways: geopolitical competition, state instability and critical infrastructure exposure. Examining the potential consequences of crossing three different tipping points offers examples of each risk pathway.

Coral reef collapse

Warm-water reefs are already experiencing global bleaching events at the world's current level of warming. These ecosystems underpin the marine biodiversity that anchors food security and economic livelihoods for hundreds of millions of people in Southeast Asia, the Pacific and East Africa. Their collapse narrows fisheries productivity in the maritime geographies where great power competition, contested sovereignty claims and existing disputes are already acute. Reduced stocks intensify pressure on the South China Sea and raise the political stakes of fisheries enforcement across the Indo-Pacific. They also accelerate challenges for subsistence fishing communities, whether by displacement into urban environments and across borders or through recruitment into extremist or paramilitary groups.[2]

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Key ocean currents weakening
A weakening or collapse of the two key ocean currents – the Atlantic Meridional Overturning Circulation (AMOC) and the subpolar gyre – which bring warm water north from the tropics would have unevenly distributed geographical impacts. It would reorder European precipitation and growing season patterns with cooler temperatures, while disrupting monsoon patterns elsewhere amid higher temperatures. The effect on domestic agricultural production in the UK and Europe would be significant, with one report finding AMOC collapse would lead to the 'widespread cessation of arable farming' in Britain.[3] Broadly, crossing these tipping points would threaten global food systems and security, and likely increase even wealthy states' import reliance and vulnerabilities to trade weaponisation.

Greenland and West Antarctic ice sheet melting
Losing these ice sheets would result in multi-metre sea level rise across the globe, amplifying and intensifying physical security risks to critical infrastructure and migration pressures. Coastal naval and port infrastructure could not be adapted; it would have to be abandoned or rebuilt inland, at significant cost. Coastal urban areas, particularly in South and Southeast Asia, would become unliveable, displacing millions.[4] While migration and coastal resilience have been part of the climate security conversation over the past few decades, the magnitude of the change in this instance is significant and harder to manage; strengthened sea walls will not suffice.

A theme across all these pathways is the upending of assumptions in foreign and security policy about the stationarity of the environment and climate, or the idea that historical averages are suitable for future planning. One analysis describes it as:

'Hundreds of planning assumptions across military enterprises relate to the availability of food and water in certain geographies, the timing of raining seasons, the accessibility of ports, airfields and other facilities, and how often training or operations may be interrupted by extreme weather events. Additionally, assumptions about other countries' national interests and position in the world order are rooted in historical assessments of climate norms.'[5]

The analysis also highlights that militaries and security institutions tend to rhetorically recognise this shift – for example, the 2021 US Department of Defense's *Climate Risk Analysis* argued that 'analyses based on historical frameworks will not be sufficient to prepare for future risks complicated by a changing climate'.[6] Yet changing practices is much harder.

SECURITY AND INTELLIGENCE ANALYSIS

None of these tipping points act in isolation: Greenland meltwater will freshen the North Atlantic and contribute to AMOC weakening. Permafrost thaw will amplify the warming that destabilises ice sheets and reefs alike. Reef collapse removes coastal protection, increasing the impacts of sea level on the same low-lying states already losing their fishing economies. Independent probability estimates for each element, therefore, systematically understates the overall risk. As already mentioned, the security community often assesses systemic political and conflict risk. The challenge here is integrating system climate and environment analysis into that risk picture.

Key arguments and recommendations for doing so, all of which could contribute to more regular efforts to assess the full security consequences of climate change, to include abrupt tipping point risks, include the following.[7]

Adjusting tradecraft
Tradecraft refers to the methodology that intelligence and security analysts use to assess data and information. Conventional tradecraft largely rests on linear projection and central-estimate forecasting, but these are poorly matched to deep uncertainty and discontinuity. Structured analytics techniques built for these conditions, such as alternative futures analysis, backcasting from a tipped state or key-assumptions checks against gradualist baselines, should move from being optional supplements to default tools. Both the 2021 US Government's *National Intelligence Estimate* on climate change and the 2025 German *National Interdisciplinary Climate Risk Assessment* briefly mention tipping points as a future risk to consider, but do not deeply account for such discontinuities.[8,9]


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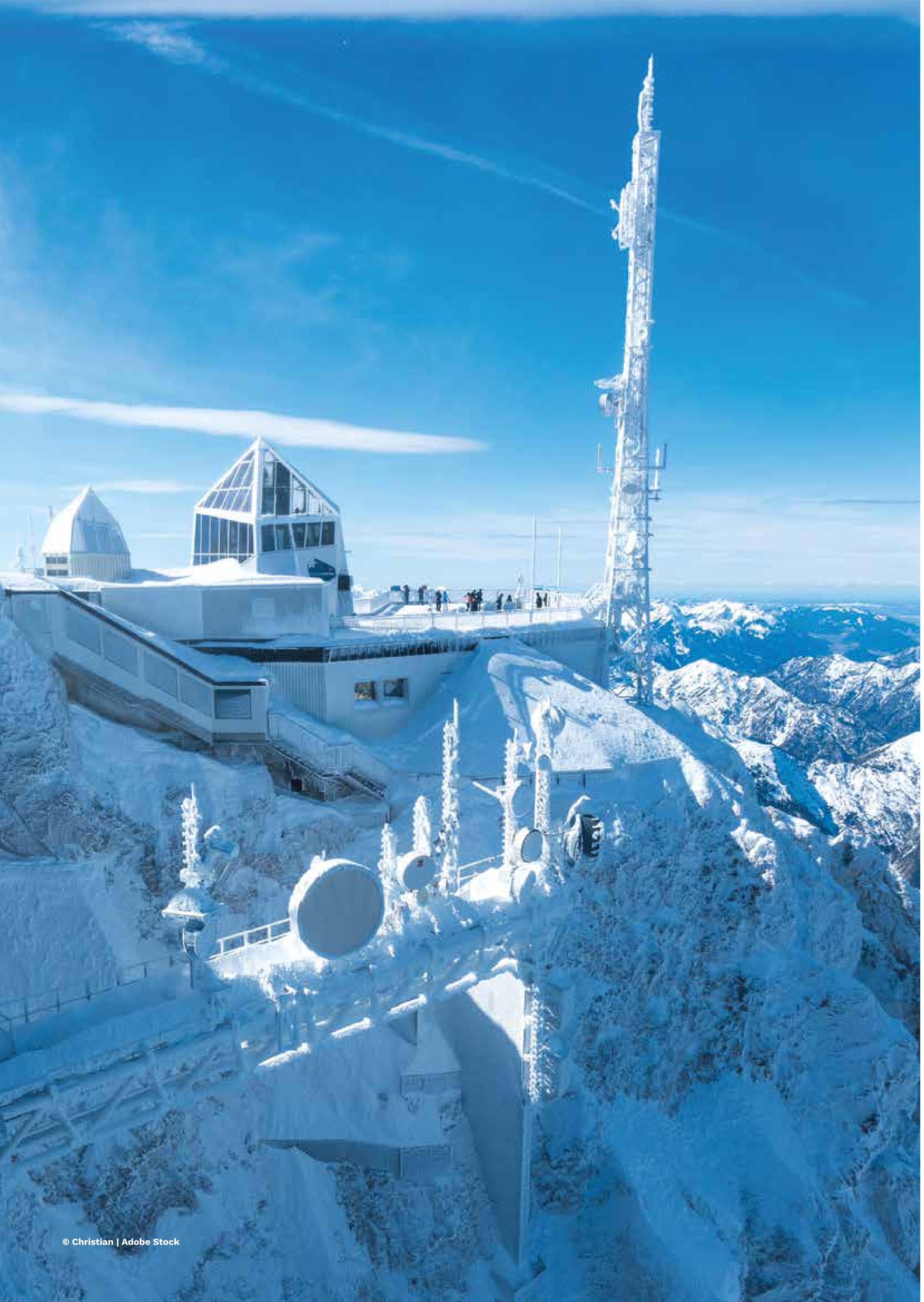
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Deepening integration
Physical climate science needs to sit inside security intelligence assessments rather than alongside them. The relevant signals such as salinity changes in the subpolar North Atlantic, glacier grounding-line retreat in Antarctica, permafrost ground temperatures and reef heat-stress accumulation are not the indicators most security analysts regularly track. Governments that build teams of scientists and security experts working side by side to develop risk analysis and warning will be best prepared to navigate tipping point consequences.

Preparing for irreversibility
Contingency planning conventionally assumes a return to baseline conditions. Tipping points remove that assumption. Plans need to be premised on the possibility of permanent state changes in the operating environment, including permanent loss of territory, fisheries and circulation patterns that existing force structure and alliance commitments treat as a given. Many security institutions are already preparing for permanent state changes in the international system given the challenges to multilateral institutions and growing geopolitical competition; they should extend this planning to the climate and environment as well.

CONCLUSION
Tipping points do not displace the threat multiplier framework. The climate-driven instabilities this framework has helped bring into focus will continue to compound. But the defining climate security challenge of the coming decades may not be how warming worsens the threats we already track. It may be how, once thresholds are crossed, the strategic environment itself reorganises into something the current national security playbook was designed to address. ES

Erin Sikorsky is the Director of the US Center for Climate and Security at the Council on Strategic Risks. She is a former senior US intelligence officer and the author of *Climate Change on the Battlefield*.[5]

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When light changes everything: a positive tipping point in Pakistan

Tanvir Ahmad details how a simple solar home system can deliver sustainability, safety, dignity and hope.

In one of the world's most energy-vulnerable settings, a modest solar kit does more than provide light. By displacing polluting, fuel-based lighting, it can reduce emissions and indoor air pollution while also enabling safer mobility for women after dark, extending study hours for children, and improving household privacy and hygiene. In doing so, it illustrates how decentralised clean energy interventions can deliver both environmental and social gains in resource-constrained contexts.

WHAT IS A POSITIVE TIPPING POINT?

A positive tipping point refers to a small, targeted intervention that triggers self-reinforcing and cascading improvements across a system.[1]

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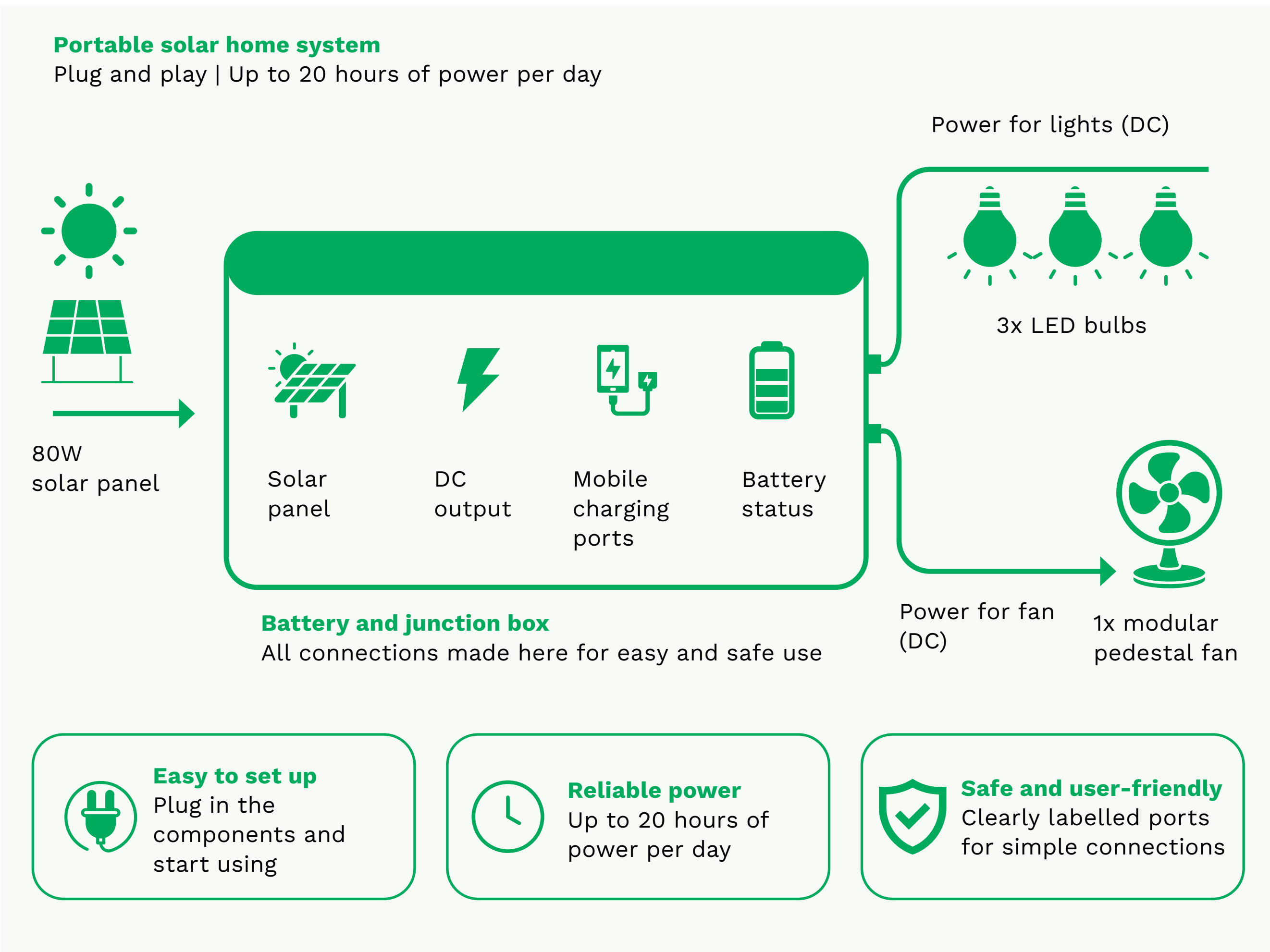
In climate and energy systems, such tipping points are critical because they can accelerate transitions towards low-carbon, resilient and sustainable pathways. Decentralised renewable energy technologies, such as solar home systems (SHSs), can act as catalysts by simultaneously reducing greenhouse gas emissions, improving energy access and enabling adaptive capacity in vulnerable communities (see **Figure 1**).

SOLAR HOME SYSTEM DEPLOYMENT

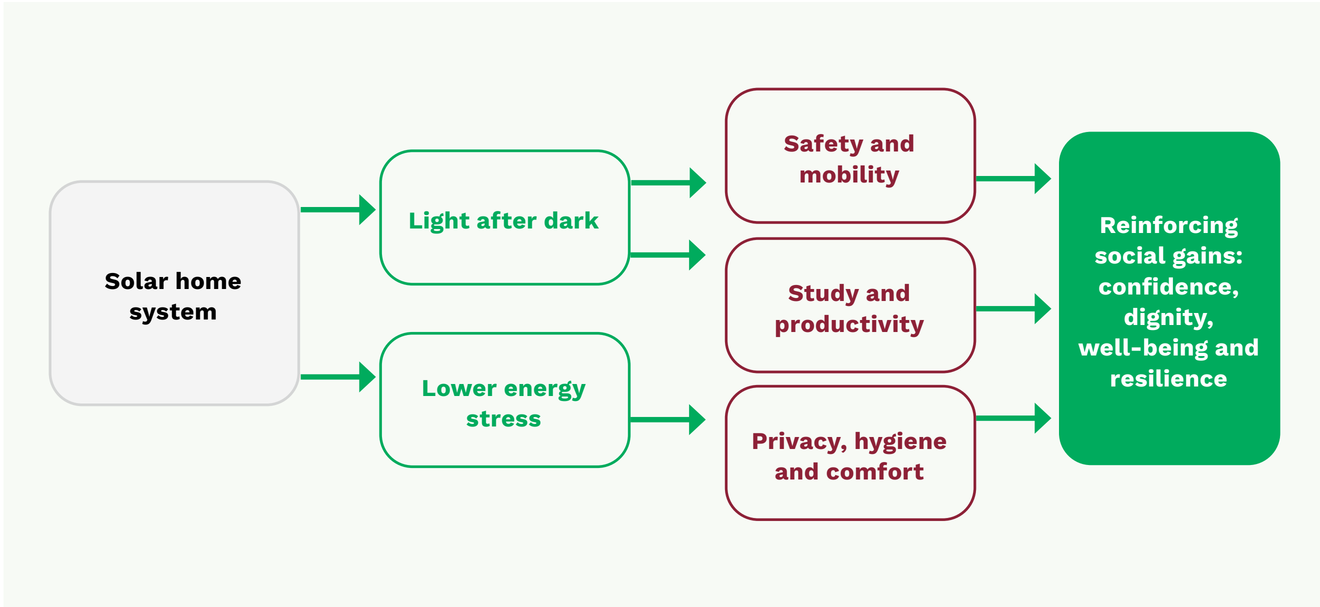
In parts of Pakistan, particularly in vulnerable and displacement-affected communities, access to reliable electricity remains limited. This is demonstrated in refugee villages in Khyber Pakhtunkhwa and Balochistan, where infrastructure constraints, economic vulnerability and exposure to climate stress have left many households dependent on kerosene, candles and disposable batteries – energy sources that are costly, carbon-intensive and hazardous. Here, sunset once meant the day had to end.

Meals were prepared before darkness. Children hurried through homework before natural light faded. Women often delayed essential tasks, avoided being outside after dark and compressed daily routines into a narrow window of daylight. In such settings, darkness was not simply the absence of electricity; it shaped safety, privacy, learning and choice.[2] This experience reflects a wider global challenge. Hundreds of millions of people still live without electricity, while many more have only poor-quality or unreliable energy access.[3]

In response, the United Nations High Commissioner for Refugees (UNHCR) Pakistan implemented a decentralised solar initiative, distributing more than 34,000 SHSs across these communities.[4] Drawing on 2,738 household interviews and six focus group discussions, it is clear that even a modest clean energy intervention can generate wider environmental and social benefits. The SHSs are simple: a portable solar panel, battery unit, three efficient lights, a fan and phone-charging ports with a one-year manufacturer warranty and basic operation and maintenance training for users, enabling both immediate use and longer-term sustainability.



▲ **Figure 1. Schematic of the solar home system.**



▲ **Figure 2. A simplified positive tipping cascade for solar home systems in vulnerable communities.**

In this challenging and energy-vulnerable setting, a modest solar kit delivered both environmental and social transformation. By replacing kerosene lamps and other polluting lighting sources, the SHS reduced household-level carbon emissions and indoor air pollution while also reshaping how women moved around outside after dark, how children studied, how privacy and hygiene were managed within households, and how communities perceived pathways to improvement. A simple intervention can have wide-ranging impacts beyond the technology itself (see **Figure 2**).

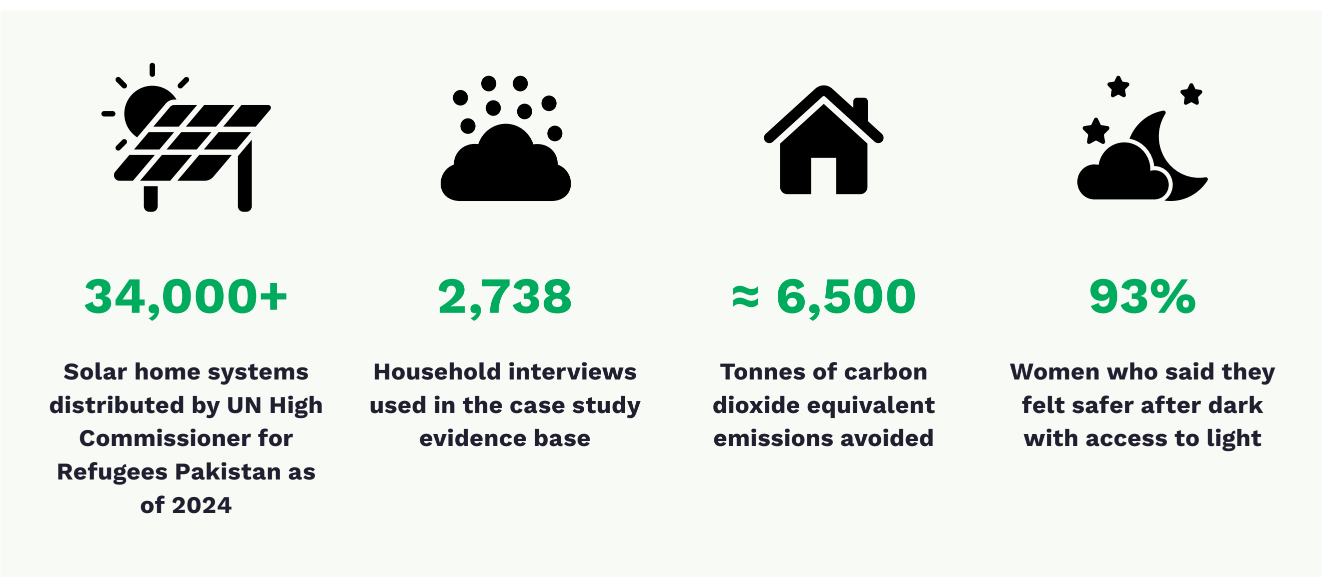
The focus group discussions that formed part of the UNHCR Pakistan programme pointed to conditions that lead to enduring changes, including community engagement, training, safe and reliable equipment, after-sales support (warranties) and design choices that reflect how women and girls use energy. Privacy, dignity and hygiene are not peripheral concerns but central outcomes. The importance of the SHS technology is based on its simplicity, modularity and easy replication. It lends itself to economies of scale and social contagion for rapid deployment and scaling in ways that larger, more complex solutions do not.[5]

There are also limits. SHSs require maintenance and batteries need replacement. The effects of SHSs on livelihoods may be less immediate than on safety and well-being. Scaling impact depends not only on technology but on programme design and long-term support as well. In this sense, successful SHS interventions can also generate a broader positive tipping dynamic: visible and well-evidenced improvements in one community can increase trust, social acceptance, donor confidence and policy interest, encouraging similar programmes to spread more rapidly across comparable displacement and low-energy settings.

CATALYSTS FOR COMMUNITY PROTECTION

The deepest social changes arising from the SHS implementation were reported by women and girls. More than 93 per cent of women surveyed reported feeling safer at night after receiving solar lighting.[2,6] Householders also reported improvements in privacy, hygiene management and comfort when carrying out domestic activities after sunset. Many respondents perceived reduced exposure to risks associated with darkness, including accidents and threats to personal safety (see **Figure 3**).

These outcomes matter because they go beyond convenience. They relate to protection, well-being and agency. This demonstrates that change rarely arrives as a single dramatic event; more often, it begins when one bottleneck is removed. In this case, the SHS acted as an enabling device.



▲ **Figure 3. Key statistics from the solar home system implementation programme in refugee villages in Pakistan.**

It reduced one constraint, and that reduction opened several pathways at once. Its simplicity matters – the system does not require grid expansion, large infrastructure or complex fuel supply chains. It can be deployed quickly, used immediately and understood easily.

That makes such systems particularly relevant where communities face displacement, low incomes, uncertain services and climate stress – for example, those in polycrisis or migrating due to environmentally induced tipping-point changes. Therefore, a solution does not have to be large to be systemically important.

The gains in safety, health and power resilience are not isolated. They begin to reinforce one another, creating a positive social tipping point. child who studies for longer may have improved prospects. A woman who feels safer moving outside at night experiences greater autonomy. People in a household less disrupted by darkness have more capacity to plan, cope and adapt.

WIDER IMPACTS AND GLOBAL SCALABILITY

The relevance of this intervention extends beyond one refugee context. It speaks to how decentralised clean energy can support humanitarian response, climate adaptation and inclusive development more broadly. It suggests that small-scale technologies may deliver larger value when assessed through everyday realities rather than through energy outputs alone.

Such insight matters where communities face energy poverty and climate vulnerability.

Additionally, each SHS replaces typical kerosene consumption for lighting, which can emit approximately 100–200 kg of carbon dioxide per household annually, alongside black carbon, a potent short-lived pollutant.[7] At scale, the deployment of over 34,000 SHSs represents a substantial cumulative reduction in emissions while also lowering indoor air pollution exposure, a major environmental health risk in energy-poor settings.

Similar decentralised solar interventions can be deployed across sub-Saharan Africa, South Asia and Small Island Developing States where energy poverty and climate vulnerability intersect. Environmentally, these systems can help lower emissions, ease pressure on forests, and improve air quality.

At scale, widespread adoption can contribute to a positive environmental tipping point: as uptake increases, costs decline, awareness spreads and supply chains strengthen. This creates a self-reinforcing transition towards clean energy systems, accelerating decarbonisation while enhancing climate resilience in underserved regions.

ACCESS TO LIGHT EQUALS ACCESS TO HOPE

For vulnerable communities, transformative change need not arrive in a dramatic way.

▲ **Extreme weather causes flooding in Pakistan. © Ali Magsi | Adobe Stock**

It may appear as a portable panel, three bulbs, a fan and a charging port. But when that small system simultaneously improves safety, learning, privacy and confidence, it becomes something bigger: proof that progress can begin where vulnerability is deepest. And that access to light can also be access to hope. ES

Dr Tanvir Ahmad is a Research Fellow at the Global Systems Institute, University of Exeter, researching climate tipping points, energy access and climate-resilient development. He previously led energy and climate initiatives for UNHCR Pakistan.

✉ **t.ahmad3@exeter.ac.uk**

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Ocean melting of Greenland's ice: a GIANT problem?

Kelly Hogan, **Pierre Dutrieux**, **Jonathan Nash**, **Paul Holland** and **Rosie Williams** share how their research is shaping scientific understanding of the cryosphere and its tipping points.

Over the past five decades, satellite observations of the Earth's surface have highlighted a concerning change occurring in our ice sheets: they are losing mass at an increasing pace, spewing more and more ice as solid icebergs and as liquid meltwater into the oceans around them, and transferring land ice into the ocean. Ice sheets are now a leading factor in global sea level rise, with the Greenland ice sheet losing ice up to seven times faster than it did in the 1990s.[1] This step change in ice-sheet behaviour has affected both the Antarctic and Greenland ice sheets, although to differing degrees, and it has also provoked a mindset change within the glaciological science community. Instead of thinking of ice sheets as static, long-lasting parts of the environment, we now understand them as being dynamic, highly responsive, and in delicate balance with the atmosphere, ocean and climate around them.

THE MECHANISMS OF ICE LOSS

As our planet warms, predicting the rates at which ice sheets lose mass, contribute to sea level rise and impact other global core climate tipping systems is essential information for policy-makers looking to mitigate and adapt.[2] Determining what factor(s) kicked off this trend of increased mass loss is complex but recognition of the step change must, in part, be attributed to poorer observations of ice sheets and their mass changes in the pre-satellite era.

Much excellent research has now identified numerous physical processes that interact to dictate ice-mass changes including precipitation (as snow) and surface melting, variable ice-flow speeds over the underlying bed, and ice–ocean interactions at the edges of ice sheets. Our research focuses on the seemingly ubiquitous (dominant?) process when discussing recent ice-sheet mass loss: warm, salty sub-surface ocean waters enhancing ice-melt rates, thinning their margins and releasing the friction buttressing the upstream flow of ice.[3]

Unlike the much larger Antarctic ice sheet – that is at around 59 m of sea level equivalent (SLE) – under strong atmospheric warming, the surface of the Greenland ice sheet (around 7 m SLE) now melts more intensely during the summer, forming azure-blue river networks and lakes. This meltwater is channelled down moulins (surface-to-bed drainage pipes) and crevasses towards the base of the glacier, lubricating the bed underneath and accelerating ice flow. Associated with this significant atmospheric warming, tipping of the Greenland ice sheet is thought to be mainly restricted to melt–elevation feedback that takes place over a timescale spanning centuries to millennia: as an ice sheet surface is melted from above, it will sit in warmer air masses at lower elevations that in turn lead to further melt.[4]

In contrast, long-term atmospheric warming in Antarctica does not yet lead to persistent surface melting in summer, so the cause of the accelerating ice loss there, which is focused in the Amundsen Sea Embayment, arises elsewhere: increased inflows at the ice margin by relatively warm ocean waters more than 3C above freezing. Warm ocean waters melt and thin Antarctica's fringing ice shelves (the floating extensions of the ice sheet) and provide ample perturbation to trigger a potential marine ice sheet instability.

This positive feedback occurs because much of Antarctica's ice rests on a bed that is below sea level and gets deeper inland. At a basic level, the flow speed of these ice streams gets faster if the ice thickness below sea level is greater. This means that as the ice retreats into deeper water inland, the ice stream speeds up. This faster flow causes ice loss, so the grounded ice sheet retreats further inland into deeper waters and speeds up again, and the whole process feeds back onto itself. Through this mechanism, a small change to the glacier geometry at the ice margin can result in an irreversible, self-sustaining inland retreat that continues even after the perturbation ends.[5]

In Greenland, the ice sheet geometry is distinctly different. As the ice sheet flows viscously (like golden syrup spreading out) towards its thinning margins, it also eventually reaches the ocean but this time via a network of more than 200 fjords. There, ocean-related feedbacks (e.g. marine ice sheet instability) can still occur at glacier faces, although over much smaller scales. Interestingly, the ice is thin and damaged enough and the climate is warm enough in most places that most fjords do not host an ice shelf. Instead, they harbour vertical ice cliffs that are tens to hundreds of metres high, which regularly break and crumble into the ocean forming icebergs large and small. In such a situation, the interaction

▲ **Figure 1. RRS *Sir David Attenborough* in an East Greenland fjord in 2024. The crumbling ice face is approximately 50 m tall. (© John Howe)**

▲ **Figure 2. One of the autonomous underwater vehicles, *Freya*. (© John Howe)**

between the ice and the ocean is complex: the near-vertical ice face is melted differentially at various depths and locations, resulting in gigantic overhanging or underhanging ice structures that eventually either break under their own weight or are broken by the buoyant forces pushing light ice towards the ocean surface. The large numbers of icebergs produced by Greenland's glaciers sometimes choke individual fjords, providing attenuated but effective buttressing to glacier flow into the ocean.[6]

The properties of the ocean water and its ability to extract heat from the ice and cause melting is, in turn, dictated by a combination of currents bringing warm waters into the fjord (occurring over scales of 10–100 km), water circulation (100 m–10 km) and modification (1–100 m) as it interacts with the local atmosphere and drifting icebergs. Furthermore, the efficacy of the exchanges occurs across the very thin (from a few cm to 1 m) ice–ocean boundary layer.

MAKING PROGRESS: THE GIANT PROJECT

To make our own step change – firstly, in understanding ocean-forced melting and the calving of Greenland glacier ice and, secondly, in the way we simulate these processes and the resulting mass loss from the ice sheet – requires a significant and coordinated effort.

The advent of the UK's Advanced Research and Invention Agency, specifically the Forecasting Tipping Points programme, has enabled funding on the scale required to take on this challenge. Our group has designed a substantial project – aptly named GIANT (short for Greenland ice sheet to Atlantic tipping points from ice loss) – with the primary aim to better understand and model ocean melting and iceberg calving at Greenland's fjord glaciers. This five-year project runs until 2030 and consists of around 50 per cent ice and ocean observations made by frontier technologies, and about 50 per cent numerical modelling. There are more than 50 scientists and engineers across five countries already working on the project from 13 institutions and five technology partners.

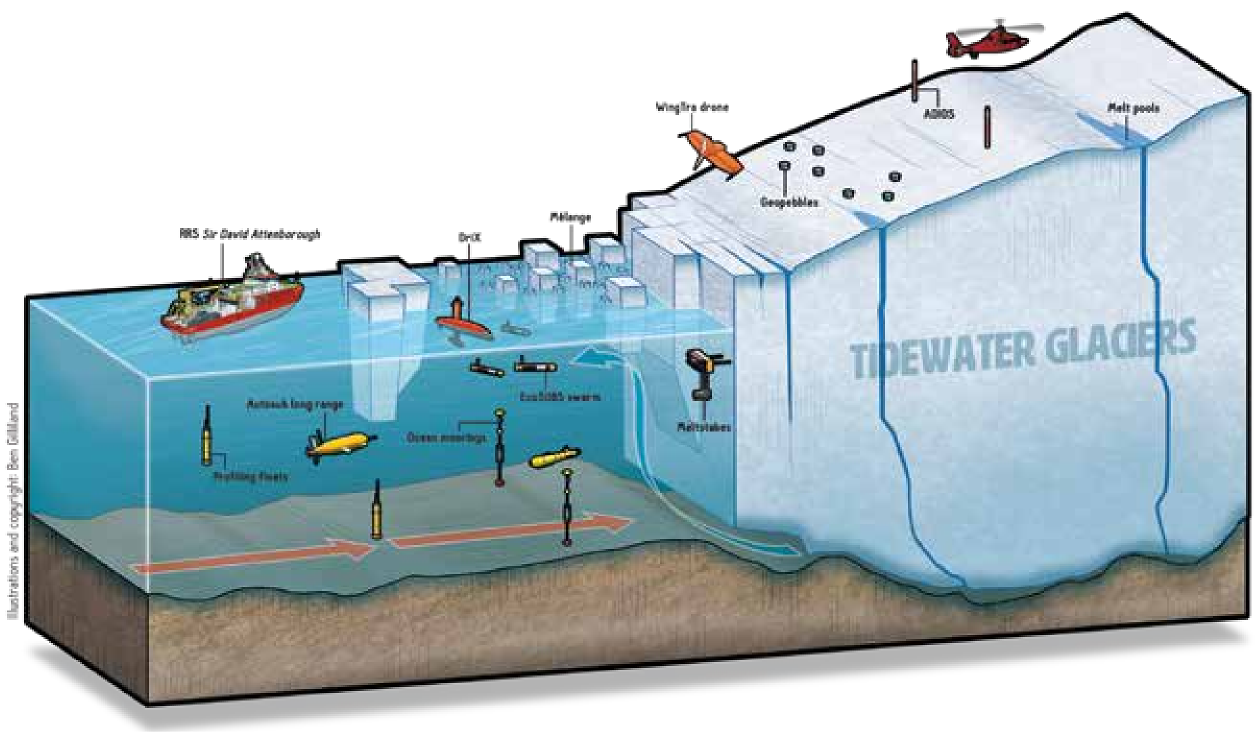
Making observations at remote and treacherous crumbling glacier cliffs is extremely challenging and, therefore, these datasets are rare and difficult to obtain. However, advances in both underwater and airborne robotics are now paving the way for new possibilities and discoveries. We are about to embark on GIANT's first fieldwork period, travelling to the fjords of East Greenland on board the UK's polar research vessel, RRS *Sir David Attenborough* (see **Figure 1**). The research vessel will be used in parent-ship mode from which we will launch a fleet of marine autonomous vehicles, two types of airborne drone and a helicopter to survey the glacier cliff and its damage zone just upstream.

Adjacent to the ice face itself, our swarm of relatively small autonomous underwater vehicles (AUVs) (1–4 m long) will move along the ice face at different water depths to capture the shape of the ice with sideways-looking sonar (see **Figure 2**). Fascinatingly, the ice shape can vary from scalloped to runnelled (long vertical grooves) or simply be a rough vertical face, and the number of slopes or overall ice roughness affects how quickly it is melted by the ocean.

The AUVs will simultaneously collect ocean-water properties such as temperature, salinity, dissolved oxygen and current flow. A few hundred metres further away from the ice, an uncrewed surface vehicle (7.7 m long) will repeatedly survey across the fjord, collecting the same ocean-water properties data and allowing us to track both the ocean currents and heat moving towards the ice as well as the colder freshwater and nutrients moving away from it. Perhaps the most famous AUV (known as Boaty McBoatface and around 4 m long), will be sent under a mixture of large icebergs, sea ice and iceberg fragments (known as bergy bits and as small as crushed ice cubes) to map the underside of this floating mélange of ice and record ocean properties.

Above the waterline, we plan to use a quadcopter drone to map out the vertical ice cliff. Eventually we will splice this information together with the underwater ice geometry from the AUVs to reproduce the full ice face in 3D. A second, fixed-wing drone will map out the upper surface of the damage zone around 5–10 km up from the ice edge. By also placing instruments into the ice surface in the damage zone (e.g. seismometers and ice-observing stations) we will listen for cracking in the ice and measure small-scale ice movements. We can then combine these records with the damage identified by the drones to track how cracks propagate and turn into iceberg-calving events.

Taken together, our fleet of autonomous assets aims to collect simultaneous measurements of the ocean through the fjord, across the boundary layer towards the ice and of the resultant ice shape (see **Figure 3**). Each of these observations is unique and novel, although the real significance of the work is in collecting all of them simultaneously and feeding them into a suite of ice and ocean numerical models for things like ice fracture and meltwater plume dynamics. Therefore, we aim to capture the various scales and complexity of ocean forcing in the fjord and up to the ice, as well as the ice response in terms of direct melting or iceberg calving.



▲ **Figure 3. GIANT fieldwork at East Greenland glaciers. (Source: Created by Ben Gilliland)**

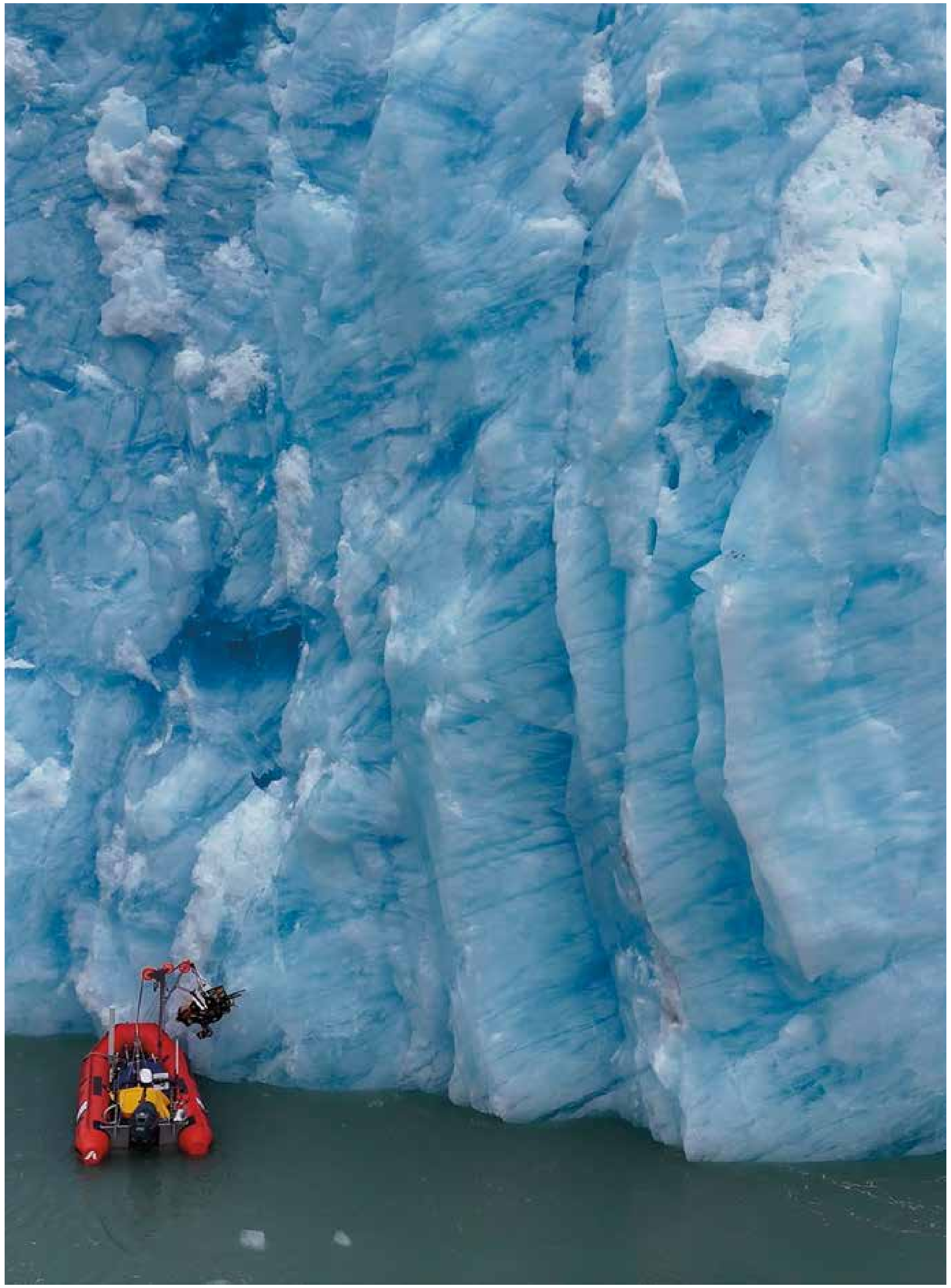
Ultimately, via our integrated framework of models, we hope to produce a new, constrained parameterisation of the ice–ocean interactions that dictate melting and calving to be used in scientific numerical models beyond GIANT, including the UK's Earth System Model (UKESM). Such models are most often used to explore global tipping points, but to robustly include ice-sheet tipping requires the use of ice-sheet models that respond to the changing ocean forcing.

As well as incorporating these processes into the UKESM, we will also probe the development of a dedicated early-warning system for Greenland glacier tipping points. This early-warning system will use ice observations (direct and satellite) to guide statistical emulators of ice dynamics, with the very ambitious aim of detecting sudden changes in fjord glacier behaviour that could affect future ice loss. As we saw in the early 00s, this type of sudden glacier change in the fjords around Greenland impacts large-scale patterns of ice-sheet loss.

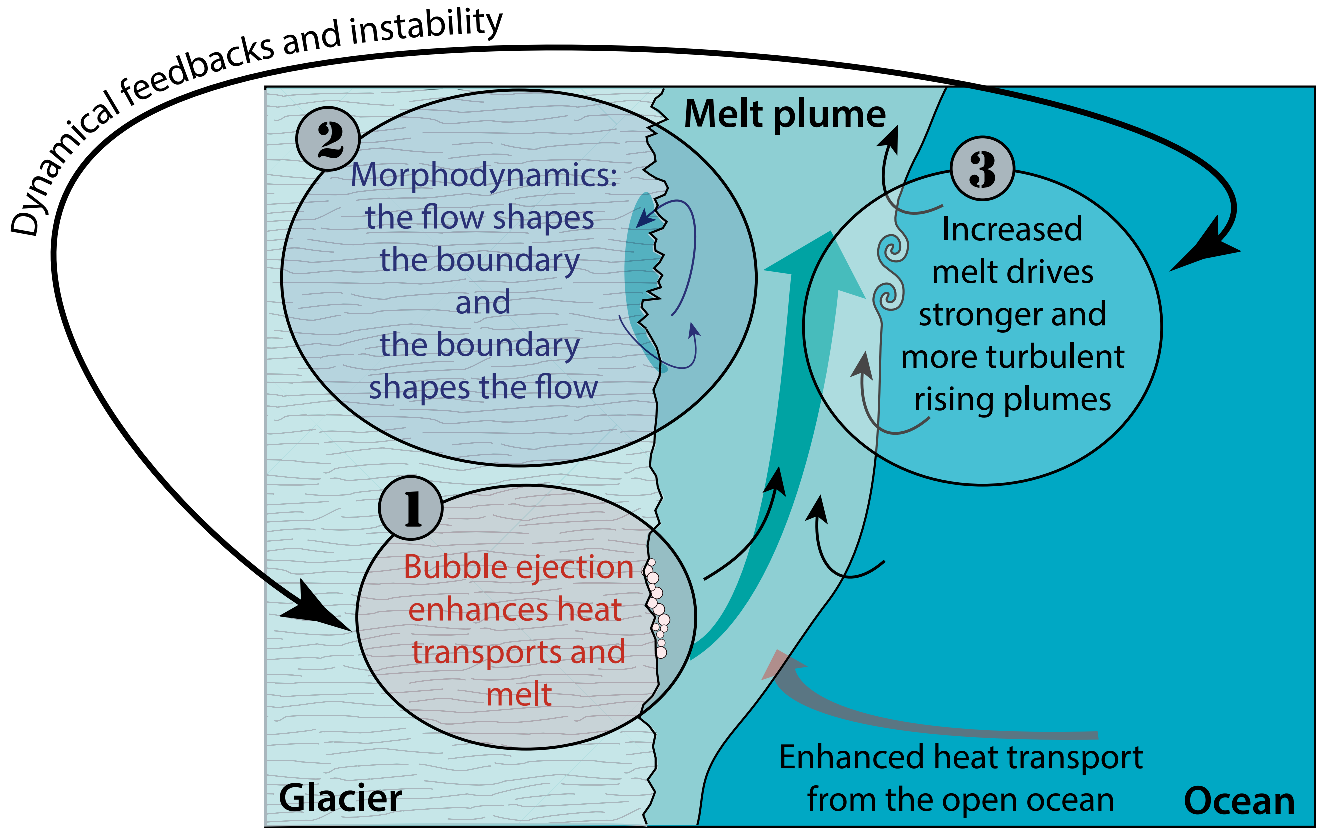
HOW TO MEASURE ICE-FACE MELTING

Until recently, scientists were unable to get instruments into the extremely hazardous region next to the calving glacier faces. This is where the most critical physics of ocean-forced ice melt takes place: in the centimetres-thin boundary layer where ice meets ocean, and in the chaotic meltwater plumes and eddies that rise and swirl just beyond it. The scientific community barely knows what these submerged glacier faces look like, because it is challenging to create images of them, even with advanced underwater sonar technologies (acoustics).

The GIANT project is changing this by combining a new generation of autonomous robotic systems with sensor technologies specifically designed to probe the ice–ocean boundary. The robotic system developed by Oregon State University in the USA is one example. Small autonomous surface vessels – robotic boats carrying many sensors and instruments – navigate to within metres of a calving glacier face and lower a remotely operated vehicle into the water below (see **Figure 4**). That underwater robot carries an instrument called the MeltStake that is screwed directly into the face of the glacier at depths of 50–100 m below the surface.[7] There it sits, measuring the temperature, turbulence and melt rate of the ice in real time, periodically screwing itself deeper to keep pace with the ablating (melting backwards) face. Such frontier systems



▲ **Figure 4. MeltStake instrument being deployed at a glacier face in Alaska, USA. (© Erin Pettit)**



▲ **Figure 5. Controls on ice melt at Greenland glacier faces. (Source: Created by Jonathan Nash)**

obtain measurements, photographs and audio recordings that have never been obtained before.

What those measurements are revealing is significant. The dominant picture of how glaciers melt, enshrined in the numerical models that underpin sea-level rise projections, has long treated the ice–ocean boundary as relatively simple: warm water arrives, heat is transferred, ice melts. But direct observations from suites of instruments deployed through GIANT are describing a more complicated and, in some cases, more alarming story.

One example is something as small as the bubbles of ancient air trapped in glacier ice that are freed during melting. These rise along the ice face and can potentially intensify the turbulent mixing that drives heat transfer. Sediment suspended in the water plays a similar role. These feedbacks are not currently represented in global climate models; they are not even listed as priority processes in many modelling programmes (see **Figure 5**).

This is just one of the dynamics that the GIANT project seeks to reveal. Take a small effect and multiply it across the hundreds of marine-terminating glaciers draining the Greenland ice sheet, and the implications for sea level projections become considerable. What we are talking about are 'unknown unknowns' in the physics of ice–ocean–climate system and, when taken together, we do not yet know if these interacting feedbacks will enhance or suppress ocean-forced ice loss. Since these processes do not exist in our models, the predicted tipping point behaviour is highly uncertain. At worst, the absence of these processes could even create or remove climate tipping points altogether.

The ambition of GIANT is to translate the direct, small- and large-scale observations of the ice and ocean into improvements to the computer climate models that policy-makers depend on. This requires building what scientists call a parameterisation: a mathematical description of the small-scale physics but compact enough to be incorporated into large-scale simulations that cannot resolve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centimetre-scale turbulence directly. The GIANT field campaign will add to the observational foundation on which better parameterisations can be built. The goal is not merely to understand why glaciers are melting faster than expected. It is to produce models capable of telling us how much faster they will melt in the decades ahead with more confidence, because they are based on real physics, and to provide the decision-relevant predictions that societies navigating a rising ocean will urgently need. ES

Kelly Hogan is a Marine Geophysicist at the British Antarctic Survey. She uses sonar methods to map the seafloor and ice faces. Kelly's work focuses on the ways ice sheets retreat typically over decades to centuries, and she also investigates how detailed morphology (seafloor or ice) affects ice-sheet flow and melting.

Pierre Dutrieux is a Physical Oceanographer at the British Antarctic Survey who specialises in using pioneering autonomous platforms to decipher how ocean heat approaches ice sheets and causes melting. His work combines observations from autonomous vehicles, ships and satellites to improve numerical models of ice–ocean processes.

Jonathan Nash is a Professor of Physical Oceanography at Oregon State University studying turbulence, ice–ocean interaction and autonomous ocean systems. He specialises in measuring the fine-scale details of geophysical processes, as these often uncover the unexpected. He led the team that developed MeltStake, the first instrument robotically deployed on an actively calving glacier face.

Paul Holland is an ice–ocean scientist at the British Antarctic Survey. The Antarctic and Greenland ice sheets are losing ice, causing sea level rise and interfering with ocean currents. Paul uses computer simulations to understand why this ice loss is occurring, how it might change in future and how it is related to human-induced climate change.

Rosie Williams is an ice-sheet modeller at the British Antarctic Survey. She specialises in simulating both the Antarctic and Greenland ice sheets by combining observations with computer models. This allows exploration of the drivers for present-day ice loss and prediction of how rates of ice loss might change in the future.

The GIANT team consists of more than 50 scientists, engineers and operational specialists from 13 institutions: British Antarctic Survey, Scottish Association of Marine Sciences, University of Leeds, University of Stirling, Edinburgh University, Cambridge University, University of St Andrews, The Alan Turing Institute, University of Reading, National Oceanography Centre, Oregon State University (USA), Danish Meteorological Institute and Greenland Institute of Natural Resources. Apart from the authors, key contributors to the proposal funding the project are Rob Arthern, Tom Cowton, Anna Crawford, Pete Davis, Mark Inall, Anna Hogg, Scott Hosking, Oliver Marsh, Ruth Mottram, Erin Pettit, Donald Slater, Robin Smith, John Taylor and Meagan Wengrove.

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