Stabilising Earth's Systems

The case for research, leadership and preparedness in an age of overshoot



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Foreword

Almost everything governments plan and do rests on the assumption that Earth's underlying systems will behave roughly as they always have. That a certain baseline stability will persist. Perhaps it's a human instinct for survival that things will work out in the end and the possibility of disruption is remote. Whatever it is, disruption is something that may happen in the future, when things are different, when the world is more able, somehow, to deal with any changes. That assumption of stability is now being tested. This summer we saw climate catastrophes across the world; and we still face a potentially record-breaking El Niño. All this while we are still only in the foothills of climate overshoot. What worries us most is whether the efforts already underway are sufficient for a world where the gentle undulations can no longer be taken for granted; when things begin to fall apart.

Faced with a looming threat, one's natural reaction is to prepare for it. But preparation is not simply about anticipating danger. It is also about preserving choices before they narrow, giving societies the foresight and agency to shape their futures rather than merely endure them. Defence ministries do this as a matter of course, as do central banks. Indeed, insurers have already begun to withdraw their cover from places – and the people who live there – they judge to be too exposed to flooding, wildfires, coastal erosion, and so forth. Like the vanishing sounds of the natural world, as species fluctuate, disperse and disappear, these institutional changes are in fact signals of accelerating climate change. Why, then, does our climate planning still proceed at glacial pace?

The COVID-19 pandemic showed the vast cost of being caught unprepared – and the value of having invested in crisis preparedness. At the heart of such preparedness must be rigorous and relentless scientific research. This report therefore calls for urgent, concerted investigation into the full spectrum of stabilisation options, from deep emissions cuts to local ecosystem repair to planetary-scale interventions. Investigation without prejudice, and without licence to deploy. The Amazon forest's influence on weather patterns extends far beyond Brazil; if pushed past its point of no return by fire, drought, or deforestation, we will all feel the impact. Similarly, large-scale efforts to stabilise Earth's systems must be collective – never the responsibility of a single country.

The risks may be planetary, but the circumstances in which they are experienced are profoundly different. Regions vary in their exposure, their contribution to ecological overshoot and, critically, their capacity to prepare. We know that today there are millions of people across the world who have not yet had their fair chance to develop. They never had the privilege of industrialisation or energy security and now they are bearing the consequences of a crisis they had little hand in creating, consequences that threaten to stunt their growth before it ever reaches its peak. For them, destabilisation threatens not only the development gains already made, but the possibilities of development still to come.

Whilst it is clear that those who did the most damage must pay their share, accountability alone will not prepare us.

Our commitment to a change in approach must be deep and comprehensive. Over the years, U-turns have sown deep distrust; a sense that no matter how many commitments are made, progress is nowhere near fast or far enough. Furthermore, in the controversial field of Earth system stabilisation, there are legitimate concerns that research could be used to delay emissions cuts or be co-opted by unaccountable actors. That is why it must be publicly led, driven by international collaboration rather than unilateral actions, transparent, and bound by strict rules and principles. Equally, such concerns cannot lead to inaction. Doing nothing is not a neutral choice. Doing nothing leaves us all exposed to worsening instability, starting with the most vulnerable.

We hope this report is read by finance ministers as well as environment ministers, and in the capitals of the South as much as the North. It asks governments to start preparing now, and to do it together.



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Key Recommendations

The research agenda:

1	**See the danger:**	Rebuild and expand Earth-system monitoring and modelling – across clouds, oceans, ice sheets, glaciers and forests – to track approaching thresholds in real time, and to underpin early warning systems.
2	**Evaluate frontier options:**	Investigate the strengths, limits, risks and interactions of large-scale carbon removal from the atmosphere and solar radiation modification through stage-gated modelling, laboratory studies and small, controlled field trials.
3	**Tackle short-lived climate pollutants:**	Fast action and targeted research to cut short-lived climate pollutants – methane, black carbon, tropospheric ozone and HFCs – are central to any near-term stabilisation strategy.
4	**Build the capacity to decide:**	Fund governance, legal, social and political research in parallel with – not after – physical science, so the work produces capable institutions.
5	**Back Global South and Indigenous leadership:**	Prioritise and fund Southern and Indigenous-led research capacity, South-South scientific collaboration, and systematic information sharing from the outset.

The calls to action:

1	**Fund at the scale of the challenge:**	Start now with a 'Mission Innovation' effort for stabilisation, scaling up public funding models such as ARIA. This will be a new research fund of billions per year from public sources, framed, managed and distributed as a coordinated risk management research fund for the world – strictly additional to climate finance and never carved from mitigation, adaptation, loss and damage or development. This is the insurance policy that pays out by preventing disaster instead of simply responding to the damage once it has happened.
2	**Make stabilisation someone's job in government:**	Each government should be required to identify and name the senior public servant or Minister with responsibility for Earth-system stabilisation, giving explicit executive power and cross-departmental capacity that acknowledges links to treasury, national security, food, health, water, energy and economic growth. This needs no new institution, and countries such as Iceland and the UK are already moving.
3	**Insist on open, accountable research:**	Support and promote only research that is transparent and accountable; bring private sector research efforts into compliance with publicly funded research ethics, codes of practice, peer review and formal stage-gating controls in specific frontier areas – requiring independent oversight, public disclosure, intellectual property in the public interest, and free, prior and informed consent where communities are affected.
4	**Lock every action to emissions cuts:**	Increase efforts, incentives, regulation and penalties to support mitigation efforts to reduce emissions much more rapidly; without this, the impacts of other efforts are compromised. Every stabilisation commitment must be tied explicitly to deep and rapid emissions cuts from the outset.
5	**Build a coalition of the willing now:**	Work with those who are ready to be part of this – others will join in when the effects are seen. In any coalition agreement a critical clause will be commitment to existing mitigation and finance pledges.

What climate leaders told us

While this report was being written, CCAG consulted with a group of influential leaders of youth climate movements from around the world and we asked them to challenge its thinking. They help set the climate agenda, and they understand better than most the hopes and fears of the people they speak for. The session was held under the Chatham House Rule, so no views are attributed to individuals.

Three messages came through most strongly.

1. **Safeguard existing climate commitments.** The point made most often was that research must not become an excuse to delay rapid emissions reductions. Participants cited how the fossil fuel industry has used offsetting and carbon capture to justify delay, and asked for firm safeguards against conflicts of interest. Funding for research must be additional, not taken from underfunded commitments on adaptation, loss and damage, or development.

2. **Make stabilisation and stabilisation research concrete.** The term still felt abstract to the group. Participants asked for the subject to be taken out of the scientific echo chamber and tied to how instability already affects people's lives. They wanted to know exactly what is being researched, at what scale, and who could be affected. Communities distrust research, one said, when the findings are never shared with them.

3. **Get consent right.** This was the centre of the discussion. Do communities understand the wider implications of a local experiment? Who consents to research whose effects could cross borders? If one community says no, what stops a project simply moving to another? Participants wanted scientists from the Global South to co-design the research agenda before priorities are set. For frontline communities, one participant said, the question is whether they will know before anything happens, and whether they can still say no.

The group asked for engagement that is sustained, resourced and open to people without a background in the sciences. The session was the first of a planned series.

Introduction

Earth's systems are being pushed outside the parameters within which they have operated for thousands of years, mainly by the warming that greenhouse gas emissions cause. The ocean currents, the circulation and composition of the atmosphere, the ice sheets, the water cycle, and the living biosphere together regulate the conditions for life. People live inside these systems; human life co-evolved with them and depends on them.

This report is about Earth system stabilisation: understanding where those interconnected systems are losing stability and what it would take to keep them within safe bounds. Cutting emissions to stabilise the global climate is the foundation of that work, but it also requires understanding what can be done to steady the individual elements of the Earth system now under stress.

Geological and planetary changes usually run along millennial timescales. Human actions have disrupted this for the Earth and its systems. Uniquely in the Earth's evolution, rapid change has been driven by human action; and human behaviour in the immediate future – five to thirty years – will matter for the Earth and its biosphere for many centuries. Equally, what humans choose not to do now will blight the future for hundreds of years. You cannot wait until conditions are finally considered to be intolerable before acting: changes work through the Earth systems over decades to millennia. At the point of complete crisis the options available today will simply no longer exist. This report is a call out for action to stabilise what can still be stabilised. We do not underestimate the challenges that are already locked in to the Earth system changes, and the pressures they will place on humanity and ecosystems, whatever action is taken now. But we know that things can – and will – get worse in the future if action is not taken right now.

Because so much pressure and destabilisation is already unavoidable, this report addresses approaches to increasing the resilience of human societies to the new instabilities, as well as thinking about the stabilisation of the Earth system itself. Human-made systems, including economic, urban, food production and more, have evolved within the relatively stable conditions on Earth of the last 12,000 years or so. They are all vulnerable to the current destabilising impacts of Earth systems, so increasing the resilience of human-made systems is important for maintaining decent lives within these more volatile natural conditions.[1]

At a local and regional scale, some systems can often be stabilised with well-understood interventions. With care, and in the right conditions, forests can be protected and even restored, soils rebuilt and enhanced, rivers restored and revitalised, and coastlines defended.[2] These low-risk, foundational intervention measures must be scaled up urgently. Yet we also have to ask

how far they will take us on their own. Major global systems, such as the Atlantic overturning circulation and the polar ice sheets, have no local fix: the only way to protect them is to halt the warming driving their decline.

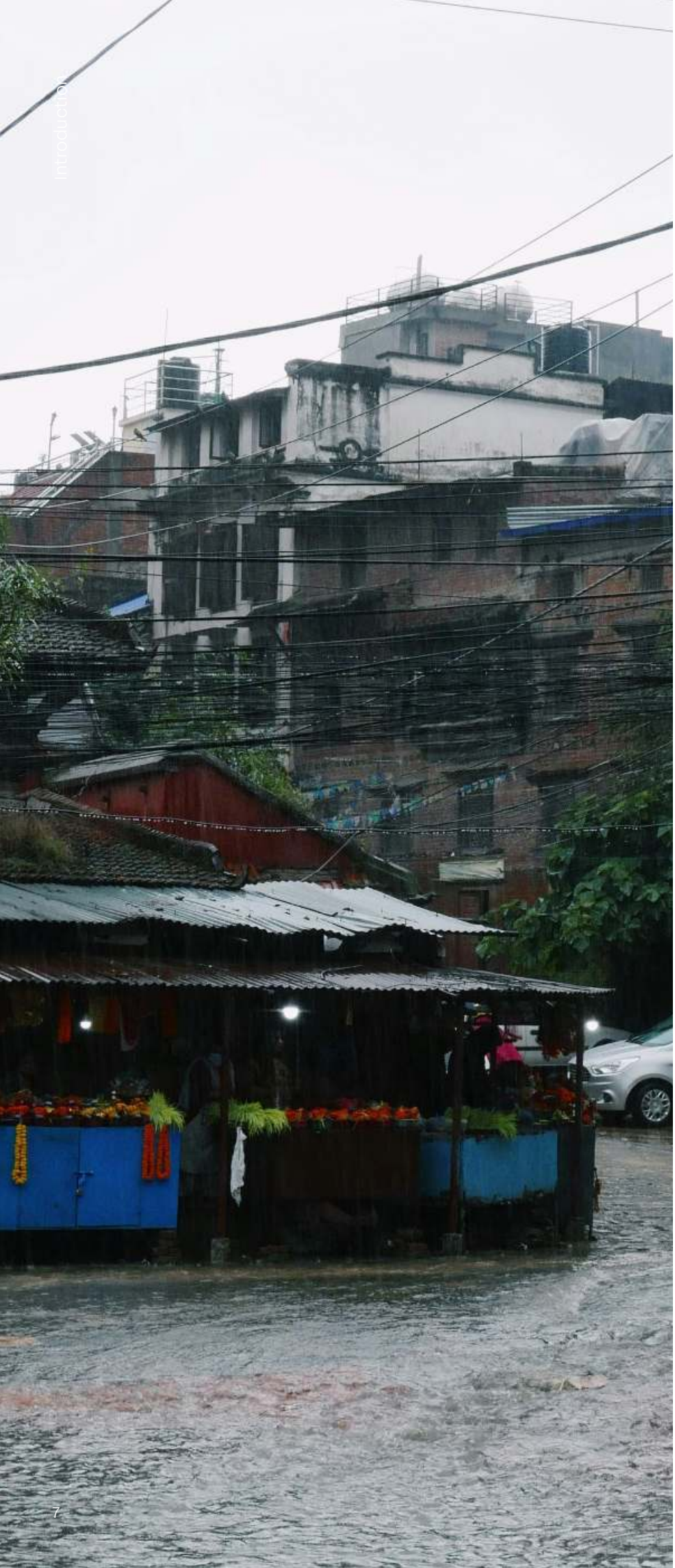
In many senses the way Earth warms runs on two time-horizons. The long-term horizon is determined by the amount of CO_2 in the atmosphere. Even if we were to stop all CO_2 emissions tomorrow, the excess gas in the atmosphere persists over centuries and into millennia, and in the meantime the planet will continue to warm.[3] On the other hand there is a short-term horizon where different dynamics can be activated. As we seek to limit the height and duration of the peak of the climate 'overshoot', defined as the period during which global warming exceeds 1.5°C, we look for approaches that deliver stronger climate management effects in the shorter term. In addition to maintaining pressure to reduce CO_2 emissions, this means targeting short-lived climate pollutants (SLCPs) that linger much more briefly in the atmosphere, whilst acting as potent amplifiers of warming. The key targets are methane, black carbon and tropospheric ozone, as well as changes to the properties of the atmosphere made by aerosols and reflectivity.[4] We talk in this report about exploring 'frontier options'; these are designed specifically to produce near-term cooling to alleviate some warming, to buy time whilst CO_2 remains in the atmosphere.

At the planetary level, the options for acting faster as we enter climate overshoot are far less understood than the low-risk, foundational interventions mentioned above. Approaches proposed to limit the peak of warming – such as marine cloud brightening and stratospheric aerosol injection – have not yet been sufficiently tested under safe, controlled conditions. Researching these frontier options is not a decision to use them, and the evidence may show that the risks of some interventions rule them out. That research is needed now, we argue, alongside the measures we already know work, so that societies understand what can and cannot help bring Earth's systems back within safe limits.[5]

The evidence of Earth system instability is already compelling enough to demand action – especially as recent observations suggest the climate is more sensitive than models previously predicted. Yet we still lack the monitoring and modelling capacity to track how close critical thresholds are, and the governance capacity to decide how to respond. Neither is being built at the pace the risks demand, and both must be in place before a crisis forces decisions.

As long as these gaps persist, decisions about the future of Earth's systems will continue to be made by default. Continued emissions are setting the planet's course, and the people who did least to cause the instability remain the most exposed to it. Governments have the capacity to lead this kind of research in the public interest, yet few have used it.

This report calls for a deliberate change of course. In the sections that follow, we set out what is happening to Earth's systems, what research is needed, who should lead it, how it should be paid for, and how to mobilise it now.



Nepal 2026: a mass-fatality climate event

On 26 August 2026 Nepal suffered a glacier collapse resulting in flash floods, wiping settlements off the map in a matter of minutes, and leaving 5,300 people permanently 'missing', with bodies of around 1,500 people recovered.[6] Twelve power stations stopped working, and fifteen under construction were damaged.[7]

This was the third glacier-linked disaster in the Himalaya region in about 14 months, and Nepal is under further threat.[8] A barrier lake at the collapse site is still a risk for future floods.[9] A 2020 study identified 47 potentially dangerous glacial lakes in the region.[10]

Loss of power stations, schools, clinics and entire towns and villages shows economic impact and human cost interacting. Hidden behind any GDP loss figure for Nepal is the devastation of entire neighbourhoods, deaths and lost people in their thousands, and ongoing pain for survivors. Inevitably there will be further illness and death because power, water and sanitation systems are compromised; travel will be difficult, and homes as shelter are gone. A generation of children will lose their access to education and the opportunity to thrive. The cost of the early recovery efforts and rehabilitation is put at around $5 billion.[11]

Scientists were aware of the unfolding disaster in July 2026, within a timescale that would have allowed escape for many of those who died. But the satellite images that showed it were held outside Nepal, and no agreement was in place to pass them on in time. Within Nepal, the early warning systems in place were also unable to help. Designed primarily to measure flood height, the systems were wiped out by the force of flash flooding before they had even registered there was a problem.[12]

Defining stabilisation

In climate discourse, the meaning of ‘stabilisation’ is not settled. The UN climate convention uses the term to mean stabilising concentrations of greenhouse gas in the atmosphere, while climate scientists speak of ‘stabilisation pathways’ and ‘stabilisation wedges’ – the emissions cuts needed to hold warming at a chosen level. By contrast, glaciologists may talk of stabilising an ice sheet to prevent it from collapsing into the sea. More recently, 'climate stabilisation' has widened to include measures that counteract warming directly, such as solar radiation modification and greenhouse gas removal. Others talk about 'climate interventions' or ‘geoengineering’.

In this report, ‘stability’ means achieving the comfortable range within which Earth’s systems have fluctuated predictably over the last 12,000 years or so: the period known as the Holocene. Accordingly, we use Earth system stabilisation to mean understanding the processes pushing the planet’s systems out of stability, finding where they can be supported or repaired, and keeping Earth within conditions that provide a safe, manageable future for humanity.

A critical element of a stable future is rapidly returning the average global temperature to no more than 1.5°C above pre-industrial levels; global warming feeds into many elements of the Earth’s systems, destabilising and amplifying disruption. Given the rate at which the Earth is currently heating, and the current concentration of CO_2 in the atmosphere, future stability depends on the most rapid and effective action now. It must reduce greenhouse gas impacts and help Earth systems recover a stable, healthy, planetary balance.

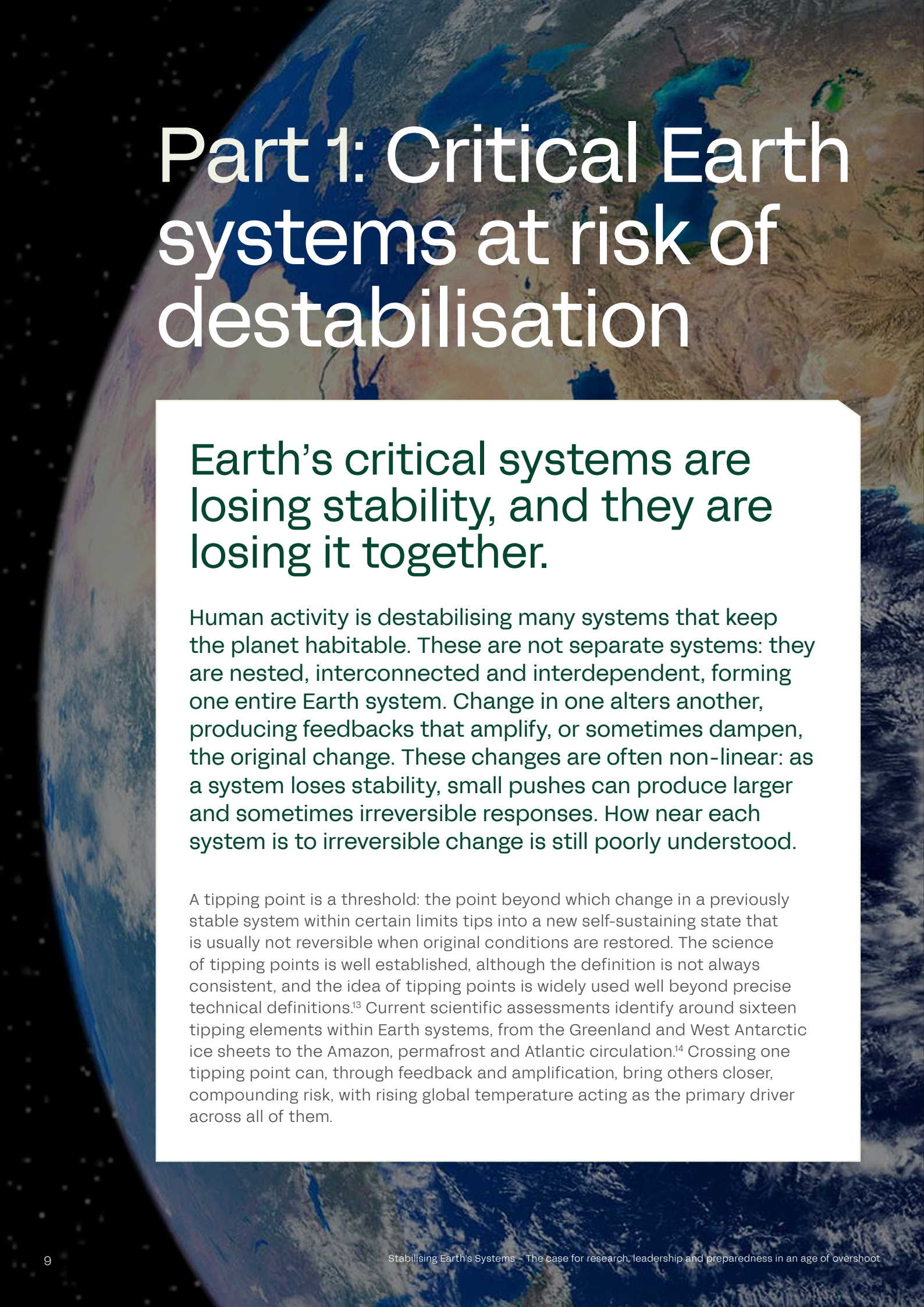
Earth system stabilisation is about more than temperature. Alongside climate systems, it encompasses the oceans, forests, natural vegetation, soils, monsoons and local ecosystems, with all their biodiversity, that billions of people depend on. Because it also involves the work of protecting and restoring those systems, it raises two fundamental questions we will return to: whose stability, and who benefits?

Stabilising the Earth draws on all four pillars of CCAG’s 4R Planet strategy:

- **Reduce** emissions rapidly and at scale
- **Remove** excess greenhouse gases from the atmosphere
- **Repair** damaged natural and Earth systems
- **Build Resilience** to the impacts already unfolding, and those locked in for the future

The lever for restoring stability depends on what is being destabilised. For ocean acidification, the only route is to cut emissions and draw down greenhouse gases, under **Reduce** and **Remove**. For damaged ecosystems, targeted intervention may be possible under **Repair**. **Resilience** applies in every case.

Researching an intervention is not a decision to use it – a distinction we set out in full in Part 2.



Part 1: Critical Earth systems at risk of destabilisation

Earth's critical systems are losing stability, and they are losing it together.

Human activity is destabilising many systems that keep the planet habitable. These are not separate systems: they are nested, interconnected and interdependent, forming one entire Earth system. Change in one alters another, producing feedbacks that amplify, or sometimes dampen, the original change. These changes are often non-linear: as a system loses stability, small pushes can produce larger and sometimes irreversible responses. How near each system is to irreversible change is still poorly understood.

A tipping point is a threshold: the point beyond which change in a previously stable system within certain limits tips into a new self-sustaining state that is usually not reversible when original conditions are restored. The science of tipping points is well established, although the definition is not always consistent, and the idea of tipping points is widely used well beyond precise technical definitions.[13] Current scientific assessments identify around sixteen tipping elements within Earth systems, from the Greenland and West Antarctic ice sheets to the Amazon, permafrost and Atlantic circulation.[14] Crossing one tipping point can, through feedback and amplification, bring others closer, compounding risk, with rising global temperature acting as the primary driver across all of them.

Here we look at this web of Earth's systems through four windows, each chosen because a critical process inside it is driving destabilisation: the planet's energy balance, through reflectivity, absorption, clouds and ice; the ocean, through its circulation and its chemistry; the living world, through forests, soils and drylands; and the human systems where impacts are felt. They are deliberately different in kind. One is a physical mechanism, one the planet's great regulator, one the living world, and one the human system that depends on all three.

For each we ask: what would stabilising this system look like; what would it take to prevent further destabilisation; and where can research clarify the opportunities and limits of intervention. The panels that close each example are entry points to one research agenda, set out in Parts 2 and 5.





Window A

Ice, clouds, reflectivity and absorption

The Earth's energy balance is the difference between how much sunlight the planet absorbs and how much energy it returns to space. This section looks at what is changing that balance: in simple terms, the planet is getting darker and we explain why that matters.

The planetary energy imbalance

The Earth's energy balance is directly affected by how much of the incoming sunlight the Earth reflects straight back into space. Earth is now reflecting back less sunlight than it has for millennia. Less reflection means more solar energy is absorbed by the Earth system, adding to the energy imbalance. Global warming itself reduces the Earth's reflectivity, as snow and ice shrink and cloud patterns change. The interaction between the heat-trapping effect of greenhouse gases and the changes in reflectivity create feedbacks that amplify the original warming.

The rate of change of the energy imbalance is important: between 2005 and 2019, the imbalance roughly doubled, contributing to a recent rapid rise in the rate of global heating.[15] Changes in cloud cover and of reflectivity of parts of the Earth's surface have contributed significantly to this.

How Earth's energy budget works

Earth is warmed by sunlight – the energy arriving from the Sun. Some incoming sunlight is reflected straight back into space by clouds, snow, ice and other reflective surfaces; the remaining solar radiation is absorbed by the Earth system through its land, oceans and atmosphere. The Earth system itself also emits energy back towards space as infrared radiation.

Over long periods these flows of energy broadly balanced, and Earth's average temperature remained quite stable for more than ten thousand years.[16] Greenhouse gases have affected the balance by absorbing and re-emitting some of the outgoing infrared radiation back towards Earth, reducing the energy that escapes to space. If more energy stays in the Earth system than leaves it, the system warms. As the Earth system warms, it increases the amount of infrared radiation it emits until a new balance is established – though at a higher temperature.



Shrinking ice: reduced albedo and the warming feedback loop

Earth's reflectivity, or 'albedo', is an important component of the Earth system's energy balance. Different surfaces reflect widely different amounts of sunlight. Bright surfaces like snow and ice can reflect more than 80% of incoming sunlight, while the dark surface of oceans absorbs most of the sunlight that reaches it.[17]

The ice albedo demonstrates how changes in one part of the Earth system can create a feedback to reinforce climate change globally. When temperatures rise, ice and snow melt and expose the dark surface of the open ocean, and that absorbs more of the sun's energy. That additional energy causes further warming, and that causes further melting.

The Arctic is an entire region where the ice-albedo feedback plays out. For thousands of years, a very large area of Arctic sea ice provided a stable, very reflective surface. Within the last 40 years, that stability has changed completely. Arctic sea ice is becoming thinner and younger. The proportion of sea ice at least four years old - meaning it has survived the Arctic summer without melting – has fallen from about one third, to about 5% today. Summer sea ice has declined fastest, but winter sea ice is also declining at an average rate of 31,000 square kilometres a year over the same period.[18] Record low winter ice was recorded in both 2025 and 2026.[19]

Ice-albedo is affected by pollution as well as by actual loss of ice. Dark particles on ice and other reflective surfaces reduce reflectivity; black carbon produced from incomplete combustion of fossil fuels, is a powerful light-absorbing material. Black carbon on snow and ice darkens the surface and increases the amount of energy absorbed, adding to the melting and the cycle of further warming.[20] Arctic ice, once bright and white, is gradually becoming less reflective. The remaining ice is tending to become darker and more contaminated.

Tundra landscapes are highly sensitive to climate change, and their thaw also alters Arctic albedo.[21] After thaw, changes in plant cover, snow cover and surface water mean that surfaces tend to be less reflective than the original tundra.[22] Shrub growth can independently change the permafrost dynamics. There is a risk of turning a long-term carbon store into a source of greenhouse gases, although the pathway for such emissions is uncertain.[23]

Antarctic changes are less well understood than those in the Arctic, but are just as important for the energy system of the Earth. Big changes in sea-ice and seasonal behaviour are now being observed by scientists, who work in extremely hostile conditions to build a picture of what is happening.[24] The Antarctic summer sea ice coverage has reached new record lows. Changes in the timing of the summer melt season have begun to affect the strength of the ice-albedo feedback.[25]

Antarctic ice sheets contain about 90% of Earth's ice. A major loss of the West Antarctic ice sheet would accelerate sea level rise and increase global heating through the alteration to the whole Earth system.[26] No direct mechanism for stabilising the ice will stop the unfolding changes, so stabilising the Earth's climate 'with minimal overshoot of 1.5°C is imperative'.[27]



Glaciers are another large, reflective, part of the Earth's ice system. They are shrinking at record and increasing rates.[28] Losing glaciers weakens the Earth's albedo and also affects interconnected regional systems, including hydrology and ecosystems. The regional impacts are greatest in the Himalayas. Catastrophic failure of glaciers create massive natural disasters. Glacier-fed water supplies, dependable for thousands of years, are part of the life-support system of billions of people.[29] Nothing can stop glacier loss unfolding in the near term, so 'stabilisation' means thinking about societal effects, climate adaptation, disaster risk reduction, and water governance.[30]

Impacts of ice loss

Regional impacts: the Arctic

The Arctic has warmed nearly four times faster than the global average in the last 50 years.[31] The amplified heating destabilises all of the interconnected Arctic systems – sea ice, snow cover, permafrost, glaciers, ocean systems, atmosphere and ecosystems – and the Earth system reacts far beyond the polar region. However, local communities feel the changes in unique ways.

The consequences of destabilisation are felt acutely by Arctic communities and their local ecosystems; they are already living with difficult changes. Disruption to the ice systems and ecosystems interferes with food sources, transport, infrastructure and ways of life. For Indigenous Peoples whose livelihoods and cultures are so closely connected to the natural environment, these consequences can be profound. Traditional food sources are disrupted and changes to landscapes, wildlife and access to the sea threaten settled ways of living. Human health risks in the region now include exposure to released contaminants in water, soil, and food chains because of flooding and thawing landscapes.[32]

Global impacts: sea level rise

Ice loss from land reaches every coast in the world through rising sea levels. On current global emissions and their pathways, if coupled with ice destabilisation in the Antarctic and Greenland, risk management planning should be taking account of a possible global sea-level rise of a metre by 2100, and addressing the possibility of over two metres under high emissions.[33] An estimated 230 million people live less than one metre above current sea levels.[34]

Risk management approaches look at the probability of something happening and the severity of impact if it does. Given the severity of impact of sea-level rise on humanity, it is essential to plan for high impact, though low probability events. High impact events with a one-in-five chance of occurring by 2100 (20%) should be routinely addressed in planning decisions – although they are not the central estimates, they are plausible possibilities. Extremely high impact events need to be addressed even if their likelihood is as low as one-in-twenty by 2100 (5% chance) – these are the low probability 'long tail' risks that show up as the most difficult outcomes to manage; the loss of cities is irreversible.[35] In general, the higher the emissions pathway the Earth follows, and the more destabilisation there is of ice sheets in Greenland or the Antarctic, the greater the risk of the higher end sea-level rise by 2100, and thereafter.[36]

Credible studies put the upper end, under high emissions, as high as 2.3 metres by 2100 if the Greenland and Antarctic ice sheets disintegrate faster than central modelled projections assume.[37] The lowest, possibly more reassuring, sea-level rise figures of around 0.5 metres assume that decarbonisation of the world's energy system will go faster than the world is currently on track to achieve.[38] The estimates of 1m to 2m for risk planning that we have used reflect the widely acknowledged uncertainty about whether and at what rate global ice sheets will disintegrate or collapse.

The breadth of possibilities reflects a particular uncertainty: how the Greenland and Antarctic ice sheets will behave as Earth continues to warm.[39] Thermal expansion and glacier melt are comparatively easy to model and contribute far less to the uncertainty. Both Greenland and Antarctic ice sheets are governed by dynamic processes. These include the development of marine ice-sheet instability, risk of ice-cliff collapse and accelerating surface melt.[40] All of these events are physically plausible, and have been observed, but they are not well represented in models used to generate most sea-level rise projections.

Sea level is also already higher, in many places, than most assessments say. Calculations often rely on outdated global reference models rather than direct measurement. In Southeast Asia in particular, real coastal sea levels may already be around a metre higher than generally believed. The practical consequences of this are that the impacts of further rise are typically understated.[41]





Cloud dynamics and reflectivity

Clouds are the greatest source of uncertainty in climate modelling.[42] They are dynamic: they move and change in infinite variance, and are difficult to account for in climate models. Their impacts on the Earth's energy balance are complex and depend on altitude, colour, thickness, composition and other characteristics.[43] Understanding what is changing, and why, is important for understanding current climate conditions and the trajectory of future warming.[44]

Bright, low-level clouds, below 2,000 metres, reflect sunlight well, and cover large areas of oceans; they are particularly important because they reflect sunlight back into space before it can be absorbed by the ocean. These clouds therefore have a cooling effect, acting as a kind of 'sunscreen' for the Earth.[45] High, cold clouds have a different effect: they can trap some of the infrared radiation emitted by the Earth system that would otherwise escape to space, producing a warming effect.

Low-level cloud cover has reduced since the beginning of the 21st century. This lets more sunlight reach the oceans and increases the amount of sunlight absorbed by the Earth system.[46] Even a small reduction in low-level cloud cover, at about 0.05% per decade, has had a surprisingly large effect. Between 2003 and 2024, it contributed about half of the increase in the Earth's energy imbalance over that period.[47] This reduction in low-level cloud seems to be driven in part by global warming itself. In the amplifying feedback, warming reduces low cloud cover; reduced cloud cover allows more sunlight to be absorbed by the ocean, and the additional absorbed energy leads to further warming.[48]

Aerosols further complicate reflectivity. Particles from pollution brighten clouds and reflect sunlight, so cleaner air has an unintended warming effect. When international rules cut the sulphur in shipping fuel in 2020, the loss of that reflective haze added significantly to the recent rise in the energy imbalance. How aerosols and clouds interact is emerging as an important area for research, with a pressing need to understand more.[49]

This forms part of the near-term cooling challenge we face. As we continue to clean up sulphate pollution, for health and wellbeing, it has an unavoidable consequence of removing a hidden cooling effect that was masking the true extent of global warming; cleaning up the pollution will accelerate heating in the near term. To balance that heating, cutting methane and black-carbon emissions plays a critical role, providing a near-term cooling effect, and allowing some headroom for a safer future to be achieved. It is this science – the cooling effect of 'pollutants' (which may have been unintentional in the past) - that stratospheric aerosol injection seeks to take advantage of; it is argued that research could be deployed to explore the opportunities and risks of creating a deliberate, controlled version of the aerosol cooling that has already been implemented by accident for many decades. In this sense reflectivity, aerosols, methane and solar radiation modification (SRM) are all part of the complex and interconnected question about near-term warming or cooling of the Earth.

A 2026 study that reanalysed satellite observations going back to the late 1970s – 47 years of data – also raises challenges.[50] Over much of that period low cloud cover increased, producing a cooling effect that partly offset warming, before the recent decline set in. The lesson is that cloud behaviour is dynamic and may have masked some of the warming already under way.



The same study found that the climate models which best reproduce observed cloud behaviour are among those projecting the strongest future warming.

What stabilisation means here

Lever: Repair. Protection and restoration of existing reflectivity, where that is still possible.

Research: Whether cloud brightening could be controlled and reversed if necessary, and how aerosol change affects the energy imbalance.

Research on reflectivity

Research here runs along three strands:

1. Understanding how clouds and ice are changing the Earth's reflectivity, and why
2. Whether cloud cover and brightness could be protected or restored
3. Whether reflectivity could be increased by other means

Some possibilities focus on protecting or restoring different parts of the Earth's existing reflective system. If the recent decline in low-level cloud cover, and its contribution to warming, were halted, and even reversed to levels of a few years ago, more sunlight would be reflected back into space, and less absorbed by the ocean.[51] In the same way, increasing the brightness or reflectivity of some clouds could increase the amount of sunlight reflected away from the Earth.[52]

A different approach goes beyond protecting or restoring natural reflective surfaces, and thinks about increasing how much solar radiation gets reflected back into space from the Earth system. These lines of thought are generally described as SRM. They include ideas for modifying clouds, such as marine cloud brightening, and ideas such as stratospheric aerosol injection, which would put new reflective material into the atmosphere.[53]

SRM approaches are distinct from mitigating climate change through reducing emissions of greenhouse gases. They do not try to address underlying causes of global warming. Instead, they try to alter the Earth's energy balance by controlling the energy the Earth is able to absorb in order to offset some of the warming. In the case of clouds, the boundary between supporting or restoring reflectivity and deliberately modifying the climate system is not clear cut. Stratospheric aerosol injection, however, would clearly introduce a new reflective feature into the atmosphere, rather than restoring an existing one.

The approaches are not equivalent. Each flags different issues for research, including their costs, effectiveness, controllability, reversibility and wider environmental effects and governance, and they need to be considered separately. Research needs to show what might work, what the limits and risks could be, and whether a particular idea is preferable to other forms of action or doing nothing.

EarthCARE: a new eye on clouds

There are new opportunities to close knowledge gaps. The European EarthCARE satellite, launched in 2024, is carrying instruments specifically for observing clouds, aerosols and their interactions with radiation. The EarthCARE measurements are providing new insights into cloud behaviour and their effects on Earth's energy balance. Early results have already contributed to the validation and development of climate models.[54]

Forests and clouds

Even changes in vegetation and land cover are important for cloud behaviour; the changes can alter evapotranspiration and the movement of moisture into the atmosphere.[55] Recent research into boreal afforestation demonstrates that forest impacts can work in two opposite directions.[56] This is why interventions cannot be assessed in isolation.

Window B

Oceans: heat, carbon and circulation under stress

The ocean is a buffer, absorbing excess heat and carbon. But this buffer is finite.

The ocean is the planet's largest store of heat and carbon, holding some 50 times more carbon dioxide than the Earth's atmosphere. It has absorbed around 90% of the excess heat trapped by greenhouse gases so far, and roughly a quarter of the carbon dioxide emitted by human activity, though this capacity is weakening.[57] Its currents, which redistribute heat, salt, carbon and nutrients around the globe, are how the ocean influences the global climate.

This section looks at three stressors in detail, each acting on a critical process with its own tipping point: the weakening of the ocean's great circulation, acidification, and the carbon cycling that depends on marine life. Sea level rise – and in particular its impacts on human settlements – is considered in Window D.

Ocean and ice-sheet thresholds

Ocean systems have thresholds beyond which recovery to an earlier state may not be possible. The nature of the oceans and their systems and eco-systems means that points of no return can be passed without warning. The impacts may take hundreds of years to play out and potentially thousands of years to reach a new stable state.

1. **AMOC shutdown**. The overturning circulation in the Atlantic Ocean is at risk of slowing down to such an extent that northward heat transport and climate are disrupted.
2. **Runaway ice loss from land**. The point where land-based ice loss becomes unstoppable, committing the world to large sea-level rise.
3. **Ocean deoxygenation**. The point where low-oxygen zones spread beyond recovery, as warming cuts the oxygen water can hold and slows the mixing that replenishes it.[58]
4. **Local ecosystem collapse**. The point where a marine heatwave or acute El Niño event pushes a specific local ecosystem past its threshold into a different, self-sustaining state. The new condition, such as 'urchin barrens' for a kelp forest, does not revert when the heat crisis passes.[59] Coral reef collapse, driven by marine heatwaves and changes in El Niño behaviour, is believed to have crossed its tipping point.[60]

The AMOC: the ocean's weakening conveyor belt

The AMOC (Atlantic Meridional Overturning Circulation) is a very large looping system of ocean currents that transports heat, salt and nutrients between equatorial and polar waters. Warm salty water moves northwards in the Atlantic. In the cold North Atlantic and Nordic seas it cools and gets denser. This cold, dense salty water sinks and returns southwards at depth, helping to drive the overturning circulation. The AMOC transports an enormous amount of heat northwards, and is an important part of the global climate system.[61]

The AMOC is weakening as a result of global warming.[62] As the North Atlantic warms, and as additional freshwater from increasing rainfall and also Greenland's melting ice enters the ocean, surface water has become less dense, weakening the circulation. As the AMOC weakens, less salt is transported northward, further changing the density of the North Atlantic waters and further magnifying the weakening.[63]

The precise warming level and timescale at which the AMOC's threshold for 'no return' might be reached is uncertain – it is a very active area of research.[64] Several recent studies place it well before 2100, and some suggest the process may already be under way.[65] A shutdown process would then unfold over an estimated 15 to 300 years.[66] Uncertainty about when is not uncertainty about whether the consequences matter; it is a reason to continue research to understand the system better, and to act before the threshold is crossed.[67]

As the AMOC takes heat from the Southern Hemisphere and pushes it across the tropics to the Northern Hemisphere, it cools equatorial regions. If the AMOC slowed down sufficiently, or collapsed completely in the future, and leaving aside the effects of global warming, the whole Northern Hemisphere would cool down, and the Southern Hemisphere would heat up.[68]

Changes in climate patterns are already linked with the AMOC slowdown. A good example is the 'Cold Blob' in the North Atlantic, south of Greenland and Iceland. Most of the world's oceans have warmed, but this region has cooled since the 19th century. A 2026 study suggests the cooling is caused mainly by a reduction in 'ocean heat transport' into the region; the AMOC is the major component of this transport. The cooling of the Cold Blob contrasts with the Arctic to its north, which is heating much faster than the global average.[69]

The precise consequences for Northern Europe of an AMOC collapse depend strongly on background global warming at the time of that circulation breakdown. Possible changes include major shifts in temperature and weather patterns and a reversal of some sea ice trends. Winter sea ice could extend south to reach Iceland, the Scandinavian coast and the Baltic Sea.[70] Sea level rise will play out whatever other impacts occur, adding to rises already driven by global warming and ice melt. AMOC collapse would produce additional sea level rise around European coastlines and rapid increases in the North Atlantic.

Over the longer term a collapse could contribute over 50cm of global sea level rise through changes in ocean temperatures, although this would unfold over thousands of years.[71] In the shorter term, as the sea-surface slope adjusts quickly to AMOC slow-down, sea level rise of between 10 cm and over a metre will occur in different parts of the North and South Atlantic ocean.[72] This is in addition to any sea-level rise caused directly by global warming.

The wide impacts on global weather after a major weakening of the AMOC include shifts in rainfall patterns, and the weakening of African and Asian monsoons. There could be increased drought in the Sahel, changes in tropical storms and a southward shift in the tropical rain belt. These would all cause severe consequences for food production and livelihoods.[73]

There is no direct action available to stabilise the AMOC itself. There will be a tipping point beyond which the AMOC will not be capable of self-correction even if the heating of the planet is reversed.[74] The only way to avert a significant disruption is to stop the Earth from heating any further and to act as quickly as possible to stabilise the climate.[75]

What stabilisation means here

Lever: Reduce, Remove and **Repair**. Slowing global heating. There is no direct action on the AMOC itself.

Research: An early-warning system: when the threshold might be crossed, and how the Nordic seas' circulation affects the timing.

The Nordic seas: a complication in the AMOC story

The relationship between the AMOC and the circulation of the Nordic seas is complicated. Recent research suggests the Nordic Overturning Circulation (NOC) may actually strengthen at first, as the AMOC weakens, partly compensating for the weakening of the wider circulation. The same research indicates that a tipping point may be reached if deep convection in the Nordic seas shuts down, after which the NOC and AMOC would eventually disintegrate together.[76]



Ocean acidification

Ocean acidification is a direct consequence of carbon dioxide entering the ocean.[77] That absorption has helped slow global warming, but has come at a cost.[78] As CO_2 dissolves, the seawater becomes more acidic. Average surface ocean pH has fallen from about 8.2 to 8.1 since pre-industrial times. That difference sounds small, but the pH scale means this is roughly a 30% increase in ocean acidity.[79] Acidification has no local fix. It can be locally influenced by other processes, for example freshwater, nutrient and pollutant inputs, and the presence of aquatic vegetation (kelp or seagrass) that removes CO_2 from seawater at local scale. Globally, ocean acidification is driven directly and predictably by how much CO_2 the ocean absorbs, and that depends directly on how much CO_2 is in the atmosphere. Stabilising ocean chemistry is therefore not a separate task from stabilising the climate. It is the same task, seen from the ocean's side.

Why it matters: carbonate chemistry and shell-building

Many marine organisms, including corals, shellfish, and some plankton (including krill) build their shells and skeletons from a form of calcium carbonate called aragonite. Building and maintaining aragonite shells depends on there being enough carbonate available in the surrounding water. Scientists describe this using 'the aragonite saturation state'. As the ocean acidifies, that saturation state falls. Below a critical point, it is harder for organisms to build shells at all, and existing shell material starts to dissolve.[80]

This is not a distant risk. Parts of the Southern Ocean will cross the threshold by mid-century. By the end of the century, about 70% of the world's deep-sea coral reefs are expected to reach the point where their skeletons cannot be chemically maintained.[81] The organisms most at risk are usually the youngest life stages, such as coral larvae and shellfish larvae. The effects on a population can, therefore, build silently for years before appearing abruptly, once a generation fails to establish. Ocean acidification can cause stress to shellfish before they reach the point of non-calcification; as conditions become more difficult, they become vulnerable to disease and other stressors.[82]

Recent field research looked at coral reefs near natural undersea vents where volcanic CO_2 seeps into the water: these areas are made more acidic. This research offers a real-world view of what a more acidic ocean will look like in the future; it suggests that acidification tends to change reef communities gradually rather than at one sharp threshold. Corals and reef-building species decline steadily as conditions worsen, and non-calcifying algae expand to take their place.[83] Nonetheless, a gradual decline ends in a very serious, irreversible loss of reef structure, with all the biodiversity it supports.

Where the science stands

Long-term ocean monitoring is what allows scientists to track acidification with confidence, and to identify which regions and species are most at risk, and also to identify locations or habitats (known as 'refugia') that remain relatively unchanged by significant environmental shifts towards acidification stress. While records span multiple decades, there is a significant challenge in getting enough long-term measurements to track and understand the impact of ocean acidification on different regions of the world.[84] This is quite a straightforward research need: sustained investment in observation. It already delivers results.

A more open research question is whether acidification can be countered, rather than just monitored. 'Ocean alkalinity enhancement' is an active area of research, with field trials now underway. Experiments add alkaline material to seawater to help it absorb more CO_2 and locally reduce acidity.[85] But current evidence is not optimistic. Realistic-scale trials have restored calcification rates in affected species by around half, at best. The underlying climate benefit appears to be weak because the amount of CO_2 the approach can durably remove from the atmosphere declines over time.[86]

Ocean alkalinity enhancement research exposes its limits. It might offer a partial, local supplement in specific high-value places, such as a particular reef or shellfish fishery. On current evidence, it is not a substitute for reducing emissions. There may, in any case, be sound environmental reasons not to deploy the approach at scale. The point of the research is to explore these factors.[87]

What stabilisation means here

Lever: Reduce and Remove. Cutting global CO_2 emissions.

Research: Sustained monitoring, and whether alkalinity enhancement can protect particular reefs and fisheries.



Marine life and the carbon cycle

Marine life actively drives how carbon moves, especially vertically within the oceans, and defines how and where carbon gets stored. Warming and the depletion of marine life put this transfer of carbon at risk.

How marine life moves carbon down to deep oceans

The fundamental processes are a series of 'pumps'.[88] Each pump has a separate mechanism. Most organic matter is broken down in the upper few hundred metres of the ocean. The portion that escapes that 'recycling' goes down into the pumps' long-term deep, cold ocean storage.

One physical and chemical pump consists of the ocean's ability to hold dissolved CO_2. Cold water can hold more CO_2 and cold water sinks, so CO_2 is carried into the deep ocean. Another similar process is driven by shell-building creatures. They use calcium carbonate to build their shells, and when they die this carbon sinks to the bottom of the deep ocean.[89]

The classic biological pump involves phytoplankton photosynthesising at the surface, producing organic matter that becomes 'marine snow'. This is formed of dead cells and faecal pellets. At depth the debris is broken down, and the carbon moves downwards as nutrients are released back up.[90] The microbial carbon pump is a newly recognised biological pump. Bacteria and archaea convert dissolved organic carbon into a stable form that can last in deep oceans for centuries to millennia.[91]

The final category of 'pumps' is the migration-driven.[92] Creatures move the carbon as part of their own activities. Some zooplankton and small fish feed near the surface by night and go down to depth in the day, carrying carbon through their own metabolism. Seasonal lipid-storing copepod migrations, and great whale vertical feeding movements, work on the same principle.

The decline of marine life is felt first and most sharply at local level: a depleted fishery or a degraded reef is an immediate loss of food, income and cultural heritage. This occurs long before the change is registered as a global biodiversity statistic. Stabilisation here means both protecting what remains and, if possible, actively restoring what has been lost.

Marine protected areas can protect the carbon stored in mangroves, seagrass beds, salt marshes and other coastal wetlands; they can also stabilise fish and wider marine life populations, helping to sustain the biological 'pumps'.[93] But recent research shows that how well an area is governed and enforced matters more than how much ocean is covered.[94] Two examples show how marine life and carbon cycling are linked: seagrass meadows and whale populations.



Seagrass and whales: marine life in the carbon cycle

Seagrass

Seagrass meadows sequester carbon in the sediment beneath them, much like forests sequester carbon in the soils below their trees. In ocean systems, this is referred to as 'blue carbon'. Restored seagrass meadows can eventually store carbon at rates comparable to natural, undisturbed meadows – but this takes time. Measurable storage gains can be negligible for the first five years, and only become clear after about a decade.[95] Restoration efforts are working in the face of an ever-shrinking baseline. Seagrass is being lost at a rate of around 7% a year globally, and climate change is expected to shrink suitable seagrass habitat even more in vulnerable regions.[96]

Whales

Whales move nutrients vertically through the ocean, and across it. Baleen whales feed on krill at depth (which migrate for safety to deep waters during the day) and release fertilising faecal plumes when they return to the surface to breathe. This cycle keeps surface waters fertile for phytoplankton that absorb carbon dioxide during photosynthesis – and in turn provide krill with food (during safer night-time feeding migrations to the surface). This movement pattern is the 'whale pump'. Baleen whales also carry nutrients across oceans on their migrations, from high-latitude waters where they feed in summer to tropical and subtropical waters where they overwinter.[97]

Commercial whaling reduced baleen whale populations to less than a tenth of their original numbers.[98] This cut the flow of nutrients on which the phytoplankton and krill populations depended. The krill died back too, and the ocean lost part of its productivity: baleen whales are estimated to support around a tenth of plankton growth in offshore waters in summer.[99]

Recovering whale populations could help restore these ecosystems. There is also interest in the climate benefits, but how much carbon whales help send to the deep ocean remains largely unknown.[100]

One of the most powerful ways to restore the whale pump is to protect whales and let their numbers recover. Whether the effect could be replicated artificially is an early-stage research question.[101]

What stabilisation means here

Levers: Repair and Reduce. Enforced protection, restoration where it works, and cutting global emissions.

Research: Understanding effective design and enforcement of marine protected areas, quantifying the long and short-term storage of carbon in seagrass and other aquatic vegetation, and pathways for restoration of whale species.



Window C

Biosphere: the living world

The biosphere is the living world, on land and in the sea. It is the one system where stabilisation already works at scale, if intervention starts before an ecosystem reaches a point of no return.

Ecosystems within the biosphere remained broadly stable through the centuries in which modern human society emerged: these systems were always dynamic, but shifted within limits that allowed them to absorb some level of disturbance without loss of structure or function. Stability is now being lost for almost all of these systems. Human societies have widely treated ecosystems as resources to be extracted and converted for human use, failing to recognise their ecological importance, or our own dependence on them. Biodiversity is tumbling all over the world: the rate of species extinction is at least tens to hundreds of times higher than the average rate over the last 10 million years.[102] This accelerated loss is caused by human activity, especially land-use change. Now human-driven global warming adds yet more pressure, pushing ecosystems past the planetary boundaries that keep the Earth system stable.

The biodiversity risk is not just that individual species and their immediate network of connections disappear, although they do. The deeper risk is that depleted ecosystems ultimately lose their structure and function, sometimes to a point of no return.[103] This reduces, and can remove, their ability to provide food, water, carbon storage, climate regulation, foundations for good health and cultural stability – the things that have kept the Earth system stable through the Holocene and enabled human societies to function.[104] Climate change intensifies ecosystem pressures in multiple ways, and degrading ecosystems can also alter climate and other Earth-system processes. Feedback loops between ecosystems and the climate can speed up degradation across the Earth system. Forests that are too thin cannot manage their moisture recycling; loss of plants to desertification changes rainfall patterns locally and accelerates desert spread; loss of one species in an ecosystem deprives others of their interactions as food or protection, and further losses spiral from the first.[105] Cumulatively, these changes alter how heat moves around the planet, how much sunlight it reflects, and the circulation of air and water, destabilising the whole Earth system.

Three examples follow, each an anchor for the wider Earth system:

1. the Amazon,
2. the world's soils,
3. and the reversal of desertification.

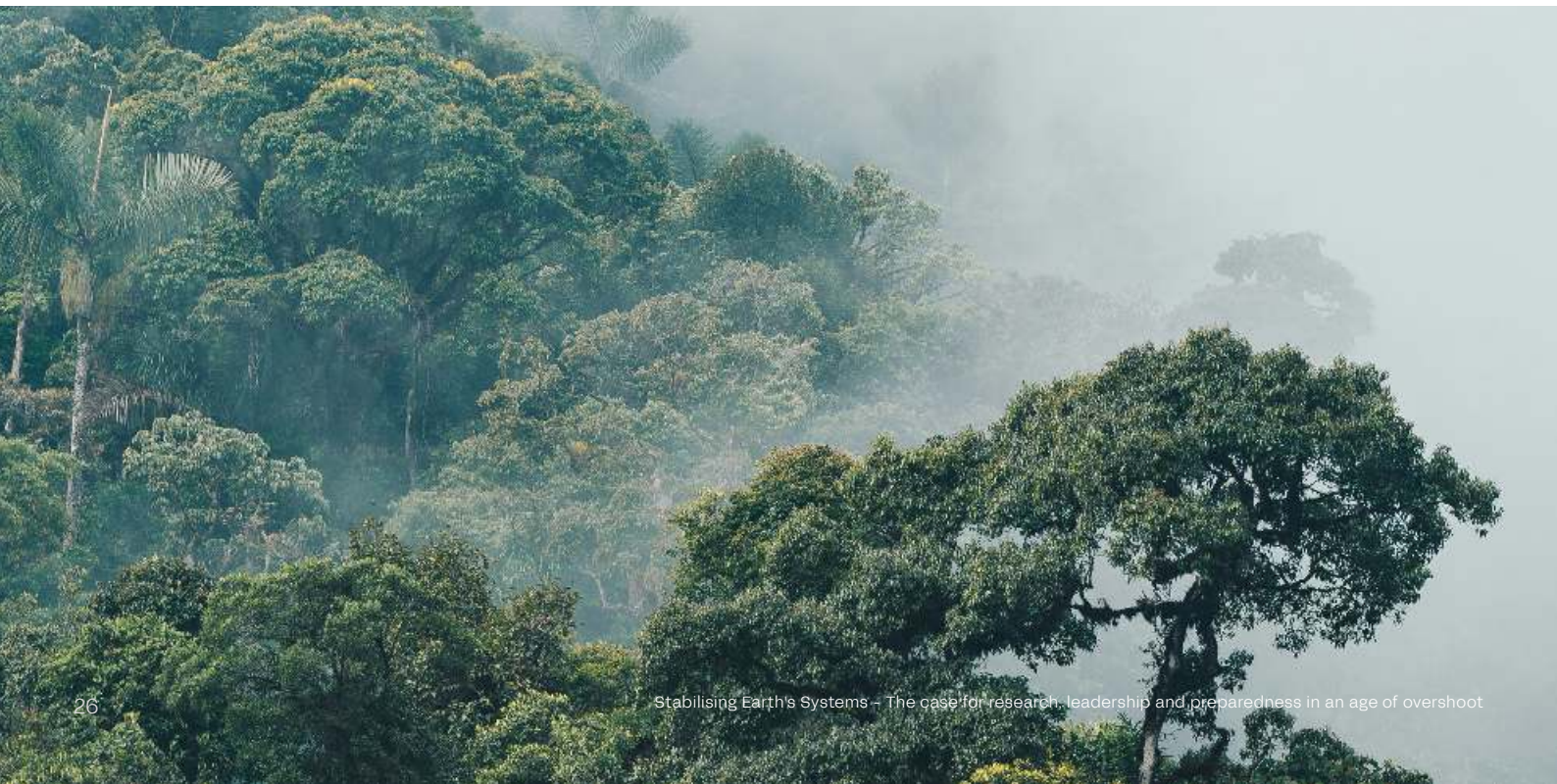
Action on each works from the bottom up: it tackles regional thresholds and, through them, feedbacks at planetary scale.

The Amazon basin: from global carbon sink to source

The 65-million-year-old Amazon forest system is shifting from its ancient stability.[106] Warming, droughts, wildfires – and large-scale deforestation – all create stress. The Amazon is one of the main regulators of the global climate.[107] It supports the integrity of the biosphere and its complex hydrology creates a self-sustaining system.[108] The forest recycles its own rainfall as well as 'exporting' moisture; this directly affects weather across the American continents.[109] These continental weather systems underpin global circulation of the atmosphere.[110] When stable, the Amazon stores carbon equivalent to 15 to 20 years of global CO_2 emissions.[111] As it destabilises it becomes a carbon emitter, less able to help maintain local, regional and global system stability.[112] Wildfires, predatory logging, degradation of landscapes and land use change have all pushed the Amazon forest close to its point of no return.[113] The thinning of forests has already damaged their ability to self-repair, to recycle water – and to export water for surrounding weather systems, supporting other biomes with precipitation.[114] Deforestation causes precipitation reduction – an effect underestimated in climate models.[115] The whole Earth system is affected by what happens in the Amazon.[116]

Most deforestation in the Amazon has been driven by demand for beef, through aggressive land-use change.[117] The greatest current threat, however, is the spread of wildfires, which have taken over from deforestation as the main driver of increasing instability and fragility. In 2024, widespread fires caused devastation at a time when deforestation had actually decreased.[118]

Like deforestation, wildfires are driven by human activity and consumption habits, and thinned-out forest is much more prone to runaway fires.[119] Healthy forests have built-in resistance to burning because of their dense humid canopy that seals in moisture and keeps the forest floor cool.[120] By contrast, thinned and dried out forest areas where the canopy has been reduced are highly flammable. Once burnt they recover slowly and stay warmer than intact forest areas for decades.[121]



Brazil's other biomes depend on the same weather systems and are under threat from global warming in their own right: Cerrado (savanna), Caatinga (semi-arid forest), Pantanal (tropical wetland) and Pampa (temperate grassland). Each stores carbon and is home to many communities and to species found nowhere else.

Studies show that the forests can regenerate naturally if deforestation and degradation are stopped.[122] Local and Indigenous stewardship can also support forest protection and stabilisation, particularly when backed up with policy and enforcement to prevent illegal logging and mining, for example.[123] But remediation and protection remain under constant pressure from commercial land-use change, and increasingly severe climate-driven disturbances, including drought and fire.[124]

What stabilisation means here

Lever: Repair. Policy and enforcement against deforestation and degradation, backed by local and Indigenous stewardship

Reduce: Reducing demand for products requiring land-use change, especially shifting diets to reduce red-meat consumption since beef/cattle ranching is the main driver of deforestation.

Research: How close the forest's moisture recycling is to its threshold, and how much repair remains possible once it is crossed. What works to promote plant-based diets.





Soil regeneration and food security for the most vulnerable

Improving soil health and soil management is a global challenge. Soils are not just a growing medium for staple food production; they are highly complex living ecosystems whose formation involves physical, chemical and biological processes operating over long timescales. They harbour a huge diversity of organisms and ecological interactions.[125] There are significant knowledge gaps in understanding of soil and its dynamics.

Degraded soils can sometimes be supported to recover important functions, but this may be quite different from rebuilding the original soil ecosystem; some soil ecosystems may be irreversibly lost, putting global food security and biodiversity at risk.

Some functional restoration can however provide positive support to Earth system stability, even where it is not equivalent to the stability of the original ecosystem. Well-restored soils have the potential to create a global-level public good: more stable and sustainable food production alongside increased carbon sequestration, nutrient retention and water management.[126] 'Regenerative agriculture' prioritises soil health, along with biodiversity and ecosystem resilience; it therefore offers an important contribution to Earth system stabilisation. Regenerative approaches can also make farms more profitable.[127]

The difficulty is that the full global benefit of soil enhancement through regenerative approaches ultimately has to be delivered through decisions made by millions of individual people field by field. A lot of the world's agricultural land is managed by smallholder farmers. They often farm with limited access to finance, equipment, inputs, knowledge and secure land tenure. Regenerative farming systems are known to be resilient and productive, but they take time and money to introduce. New knowledge and skills have to be co-designed and shared, and the whole transformation involves risk and effort. The changes cannot just be imposed from above.[128]

The benefits of additional carbon storage are global, while the costs and risks of changing farming practices are often borne by individuals. Over time, improved soil management could make farming more productive, sustainable and resilient.[129] But transition programmes have to avoid transferring risks and costs to hundreds of millions of farmers, who are already among the world's most economically vulnerable people, and the billions of others who depend on their farms.[130] At the same time, regulation and policy support must ensure that large companies and traders in the agribusiness sector are also required to improve soil and farming practices for carbon storage.

The potential is worth pursuing. Soil and grassland could add a substantial global carbon sink whilst strengthening local agricultural resilience. So far much of this potential is unrealised. The IPCC identifies improved soil-carbon management in croplands and grasslands as having significant mitigation potential, particularly where soils and grasslands have been degraded and soil organic carbon depleted.[131] The scale of the underlying problem is large: in sub-Saharan Africa around 65% of arable land is degraded.[132] Soil erosion removes millions of tonnes of nutrients each year, and reduces production, imposing additional costs estimated at over $4 billion annually.[133]

There are many ways of improving soil health. But there is no single system that can be rolled out everywhere. What works depends on soils, climate, crops, livestock, land tenure, cultural context, labour, markets and local knowledge.[134]

The general approach should therefore be to enable and support farmers to regenerate their own soils. That requires investment in research and locally relevant knowledge, as well as effective extension services. It needs access to appropriate financial services and markets, along with secure land rights. It also requires policies that recognise the wider public value of resilient farming, healthy soils and carbon sequestration.[135]

What stabilisation means here

Lever: Repair. Institutional. Extension services, finance, markets and secure land rights.

Research: Locally relevant knowledge and credible carbon accounting, rather than new techniques.

Reversing desertification at scale

Drylands cover around 41% of the Earth's land surface and are home to over 2 billion people.[136] Healthy, stable drylands store carbon in their soils, and also in their sparse vegetation. If drylands become degraded the soil becomes eroded, complex soil-based ecosystems are damaged and carbon storage is lost; the vegetation is no longer sustainable; local convective rainfall can be suppressed; weather patterns thousands of miles away can be disrupted by dust plumes that travel across oceans. Desertification destroys the ability of vegetation and healthy soil to regulate water movement, with water running off the surface instead of being stored in healthy soils.[137] Flash floods during heavy rain are coupled with severe droughts, and the ecosystem becomes less stable, and more fragmented.[138]





These changes push against three of the planetary boundaries: land-system change, biosphere integrity and freshwater change. When drylands destabilise they act as a climate feedback amplifier, with CO_2 emissions replacing the ability to store carbon, accelerating global warming.[139] About 40% of the world's land is already degraded.[140] Between 2015 and 2019, at least 100 million hectares of productive land were being degraded every year.[141]

Desertification and severe land degradation can often be reversed to a helpful extent for stabilisation of the Earth's systems.[142] In different regions degraded soils, vegetation and farming systems have been stabilised and restored. The most successful examples combine research with practical experience: methods are tested, adapted to local conditions and then applied at scale.[143]

In China, on the Loess Plateau, severe erosion caused by over-farming over many centuries was tackled across an area the size of Belgium. A combination of terracing, improved water management, restrictions on cultivation on steep slopes, and restoration of trees, shrubs and grasslands transformed the landscape.[144] Vegetation cover increased, sediment entering the Yellow River fell by more than 100 million tonnes a year, and agricultural and rural incomes improved. More than 2.5 million people were lifted out of poverty.[145]

Strong evidence for farmer-led restoration comes from the Sahel. In southern Niger and Burkina Faso farmers have used Farmer Managed Natural Regeneration (FMNR) to protect and manage trees and shrubs that regenerate naturally on agricultural land. Farmers continue to grow crops whilst maintaining useful trees. This approach restores degraded land and the new stability allows increased food production.[146]

What stabilisation means here

Lever: Repair. Proven local practice applied at scale, with policy support.

Research: How these methods transfer between regions, and what makes them last.

Indigenous and local stewardship

There is growing evidence that Indigenous-managed lands, whether in conserving forests, tackling desertification or using regenerative farming methods, can deliver conservation outcomes comparable to, and in some circumstances exceeding, those of formally protected areas. A 2026 systematic review of the evidence found substantial support for the contribution to conservation of Indigenous Peoples' lands. Recognition of that contribution needs to come with practical support: secure land tenure, access and resource rights, a say in decisions, capacity building and funding, and protection from external disruption.[147]



Window D

Human systems: people, cities and the economy

The systems we have looked at so far are Earth's own. Human systems are where people experience their instability, as heat, flood, failed harvests and much else.

Human systems are vast, taking in health, food, water, energy, migration and economies, alongside the places we inhabit.

Here we look at three examples.

1. The first is people themselves and the limits of what the human body can bear as heat rises.
2. The second is cities and settlements, where most of humanity now lives, and where these systems are most tightly bound to one another, seen through rising seas.
3. The third is the economy, which carries the costs when the other systems fail.

The stabilising levers here are not the same as for the earlier systems. There is no direct intervention on a human system, as there might be on reflectivity or a forest. What stabilises human systems is **Resilience**: adaptation and planning, carried out while heating is slowed through **Reduce** and **Remove**. Research helps by showing which places and groups reach their limits first, how to implement effective and fair resilience measures, and how to plan for the low-likelihood, high-impact end of the range of events. Communities that have developed in places where heat, water availability or food production were already close to their limits can be particularly exposed as climate change pushes conditions beyond those limits.[148]

Extreme heat and human limits

Human settlements have for thousands of years clustered in hospitable climate zones – a 'surprisingly narrow' band from amongst the climates on offer across the Earth.[149] The preferred annual average temperature is around 13°C. It turns out that humans, like all animals, have an environmental niche. Within this hospitable band humans have successfully lived, produced food and livestock, and created complex human systems that sustain civilisation. This pattern provides evidence that habitability limits for humans are real, not just a preference.

The geographical location and range of humanity's climate niche is moving more rapidly now than it has since the beginning of human civilisation. By the end of this century a large number of people will be trying to live far outside the comfortable climate niche that has been the foundation of human well-being. Some will try to adapt, some will not survive – and some will try to move to better locations.

Heat, humidity and the human body

The physiological limit that humans can cope with comes from a combination of heat and humidity; poverty and technology change outcomes because air conditioning (generally not available to the poorer people in the hotter locations on Earth) keeps people away from the direct effects of inhospitable heat and humidity.[150] If a person cannot sweat because the air immediately around them is already saturated, then the body loses its main heat controlling mechanism. This heat-humidity threat affects the elderly and the vulnerable first. It is measured as a 'wet bulb' temperature.

The most recent studies show that heat stress with clinical effects starts to happen at around 24°C wet bulb measurement.[151] This limit is reached for weeks every year across most of the tropics. The threshold was always exceeded even before human action started heating the Earth.

In the hottest regions of human settlement, where 30°C to 32°C wet bulb measurements are now more common, outdoor workers are especially at risk. The frequency of these heat events has doubled since 1979.[152] In the worst-hit areas, such as the Persian Gulf coastline, Pakistan's Indus Valley and coastal South Asia, healthy young adults doing basic tasks are at risk of death on an annual basis, and this is true in the Gulf coast stations every three years or so in current conditions.[153] As well as risk to life, heat stress is known to increase incidence and severity of neurological disease, further undermining well-being.[154]

Very rarely wet-bulb temperatures have reached 33°C to 34°C – temperatures at which nearly everyone's life is at risk without cooling.[155] Temperatures of over 35°C have been recorded a handful of times globally – a fatal level for everyone within hours. An increase in average global temperature of around 1.3°C makes 35°C wet bulb events in Persian Gulf waters a regular occurrence. The world sits today at around 1.4°C according to the latest calculations.[156] Over inhabited land near to Persian Gulf waters, 35°C wet bulb events will become regular with an increase of between 1.4°C and 3.3°C in the global average.[157]

The human cost of heat stress is high. People cannot work outside without risk of death, and very young and very old lives are also at risk.[158] Cities, with their heat-island effect, can make high temperatures even worse.[159] People are concentrated in hot cities, often in accommodation that lacks cooling. They have few public areas in which natural cooling and shade are available, such as forests and parks. In general, the poorer and more vulnerable a community, the less access they have to these natural life support systems.[160]

Analysis of heat thresholds tends to focus on what is survivable. That is a low benchmark: the aim should be for people to thrive. Heat stress deaths are undercounted – rarely showing up on death certificates, for example.[161] But high temperatures and heat stress destroy the ability to thrive long before they kill.

Adaptation needs to focus on how to thrive, especially in cities where so many vulnerable people live. Places of safety – schools, clinics and community centres – must provide access to shade and cool conditions even during high heat. Schools need adapting so they are not forced to close in every heatwave, disrupting education for whole generations; hospitals need to stay cool enough not to make sick people sicker. Longer term planning must combine shade, green spaces, better building design and low-carbon cooling to create urban environments in which people can continue to live, work, learn and thrive even as temperatures rise.[162]

As urban populations increase, there is a reduction – to less than 20% – in the proportion of people who live in rural areas.[163] Primary food production (the actual growing or catching of food) is concentrated in these rural populations, as well as small-town populations. Dependence of food production on rural people is especially true in African countries, where about half of the population is engaged in agriculture.[164] There are few adaptation measures available to farmers. If these people struggle to do their job because of heat stress they lose their income, but the other four out of five people who depend on them for food production lose their reliable source of food.

What stabilisation means here

Lever: Reduce and **Remove**, then **Resilience**. Shade, cooling and building design where people live and work, while heating is slowed.

Research: Where wet-bulb limits will be crossed first, how heat stress is measured and prevented for people who work outdoors, and which adaptations keep people working and learning through heatwaves while not increasing emissions.



Rising seas and coastal cities

A city is a system of systems. Power, water, sanitation, food supplies, transport and health all depend on one another. When one fails, the rest tend to follow, and a climate shock rarely stays contained. So rising seas reach well beyond the hazard itself.

How far seas could rise this century, and why the range is so wide, is set out in the ice section. Here we look at what that rise means for people.

Some 81% of people now live in urban areas (cities and towns), and a billion people currently live less than 10 metres above the high tide line.[165] Since the 1950s people have left rural areas and been absorbed by urban areas, especially large cities. By 2050, 800 million people or more will live in coastal cities where sea levels could rise by more than half a metre.[166] Food production is also vulnerable to sea-level rise. We focus on Southeast Asia, one of the most densely populated and exposed regions in the world, but the same dynamics would show in small island states, New York or London.[167]

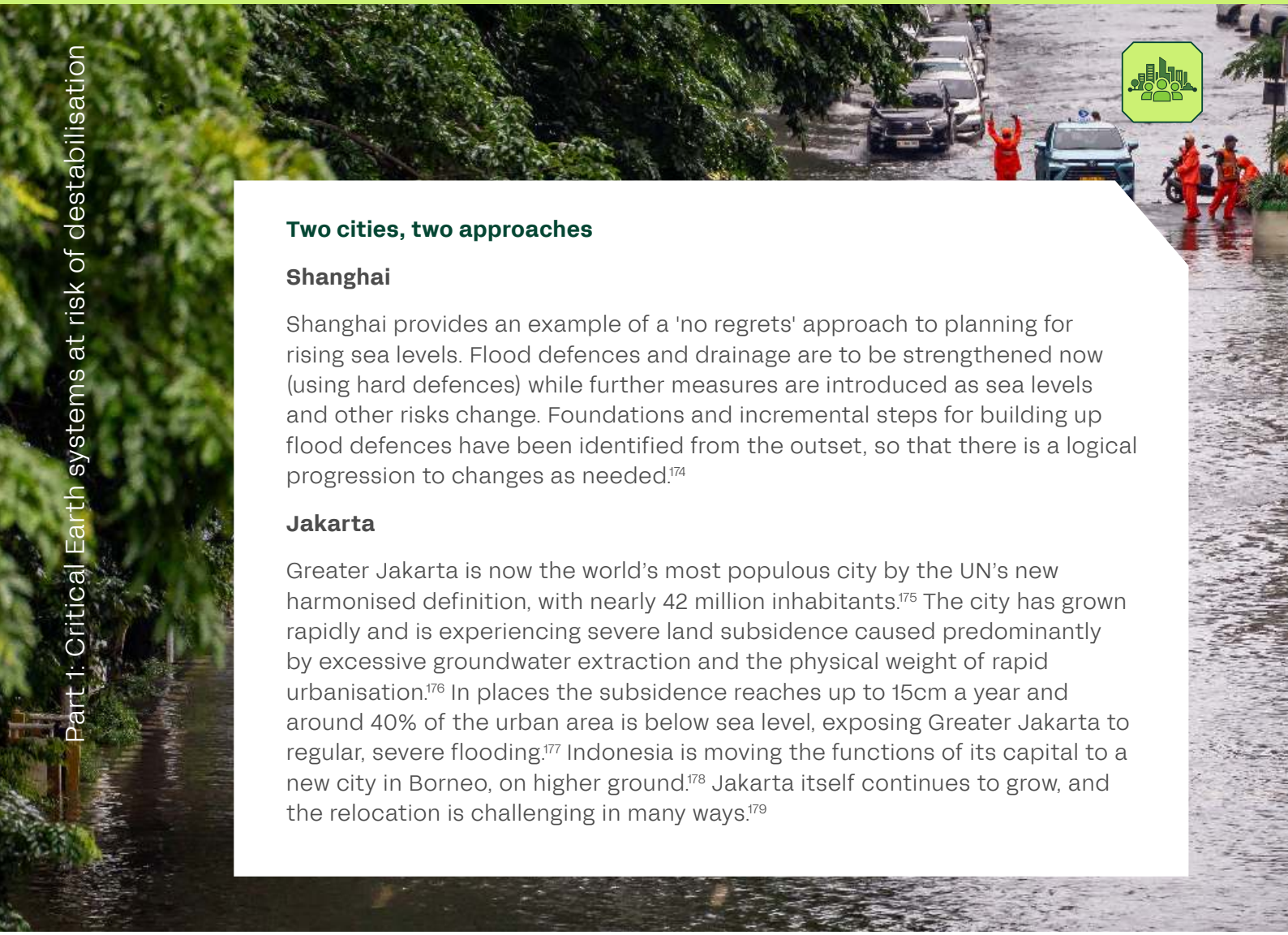
For example, Vietnam is the third largest rice exporter in the world, contributing to the global food system significantly.[168] Over half of Vietnam's rice production, and over 90% of its rice exports, come from its Mekong delta area.[169] A sea level rise of 1 metre would put about two thirds of the area at risk of flooding, making it unsuitable for feeding the millions who depend on it.[170] Assuming the current emissions pathway continues, a 2026 economic and spatial modelling study shows displacement of up to 10 million people by 2100. This is around a tenth of Vietnam's population. Economic losses in land values alone would be expected to reach $3 trillion.[171]

Managed retreat may be the only realistic option for parts of Vietnam's rural areas, and also in other parts of the world unable to withstand severe sea level rise. For other areas, and for towns and cities, coastal defences may buy time, or even protect land for the longer term.

Coastal and low-lying cities already face increasing flooding and damage to transport, power, water, sanitation and other infrastructure. Coastal farmland can be inundated and increasingly affected by salt-water intrusion. The combination of rising seas, storm surges, heavy rainfall and land subsidence can make existing flood risk considerably worse.

There is no single solution. Some nature-based solutions can achieve a lot. In some locations only hard defences such as sea walls, raised embankments and tidal barriers will work.[172] The most resilient approach may sometimes be to combine the two.

Amongst nature-based solutions, use of natural barriers, especially regenerated mangrove forests, can reduce wave energy, flooding and erosion. They may also provide some support to fisheries and other livelihoods. In Indonesia, approaches such as 'silvofishery' work on combining mangrove restoration with shrimp farming. The results have been mixed, but the aim is to allow coastal communities to retain commercial opportunities while restoring mangroves that can provide protection from coastal flooding and erosion.[173]



Two cities, two approaches

Shanghai

Shanghai provides an example of a 'no regrets' approach to planning for rising sea levels. Flood defences and drainage are to be strengthened now (using hard defences) while further measures are introduced as sea levels and other risks change. Foundations and incremental steps for building up flood defences have been identified from the outset, so that there is a logical progression to changes as needed.[174]

Jakarta

Greater Jakarta is now the world's most populous city by the UN's new harmonised definition, with nearly 42 million inhabitants.[175] The city has grown rapidly and is experiencing severe land subsidence caused predominantly by excessive groundwater extraction and the physical weight of rapid urbanisation.[176] In places the subsidence reaches up to 15cm a year and around 40% of the urban area is below sea level, exposing Greater Jakarta to regular, severe flooding.[177] Indonesia is moving the functions of its capital to a new city in Borneo, on higher ground.[178] Jakarta itself continues to grow, and the relocation is challenging in many ways.[179]

Shanghai and Jakarta each show what is at stake in the face of sea level rise. Jakarta's subsidence is partly the result of ignoring the worst-case risks involved in urban growth and climate pressures. Shanghai's 'no regrets' policy highlights a more measured and planned approach. It may place constraints on development now, and involve investment for uncertain events in the future, but it builds capacity to cope if the worst comes to pass. City planning and coastal defence are where human systems and climate change meet most directly. Planning should not be based solely on the outcomes perceived to be most likely. It has to take account of low-likelihood, high-impact possibilities if it is to give people a measure of safety.

What stabilisation means here

Lever: Reduce, Remove and Repair, then Resilience. Adaptation and planning that assume the worst cases, while heating is slowed by all means available.

Research: Which coasts and deltas reach their limits first, what protection is feasible, what migration, human and infrastructure impacts are likely to follow, and how planning copes with the low-likelihood, high-impact end of the range.

The economy

21st century life depends on an implicit assumption that economic foundations are more or less stable. When that assumption is challenged, as in the 2008 global financial crisis, the impacts are devastating for individuals and very costly for states and regions. The whole world was caught out on that occasion.[180] Global, regional and local economic systems, created by human civilisation, are under pressure from climate change and Earth system destabilisation. Global annual direct losses have already reached more than $200 billion, and total annual disaster costs, including 'cascading and ecosystem impacts' exceed $2.3 trillion.[181] The assumption of stability and predictability is fundamentally shifting, with continuous impact on macroeconomic conditions.[182] This is not a case of saying that, in a climate crisis, some assets will get damaged. The risk is that models, pricing and financial institutions may not hold.[183] As attention is diverted by an intensifying series of economic crises, the capacity to take urgent steps to stabilise Earth systems is at risk of being completely derailed. Under the same pressures, political stability will be threatened, and capacity to act consensually on stabilisation will be reduced even further.[184]

Economic models (traditional Integrated Assessment Models) have acknowledged the impact of climate change on global outlooks for decades. However, their structure tends to project smooth, decadal trajectories for changing global temperatures. This does not capture non-linear interaction between different stresses on the Earth system, and by extension, on the global economic system.[185] These modelling challenges prompted the creation by the Network for Greening the Financial System of 'NGFS Climate Scenarios'.[186]

The NGFS intention is to shift from risk assessment based on 'central estimates' of outcomes – the 'mean' risk, to a more precautionary approach based on less likely, but severe impact outcomes – the 'tail' risk. In a series of Actuarial reports - including 'Parasol Lost' 2026 – the approach is to look at this 'tail-risk' using a risk-analysis lens, and looking for systemic vulnerability. These actuaries, working in the insurance and reinsurance sector, are neither scientists nor macro-economists; they are professional experts in modelling and analysing risk. They aim to quantify the financial risk of future uncertainties, with the objective of safeguarding institutional stability.

Taking the actuarial approach, the scale of risk to economic systems, and human health and mortality, is found to be large even in the near future. These are not the most likely outcomes, but they are presented as risks for which economic systems and policy makers should be making plans. In their 2025 report, the actuaries describe the world as 'possibly' or 'likely' on track for 10% to 25% GDP loss by around 2050, with mass mortality events 'possible' adding up to a loss of 10% of the human population ('decimation') – this is around 50 times more severe than the COVID-19 death rate.[187] They present the NGFS Global GDP loss projections 'under NGFS current policy scenario' showing central estimates of around 15% Global GDP loss by 2050, and over 30% by 2100.[188]

This would be far worse, globally, than the Great Depression of the early 20th Century, or the financial crisis of 2008.[189] If the response to Earth system instability remains as weak as it is now, then a 50% drop in global GDP by the end of this century is a realistic risk for which policy makers should prepare.[190] These figures demonstrate how a risk analysis lens captures the speed at which risk can ramp up.

In this economic systemic context, the climate instability crisis cannot be treated as a series of discrete pressures and challenges. Complexity, domino effects and systemic feedbacks can all be understood as risk to the viability of the economic system.[191] The Actuarial reports focus on this idea of global systemic 'Insolvency'. The consequence of insolvency does not just mean poorer. It means failure of a particular kind. Sovereign and corporate balance sheets become overwhelmed by risk and loss. Credit systems are unable to function without any of the certainties from which they emerged.[192]

Insurance withdrawal: an early warning

There are signs that a process of attrition in the economic system is under way already. Insurers are withdrawing entirely from certain 'high risk' markets and areas, where they were able to offer services before. They do not simply raise prices, as they might be expected to do in the face of measurable increased risk, although property insurance costs in the US, where it is available, have risen 70% in the last five years.[193] They choose not to insure at any price: 14% of owner-occupied homes in the US are now uninsured.[194] This is the strongest evidence currently for a kind of 'insolvency-style' failure affecting homes whose cumulative value is $1.6 trillion.[195] In some areas the effect is evidenced by governments stepping in with government-backed insurance schemes, or acting as insurers of last resort.[196]

Private system exposure has been quietly shifted to public balance sheets, and so the systemic risk is moved but not resolved. As properties become uninsurable, the credit system is directly affected. Mortgage lenders will not fund loans on properties that cannot be insured. In spite of that reluctance, insurers may still be over-exposed to climate catastrophes.[197] Looking further ahead, it is estimated that $1.47 trillion in net property values will be lost in the US over the next 30 years, driven specifically by insurance pressures and 'shifting consumer demand'.[198] This anticipatory effect highlights the systemic nature of the risks to, and from inside, the financial and economic system. It points to the critical importance of adaptation: economic forces are incentivising stronger infrastructure to withstand climate instability, or alternatively, relocation from climate-vulnerable locations.

The knock-on effects of insurance withdrawal are an accumulating pressure on the global economic system. And yet the majority of the global population live without the risk management support of insurance at all.[199] A global economic collapse will affect everyone – and the most vulnerable most severely – even though most people have never engaged with the mechanisms that could be the first triggers for a collapse. The policy response must in part be to strengthen people's capacity to absorb these risks within their lives: either by adaptation of infrastructure to reduce the impacts on their lives, or to support relocation to safer areas. But policy must also focus on stabilisation, using every tool in the 4R Planet toolbox.

What stabilisation means here

Lever: Reduce, **Remove** and **Repair** then **Resilience**. Halting the heating that drives the disasters, lowering the global temperature, and building the capacity to absorb the risk already locked in.

Research: Bringing tipping-point risk and cascading effects into economic models and financial stress tests.[200]



Part 2: Research as preparedness

Current investment in Earth system monitoring, modelling, and stabilisation research is dangerously inadequate given the scale of the risks outlined in Part 1. We understand that the Earth's systems are destabilising, but far too little about how fast, how far, or what happens when degrading systems interact.

Cutting emissions, removing excess greenhouse gases (GHGs), repairing damage to Earth systems, and adapting to locked-in impacts remain urgent imperatives, but they do not remove the need to understand the physical behaviour of the systems themselves, or to examine all ways to stabilise them where possible and appropriate. Research provides the preparedness required to see dangers coming, understand trade-offs, and evaluate options before choices are forced under crisis conditions.

What we do not yet know

Frontier science works on the questions we cannot yet answer. It has two tasks: seeing the danger coming, and testing the response.

1. Seeing the danger coming

We understand the threat from climate change only because of frontier science over the last 50 years. But there is more we need to know. First is to find out how the Earth's systems are changing, how fast, which thresholds and feedbacks could tip them, and how they interact, so that we understand the dangers well enough to see them coming. We urgently need better answers, for example, about the great uncertainties that clouds bring to climate modelling; about the rate of change of Earth's energy imbalance; about the pace and impact of changes to ocean heat; about the speed and scale of melting of the Greenland and West Antarctic icesheets, and about whether the AMOC could be significantly reduced in the near future. Many research programmes have worked in these areas, but resources can be thin and under threat of cuts.

Recent observational research has tended to show that the climate is more sensitive than models so far have predicted.[201] The underestimation often comes from the amplifying effects of climate change within, and between, systems.[202] Models have not, so far, captured all these complexities well enough for planning in a rapidly changing world. Underestimating the impacts of climate change costs lives.

The reach of climate models is one measure of the gap. Most complex models stop at 2100. Only a few run as far as 2300; and the longer-range scenarios that exist rely on simplified modelling.[203] Yet sea levels will keep rising for hundreds of years. Stabilising the Earth system would require net-negative emissions sustained for centuries. We are planning to a horizon that ends before most of the consequences arrive.

The gap is widening for immediate information gathering too. Earth observation is under pressure. In the United States, the 2026 budget request proposed deep cuts to NASA and NOAA science.[204] Congress rejected most of the cuts, but not all: NOAA's next generation of geostationary satellites has been scaled back from six spacecraft to four, and its ocean colour and atmospheric composition instruments cancelled, leaving a weather-only mission. Scientific capacity to measure what is happening now in the Earth system is declining at a point when it is most needed.



2. Testing the response

The second task of frontier science is to evaluate possible responses to Earth system risks and changes. This means investigating whether human efforts to stabilise systems, or to halt the effects of destabilisation, could work, at what scale, and with what risk. It also means asking what side effects they could have, over what timescales, who would gain and who would bear the risk, and how different interventions would interact.

We know that stabilisation measures such as soil management or afforestation must continue and will make a difference locally and globally. However, the more challenging interventions – and the focus of this section – are of two kinds. The first would be carbon dioxide removal (CDR) from the atmosphere at scale, through methods such as massive reforestation and rewilding, direct air capture (DAC) and marine carbon dioxide removal (mCDR). The second would be to reflect more sunlight back to space: known as solar radiation modification (SRM), it includes marine cloud brightening and stratospheric aerosol injection. Most have not been sufficiently tested under safe, controlled conditions to establish their strengths and limitations.[205] The exception is direct air capture, which works in principle but remains too expensive and energy-intensive to scale up to the required level.[206] The many remaining unknowns across all of these approaches can only be addressed by doing the scientific research.

Interventions sit on a spectrum, ordered by how well we understand them, how far they have been tested, and how local or far-reaching their effects might be. At one end is repairing a single landscape, such as restoring degraded farmland, which we broadly know how to do without repercussions beyond the local area. In the middle are regional measures, which could affect weather patterns or whole biomes. At the far end are the planetary-scale options already listed: solar radiation modification, and carbon removal on a scale large enough to change the atmosphere. This is where research is most urgent, and where governance and transparency matter most. In CCAG's 4R strategy, this research sits mainly within Repair, alongside carbon removal under Remove. Repair is where research has been most neglected.

As well as seeing interventions along a spectrum of range, challenges and implications, it is also important to consider what each intervention acts upon, and over what timescale. In the long-term, deep emissions cuts and carbon removal at scale are both mission critical. In the short-term, there are two levers that act fast on the rate of global warming, thereby influencing the ultimate height of the overshoot peak. The first fast-acting intervention is cutting emissions of all SLCPs; they will quickly disappear from the atmosphere, reducing the greenhouse effect rapidly. This is an essential step in every scenario for a more stable future for Earth systems: it is proven and can be done now. The second intervention is the deployment of frontier cooling options such as solar radiation modification; these are unproven techniques, and must be researched thoroughly before any conclusion can be drawn about their use. Managing the near-term overshoot peak therefore has two potential levers, but only one that can be used now. Finding out whether that second lever could ever be available is essential.

People often dislike the idea of tinkering with natural processes.[207] Many concerns are perfectly sensible: the consequences could differ from what is anticipated; unwelcome outcomes could be irreversible; starting a process and then stopping it, for whatever reason, could make matters worse than they are now; and some measures, such as reflecting sunlight, would only mask climate change rather than address it.

The loudest and most persistent objection is moral hazard – the idea that research in these areas will pull focus away from mitigation – often levelled at research as much as at deployment.[208] Objectors warn of over-reliance on 'quick fix' solutions, especially technological ones, and insist that nothing should weaken the message about the urgent need for rapid emissions reductions. The fear is that even safe research unconsciously signals that a fix must be on its way.[209]

The risks are real, but they are not a reason to refuse to investigate. Much of the research would be carried out on screens or in laboratories, and small, controlled experiments can clarify what wise action looks like. The message to the world should not be that a fix is in the pipeline, but that we do not yet know what is available, and that we owe it to people to find out. Done well, research is far more likely to shut down fantasies of a quick fix, pushing the pressure back where it belongs: on cutting emissions.

At the same time, although the moral hazard objection needs serious policy responses – including embedding stabilisation work into accelerating steps for mitigation – it sits alongside an opposing danger: 'derailment risk'.[210] Governments strained by the growing harms of climate overshoot face severe budgetary and capacity constraints, and may experience destabilising challenges to democratic governance. Yet accelerated mitigation requires expanded government capacity to steer the economy onto new foundations, develop public works, build consensus, and provide finance and regulation. If destabilised Earth systems erode state capacity and public budgets, they may derail mitigation itself. Stabilising Earth systems is therefore an important step towards protecting mitigation – keeping solutions politically and economically within reach.

In reality, the risks on both sides will play out over the coming decades within complex geopolitical environments, alongside ongoing technological and economic shifts in a global economy that is substantially decarbonising. Avoiding both moral hazard and derailment requires concrete policy – and concrete policy arguably starts with building a fully vetted menu of options, informed by science.

Without government leadership and public science, the central debate risks being captured by ideological extremes, leaving rational concerns unmanaged: dismissed on one side as an unacceptable distraction from decarbonisation, or seized on the other as an excuse to avoid the energy transition altogether. What is needed instead is an informed, transparent public discussion grounded in evidence.



Finding out is not the same as deciding

By 'research' we mean this phase alone: finding out more. Supporting research is not an argument for deploying any particular intervention. It does, however, take seriously the possibility that demand for radical interventions will grow as the world becomes less hospitable to human society and the systems that support it. Without a better understanding of what we risk by acting, or by failing to act, no one can make informed decisions.

Research is preparedness: it gives a clearer picture of which risks may be tolerable and which outcomes are foreseeable. It may show that an intervention is valuable, that a challenge should be approached differently, or that it should not be approached at all. It also keeps options open. As Earth systems change, so does the balance of risk around any intervention, and a choice that is rightly ruled out now may have to be reconsidered later. If the research has not been done by then, that decision will be made blind.

All over the world, the consequences of climate change are experienced locally: damage to vulnerable ecosystems, loss of livelihoods, food insecurity and, in turn, displacement and misery for people and communities. Those who bear the consequences are owed the best available knowledge about what is coming, and about what might be done, whether they act for themselves, through their governments, or together at the global level.

Deciding not to find out is not a neutral act. When knowledge is incomplete, the choices available are narrower and riskier. Research cannot fix everything, but it can ensure that when society decides to act, it acts upon the best possible information. Research will never tell society what values to choose or which risks to accept; those questions are for politics, ethics and governance, informed by the best available science.

Who does the research, and on what terms

To date, governments have funded almost all of the basic science that allows us to understand Earth systems today, yet few have chosen to lead research into active stabilisation.[211] If that work is to move forward safely and in the public interest, it requires an explicit commitment to open, transparent, coordinated and inclusive research.

Professional researchers within universities and research institutes work to established standards, with peer review at their core, and are governed by their institutions, legal systems and sometimes international agreements.[212] Some of the knowledge needed lies outside laboratories and universities. In many programmes, effective learning will depend on engaging with Indigenous and local communities whose relationship with their environment is deep and ancient. Academic institutions have experience in building partnerships across diverse communities and national boundaries, and these collaborations will become more important as stabilisation research deepens and broadens.[213]

The private sector is already involved, and this raises questions of oversight as much as of knowledge. Private innovators have capacity and resources. Collaboration between public and private efforts could strengthen both, while building in solid research standards. Private work is already under way in direct air capture, where investigation and deployment are proceeding in parallel with no perceived risk of runaway impacts from current removal efforts. It is generally true, though, that risk management costs, without marketable products, demand public investment.[214]

More challenging is private sector work on stratospheric aerosol injection (SAI), which is intended to change the reflectivity of the atmosphere on a global basis.[215] While public sector debate continues about whether research in this area should happen at all, private companies have begun the work. One company has used weather balloons to release tiny quantities of substances into the atmosphere for experimental purposes. Another, more significantly, is developing proprietary SAI technology with a view to finding a commercially viable route to deployment as a public contractor. Some of the work has been privately funded since the early 2000s.[216] Private work on marine carbon dioxide removal shows a similar pattern, with testing potentially getting ahead of the research needed to understand its impacts. Given the concerns about how such research is governed, it makes sense to recognise all the stakeholders involved and bring them into the same process.

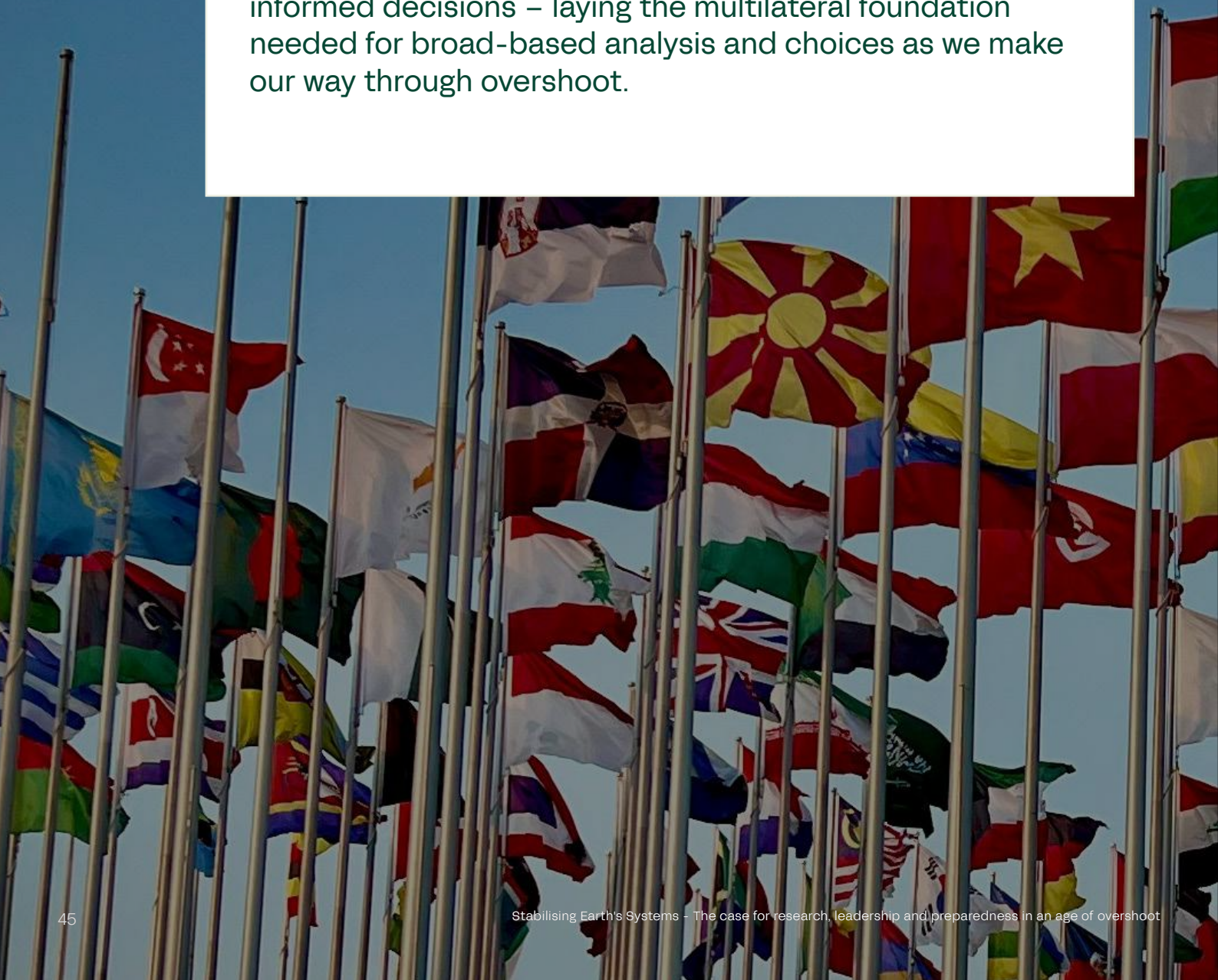
One point, however, is entirely clear: research bans are not the path forward. So far, some governments – including many in US states – have proposed (though mostly not yet adopted) penalties, including criminal sanctions, for some kinds of stabilisation research.[217] Globally, a significant group of advocates insists that not only deployment, but research itself, is unwise.[218] These anti-research views come from different socio-political perspectives in different places – largely from the political right in the US, and sometimes from the left in international circles. In either case, they would block the very knowledge needed to sensibly evaluate options, include all interests, and build legitimate processes.

What comes next

Our current trajectory means time is short. If we do not find out now, we may never have the option of using these interventions safely if they are ever needed, or of properly vetting and governing interventions that some governments or companies may propose using. Work this serious cannot move forward without strong governance built in from the outset, and it has to be paid for without compromising funding for development, adaptation and mitigation. At COP21 in 2015, governments launched Mission Innovation, pledging to double public investment in clean energy research to reach $30 billion a year, with a mandate to make clean energy affordable, attractive and accessible to all.[219] Research on stabilisation needs a commitment of similar ambition.

Part 3: Government leadership

The previous section made the case for finding out what can be done to stabilise Earth's systems. Well-designed, publicly governed research also builds the collaborative structures needed to evaluate what it finds. Involving governments, civil society, and science institutions from the outset develops the capacity to make globally informed decisions – laying the multilateral foundation needed for broad-based analysis and choices as we make our way through overshoot.





Defining governance and government capacity

Governance means the processes by which people are informed, heard and able to decide whether research, or any use of what it finds, goes ahead, and if so, in what form. It covers who consents as well as who regulates and signs off.[220]

Governance here has two jobs:

1. **Governing research.** Setting the conditions under which investigators can find things out safely, ethically and transparently.
2. **Governing decisions.** Deciding whether, where, by whom, and on what terms anything found to work is ever used, with an inventory of the information behind those decisions shared openly.

The two aspects need different safeguards and support systems, but one test applies to both: whether the people who would feel the consequences of acting or not acting are protected and given a say whenever possible, with transparent decision-making, monitoring of outcomes and evaluation of impacts.

Governance is enabled, ultimately, by government and inter-government capacity – the laws, funds, staffing, and institutions of government itself. It draws on the collaborative, multilateral, and many-layered connections of global civil society, as well as individual local, national and regional governments. Earth system destabilisation threatens that capacity by straining governments, creating a vicious cycle leading away from sensible decisions; but an upward spiral is possible too, in which the work of governance builds capacity, which in turn enables better decisions for people and the planet.[221]

The leadership gap

Governments have real capacity to drive stabilisation science: they run national laboratories, fund most of the world's climate science and already regulate field research. But they have not yet applied that capacity specifically to stabilisation. Nor have they applied their larger capacities of policy analysis, lawmaking, and budgetary design to sorting out how best to navigate the coming period of climate overshoot. Put simply: in the vast majority of the world's governments, it is no one's job to evaluate stabilisation and weave it into larger climate and economic planning.

On the most high-profile issues of climate-cooling interventions, instead of putting this portfolio squarely before senior government officials, most nations have so far moved to block research or failed to agree anything about it. Lawmakers in many US states have proposed bills that would make field research into solar radiation modification illegal; at the UN Environment Assembly, governments could not agree even an expert review of the science; and African environment ministers have called for a global governance mechanism for non-use.[222] By contrast, the UK public funding agency ARIA has established dedicated funds both for wider Earth system stabilisation research (such as forecasting tipping points) and to 'build a robust evidence base to explore – with independent oversight – if climate cooling approaches could ever be feasible, scalable, safe and governable.'[223]

The European Union and the United States have also dedicated public funds to stabilisation, and more governments are moving to evaluate the issue – including Australia's active programme to shade and protect the Great Barrier Reef.[224] Each government can find its level as it engages with these issues, on a spectrum ranging from initial evaluation to dedicated research.

Some governments are already treating instability as a security issue. Iceland has linked the risk of AMOC collapse to national security, and a recent UK security report shows how climate change and this year's super-El Niño threaten nations' security worldwide: food shortages, water scarcity, community displacement and inflation could lead to conflict, migration and disorder. The UK is to appoint a special representative for climate security, to 'place climate and nature security at the heart of national security and foreign policy decision-making.'[225]

A focus on stabilisation should be a key security concern in every government. Ownership must be at senior ministerial level, where there is capacity to see the wide implications across ministerial boundaries, and the authority to mobilise resources as needed. Making stabilisation someone's job in government does not need a new institution. The natural home of most initial work will be existing science agencies and cross-government working groups overseen and signed off by senior officials, and the government itself.



What leadership requires

Earth system instability already alters the context of almost every major government decision: food, water, health, energy, infrastructure and national security all depend on how the risk is understood and managed. A government that does not know how close the Greenland or Antarctic icesheets are to extreme destabilisation, or the Atlantic circulation or the Amazon are to a 'no return' threshold, cannot plan its food supply, its water or its security. So this science cannot sit within an environment ministry alone. It has to be built into the analytical planning and dedicated budgets of the departments that already manage those risks.[226]

No government can stabilise Earth's systems alone. Each will act in its national interest and answer to its own voters, but the systems at risk do not stop at borders. National interests include shared interests in a stable planet. The starting point, therefore, is a shared assessment of the risk – but this does not need every government at once.[227]

The work of Nobel Laureate Elinor Ostrom informed the structure of the Paris Agreement: she made clear how change is "polycentric", emerging from multiple locations at once, and often nucleated within small groups of the willing who ultimately shape global views and norms.[228] From this perspective, the challenge today is to start with sensible decisions, work with willing partners, and mobilise available capacity to secure immediate action. There is no need to resolve what the final governance structure or research outcomes will look like in ten years' time in order to make that start.

In practice, making a start means substantially increasing public funding for stabilisation research, via grant structures that drive international collaboration and transparency, tethered from the start into wider climate policy. These programmes should test ways to weave together mitigation, adaptation, and stabilisation options – exploring how we can collectively move through overshoot to a place of greater safety; programmes must engage relevant agencies and civil society to shape and answer these governance and research questions. The work can start with agreements between national science bodies, include dedicated workstreams within existing multilateral collaborations, and extend to newly created research bodies. Any group of 'first movers' needs to be representative: North and South, with Indigenous leadership included from the start.

There are recent precedents for this iterative, first-mover approach. The Climate and Clean Air Coalition was launched in 2012 by six governments and the UN Environment Programme and now brings together more than 200 members, made up of 102 governments and 113 other partner-organisations, working on methane, soot and other short-lived pollutants.[229] The Global Methane Pledge, launched at COP26 in 2021, has more than 150 signatories.[230] In April 2026, 57 countries met in Santa Marta, Colombia, to plan the transition away from fossil fuels in a forum that did not require consensus.[231]

Similarly, the Climate Vulnerable Forum has recently opened a dedicated workstream on climate interventions – a clear example of a “climate club” tackling the questions at the heart of this report. Members of the G20, which hold most of the world's scientific capacity, should be among the first movers.[232] Ambitious coalitions like this can rapidly accelerate change. Building one sits at the centre of our call to action.

The regions most exposed to instability should shape the research priorities and the rules from the outset. Some African scientists are already arguing for this. Kwesi Quagraine, Chief Scientist for the Climate Vulnerable Forum, argued with colleagues that Africa should lead the governance of solar radiation modification rather than stand aside from it: "Climate-intervention research will move forward somewhere. The choice is whether we help steer it or simply endure its outcomes."[233] The Degrees Initiative funds researchers in developing countries to study how these interventions would affect their own regions.[234] Capacity of this kind needs sustained funding, and South-South collaboration alongside partnerships with the North.

What counts as stable will look different in different places, and depends on who is represented when it is decided. Neither human systems nor climate systems are ever entirely static – and choices about outcomes are inherently political and complex. This report does not claim that stabilisation research will, on its own, remedy the larger challenges of global governance or produce neat answers. Rather, research rooted in growing multilateral collaboration is far more likely to produce sound, legitimate outcomes – even amid intense debate – than isolated or underfunded inquiry outside the context of climate clubs and scientific exchange.

Governing the research

Governing the research comes first. There have been several decades of discussion on the ethics and governance of potential stabilisation research, along with examples of research stalling because governance and engagement did not proceed in tandem. Because research has generally remained early-stage, and governments have, until recently, not focused on developing stabilisation options, there is now an immediate need to provide the core structures for public, vetted, legitimate research.

This is not a new problem: scientific research in areas of controversy is common, but proceeds successfully in fields that are considerably more perilous. For example, work on contagious diseases or nuclear energy is potentially far more hazardous than the small-scale field trials needed for stabilisation research in the short-term, and each has developed a matrix of regulatory mechanisms for governance.[235] The ice technologies needed to study glaciers, or the tiny quantities of aerosol particles used to study cloud reflectivity, operate at scales far smaller than accepted technologies deployed daily. This is not an argument for inattention, but it is a good reason to think that research can be properly governed with manageable risk.

Research is easier to govern than the deployment of an intervention. The programme of work now needed is small, contained and time-limited, operating at scales that cannot affect the global or regional climate in notable or irreversible ways. Most of it already runs under rules built for other sensitive sciences: university ethics review, funder screening and protocols for field trials. These rules need to be made clear for stabilisation research, ensuring that any larger trial that could plausibly have significant environmental effects is vetted with the same care as any other regulated activity. The challenge here is not to invent bespoke new laws for research, but to ensure that existing research regulation and environmental laws are properly applied and up to date.

A more pressing challenge is ensuring that research results, and the manner of awarding research funding, are genuinely public, transparent and well vetted. There are currently no agreed standards for transparency, intellectual property ownership, or publication in this field – which risks letting privately-backed research lock up knowledge that belongs in the public sphere.[236] When private funders and innovators bring capacity that public science lacks, the condition must be that they work to the same ethics and safety standards, and disclose what they find. Badly governed research is the quickest way to lose public consent for any of it. Existing governance frameworks around the world are often health-focused, but their architecture (including their reach into private sector research), built on national oversight, registered local review, protection of participants, and accountability, is clearly transferable to other fields of research, including climate-relevant work.[237]

The converse is also true. Research conducted publicly, collaboratively, and with funds from a range of governments is the best way to build public licence – and to deserve it. Just as the global effort to repair the ozone layer began in international scientific collaboration and built towards a successful treaty and secretariat, stabilisation research should foster collaboration across the physical and social sciences, law, and politics to inform future decisions on risk.





Researching a new technology, by stages

Just as vaccine and public health research moves through institutional review boards and careful evaluation before progressing to potentially significant public trials, work in climate stabilisation can be 'stage-gated' and evaluated by research funders and public bodies. Carefully designed research on a new technology proceeds progressively: through modelling, laboratory work, and analysis of existing observations, followed where justified by appropriately controlled small-scale field experiments. Each stage can inform whether the next should proceed.

These safeguards and stage gates should be clear, developed in advance, and publicly reviewed – and embedded in grant criteria. They follow established principles of appropriate experimental design, independent scrutiny, ethical and safety compliance, monitoring, transparency and the ability to stop or modify an experiment if evidence requires it.

The same system already handles open-environment work: GM field trials run on contained sites under strict protocols against spread, and drug trials are routinely coordinated across jurisdictions. The great majority of early-stage trials never reach public roll-out.[238]

Governing the decisions

The Earth systems at risk cross borders. To take some examples from Part 1: the Atlantic circulation shapes rainfall from West Africa to South Asia; the Amazon exports moisture to farmland far beyond the basin; Arctic ice helps set the weather of the Northern Hemisphere and beyond. Any decision to intervene in any one of these systems, or to hold back, is felt in countries that took no part in making it. The benefits of action may be local, regional or global; so too may the consequences of inaction.

Because each stabilisation pathway interacts with different existing bodies, and has its own profile of risks, benefits, and geopolitical contexts, decisions will not all come from a single forum. Views and decisions concerning the Antarctic, for example, will involve a different set of decision-makers and laws than those involving marine shipping, the stratosphere, or Arctic permafrost. Decision-makers over the coming decades will therefore face questions of the kind they already confront in contexts ranging from biotech and AI safety to economic development and arms control: Who decides whether an experiment, or any intervention that follows it, is acceptable? Who sets the conditions for it, and who monitors compliance? Who decides when to stop? And who represents the countries, communities and people who might experience its consequences without having chosen to take part? These questions are answered differently in each context, the answers may shift over time, and laws will develop accordingly.

For now, the task is not to pre-determine the political choices of the 2030s, nor to design the final decision-making architecture in advance. It is to ensure that collaborative research informs the many bodies that will ultimately make those choices – networking together the scientists, civil society organisations, and clubs of nations to provide the foundations for the governance systems that will develop.

Decisions about Earth's systems will be taken at three scales:

1. National governments

Within its own borders, a national government whether to fund research, permit an experiment, or act on what is found. No international body can take these decisions on its behalf, or hold it to account for leaving them to others. National capacity is itself part of the global public good: a government able to assess Earth system risk and act on it is an asset to its neighbours as well as its citizens.[239]

2. Regional bodies

Where a system is shared between neighbours, no one government can decide alone, and regional bodies are where they agree. Responsibility is also split between bodies for biodiversity, oceans, forests and land, each with its own remit and none with the whole system in view. A decision to stabilise a forest or a fishery has to be made across that split.



The Amazon is the obvious example. The Amazon Cooperation Treaty Organisation (ACTO) brings together the eight Amazonian countries and has worked on deforestation, wildfire, water and local participation. The forest itself is managed through a mosaic of local and national systems whose combined effect matters globally. Regional governance has to pool information, coordinate action and share resources across those systems, and stay connected to the people who manage the forest day to day. With the Amazon already close to its tipping point, any decision to intervene at scale in its hydrology or land cover would have to be made by those governments together, and ACTO is the only body in which they already sit.[240]

The African Union offers another model, working alongside the continent's regional economic communities. It increasingly speaks for Africa with one voice in climate negotiations, as the 2023 call for a non-use agreement showed.[241] A body that can take a common position against intervention could also take one on how research, and any decision to act, should be governed.

3. Global institutions

Global institutions set the rules that apply to everyone and assess the evidence they rest on. Agreements under the UNFCCC, including the Paris Agreement, all adopt the 'ultimate objective' of stabilising 'greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'[242] However, the UNFCCC has no enforcement capability, and while it sets the direction, it does not govern research or its use.

Much of the architecture that could scrutinise these decisions already exists, from the UN climate, biodiversity and desertification conventions to ocean law, the IPCC and the international financial institutions. Many bodies have a stake in the question, but none was designed expressly to govern decisions about intervening in Earth's systems, and no single one is responsible for them.[243]

The ocean and biodiversity bodies each cover a corner: the London Convention and Protocol govern what may be put into the sea, the new high seas treaty covers waters beyond any country's jurisdiction, and the UN's scientific advisory bodies on the ocean (GESAMP) and on biodiversity (IPBES) assess parts of the picture.[244]

Research funding follows the same pattern: national agencies and philanthropies pay for pieces of it, and nobody convenes or assesses it as a whole.[245] Scientific initiatives like Future Earth, the World Climate Research Programme (WCRP), and the Global Climate Observing System (GCOS) demonstrate that the global scientific community already knows how to coordinate complex research across borders; what is missing is an intergovernmental mandate to act on what they find. A new forum would add another overlapping body. The alternative is to use each existing body for what it is designed for and connect them in layers, as governments have done before.[246]

Principles for governing intervention in Earth's systems have been drafted several times since 2009, from the Oxford Principles to the American Geophysical Union's 2024 framework. They broadly agree on five points: public good, public participation, transparency, independent assessment, and governance settled before any deployment. The Hands Off Mother Earth manifesto asks the same questions and concludes they cannot be met. None of these frameworks settles who should apply them, or how the people most affected are heard.[247]

Who must be at the table

Whichever bodies decide on stabilisation research, the people affected are not evenly placed to be heard. Some communities are more exposed to the consequences of stabilisation research and intervention than others, and some are already afraid, having seen decisions made elsewhere that changed their lives. Indigenous Peoples and local communities are often the first to feel environmental change. They depend closely on the systems at risk, and have good reason to fear what large-scale intervention might do to forests, rivers, coastlines and the atmosphere itself. They also hold detailed, place-specific knowledge, built over generations, that formal scientific assessment will not necessarily capture. Exposure to the risks and knowledge of the systems, together with their rights as peoples, give them a legitimate claim to be involved in decisions that will affect them, or their lands, territories and resources.[248]

When networks of Indigenous and non-Indigenous researchers have worked together to document Indigenous knowledge of climate change impacts, they have followed a careful research protocol. As a result, culturally and place-specific understanding of environmental change was captured, with a focus on local livelihoods, while showing how barriers held back local adaptation rooted in generational knowledge. Local knowledge is context-specific and may not always align with formal scientific models, but integrating both perspectives helps prioritise locally relevant research and policy.[249]



The principle of free, prior and informed consent is set out in the UN Declaration on the Rights of Indigenous Peoples.[250] It is not always respected in practice. Research into Earth system stabilisation, and any intervention that follows from it, should be bound to governance that respects this principle from the outset. It is not a procedural step to be ticked off once decisions have been made, and given past failures a governance system that wants to be trusted will have to earn that trust in the face of understandable distrust.[251]

Not all Indigenous communities, or their members, will speak with one voice. Already, some Indigenous communities are calling for stabilisation research; others have opposed past research programmes. But space must be made for those voices while decisions are still open, not bolted on to a process designed without them.

Part 1 made the related point about marine protected areas: how well an area is governed and enforced matters more than how much sea it covers. Protection imposed on fishing communities without their involvement is more likely to fail, and to harm them.

What comes next

The institutions and the precedents already exist, even if integrative expertise inside governments must now be built. What is missing is a government, or a group of them, taking this on: assessing the risk together, funding the science, setting the terms on which anyone does it, and answering to the people affected. That costs money – though far less than the costs of instability. Scaling investments now gives us our best chance of developing the knowledge, and more critically, the governance structures and capacity needed to make decisions in as just and informed a manner as possible.





Part 4: The development and economic imperative

Earth system destabilisation hits all countries, but it hits hardest in the countries that did least to cause it, and it puts the development gains of recent decades at risk. Here we set out the case for funding stabilisation research now: why the needs of the most vulnerable should be the deciding factor; what the research would cost; when it would start to pay back; and who should pay.

What the most vulnerable stand to lose from Earth system destabilisation

In 1990, just under half of the people in developing regions lived in extreme poverty.[252] From 2000 the Millennium Development Goals coordinated international aid around shared targets, and poverty fell faster while life expectancy rose.[253] Between 1990 and 2015 more than a billion people were lifted out of extreme poverty, and child mortality more than halved.[254]

These gains took a generation of effort, and they depended on reasonable stability in Earth systems: the climate, sea level and severe weather all tended to fluctuate within tolerable limits. The destabilisation of Earth's systems could undo all of the gains in a fraction of the time.[255] Many of the development gains are focused around cities, higher-yield agriculture, networked sanitation and interconnected power grids. Because these concentrated, interconnected systems are built for a more stable climate, they are especially vulnerable to new instabilities.[256]



The poorest and least resilient countries and communities risk losing the greatest part of their development gains; more than 100 million people are at risk of being forced into extreme poverty by 2030 if policy is not responsive to climate and system instability.[257] Around 1.2 billion people live in areas exposed to floods, droughts, cyclones or heatwaves whilst being highly vulnerable to their impacts. This is particularly so in sub-Saharan Africa and South Asia.[258] No one should pay for Earth system destabilisation with a slide back into extreme poverty: yet it is the poorer countries that are losing the higher proportion of their GDP to climate events compared with wealthy countries.[259]

Development gains now face two threats that feed back and reinforce each other. The first is the destabilising impacts of the biophysical overshoot: the world is passing 1.5°C of warming, the limit governments agreed in Paris to pursue.[260] The second is inequality. The poorest have the fewest resources to organise a response. Many of the most exposed countries are also caught in a debt spiral: each disaster forces new borrowing to support recovery. The rising interest payments on these debts make investment in adaptation even less likely, even though that is what would reduce the next loss. Around 3.7 billion people live in countries where interest on debt repayment is higher than spending on health or education.[261]

The poorest people and communities tend to live in places and circumstances that are closest to the limits of human survivability, so changes in temperature, sea level, extreme weather events, biodiversity and ecosystem resources tend to affect them the most.[262] Any attempt to stabilise Earth's systems has to recognise these inequalities. No stabilisation effort can legitimately address the physical overshoot alone.[263]

Hundreds of millions of people have yet to escape extreme poverty.[264] Ending their poverty will add to global energy consumption, and raise greenhouse gas emissions, though at far lower levels per person than wealthy countries already emit.[265] The response to Earth system instability cannot come at the cost of that development. Even in the best case, then, Earth's systems will be under more strain, and the communities still climbing out of poverty will be hit hardest. The instability of Earth systems must be treated as a part of the global development conversation. The wealthier nations must acknowledge their legal and moral duty, and their economic and institutional capacity, to work with the most vulnerable. The focus must be on stabilising livelihoods and resources: building resilience to instability at multiple levels.

What the research would cost

The usual objection to funding research into Earth systems is that it cannot be afforded. The spending is better regarded as a kind of insurance: a modest, certain outlay set against very large and uncertain losses. In fact, funding research is a better safeguard than insurance, which only 'pays out' if the insured event happens. Research has immediate value because it improves decisions, and better decisions avoid the damage in the first place.

The true cost of research should be measured against the value of the information it provides – and the losses that it prevents.[266] In 2021 the US National Academies of Sciences recommended $100–200 million over five years for a national 'exploratory' research programme to 'better characterise the feasibility and risks' of solar radiation modification. They made the point that this was a small fraction of the US Global Change Research Programme annual budget of about $2.5 billion in 2019.[267] The same year, Swiss Re reported on its 'stress test' that revealed warming of 3.2°C (a severe scenario) could cut global GDP compared with a 'no climate change' scenario by 18% by 2050. If the warming were to be restricted to below 2°C, the GDP impact would be more like 4%.[268] Nominal global GDP is currently estimated to be worth about US$126.3 trillion, so a future 18% loss would run to trillions of dollars, eclipsing any research costs that might actually help to reduce or eliminate the risk exposure.

When research, like other preparedness, works, the damage never materialises, and the money saved is invisible on the balance sheet. For example, policymakers deciding what can be afforded for physical preparedness must allocate spending on flood barriers or disease surveillance, but will then have no figure for the losses those measures prevented. One way to supply that figure would be to adapt insurance-style reserving for public accounts. Governments might, for example, estimate and report the expected losses that each measure is designed to avoid, so the benefit is seen on the books alongside the cost. Funds spent by one country alone would not remove the risks from systemic Earth instability: multinational collaboration is still essential, however each nation may account for its contribution to funding.

Some low- and middle-income countries already buy insurance against the impacts of locked-in climate risk. Under 'sovereign risk pooling', they pay predictable premiums up front, turning disaster costs into a planned budget line.[269] 'Catastrophe bonds', a growing market, pass the risk to investors, who are paid interest but forfeit their capital if a specified disaster occurs.[270] In the EU, the European Central Bank (ECB) and EIOPA have proposed a public-private reinsurance scheme and an EU disaster fund to close the 'natural-catastrophe' cover gap.[271] The model works. After Hurricane Melissa hit Jamaica in 2025, the Caribbean Catastrophe Risk Insurance Facility (CCRIF) had confirmed payouts of nearly $92 million to Jamaica within days, helping to keep public services running and limit the wider economic damage.[272] Jamaica's $150 million catastrophe bond paid out in full. Research into stabilisation is a premium of the same kind, paid against risks that are not yet locked in, but with the difference that it can prevent the loss, rather than pay for its impacts.

How soon it pays back

Spending on stabilisation research and implementation pays back over decades, but the first returns can arrive within a single political term. Monitoring systems produce data from the day they are switched on, enabling better, and perhaps quicker, decisions. Early-warning systems cut losses from the first event they anticipate. A day's warning of a storm or heatwave can reduce damage by 30%. 'Spending $800 million on such systems in developing countries would avoid losses of $3 – 16 billion per year.'[273] These are measurable returns against budgets that are set for four or five years at a time. Research programmes build laboratories, train people and build institutional knowledge that outlast the programme itself, creating a separate kind of return: enhanced capacity for stabilisation research and decision-making.

The longer returns take different forms: investment, including growing bio- and green-sectors of the economy; human welfare, as fewer people die or fall ill from heat, flood and failed harvests; assets that keep their value because the risk to them is understood and managed; and the global commons of ocean, ice and forest held within their limits. This all depends on planning capacity, built on knowing what is coming.

The biggest payback is avoiding the worst outcomes. The Swiss Re calculations show that every fraction of a degree matters, and the cost of stabilisation research pales into insignificance alongside the costs of failing to act, or not knowing how to act when the time comes.[274] Stabilisation research works to keep open the option of holding critical systems within their limits while greenhouse gas emissions fall. The research has to be done before decisions are needed, so that decisions are well-informed when the time comes.



Who pays and who benefits

Building this capacity requires resources, and deciding who provides them means aligning legal and moral responsibility with physical reality. This alignment is reflected in the International Court of Justice (ICJ) climate opinion of July 2025, adopted by the UN in 2026: countries are legally obliged to protect the climate system, and failures may amount to human rights breaches in relation to the right to life, to health and to a clean environment[275]

Historically, the vast accumulation of greenhouse gas emissions has come from the wealthy countries, while many of the most damaging consequences of climate change are being experienced by poorer countries that contributed very little to the problem[276] For wealthy countries this creates a particular responsibility. Existing international agreements recognise the different responsibilities and capacities of countries in responding to climate change[277]

From that perspective, commitments of wealthy nations to allocate finances, address loss and damage, share knowledge and technology, and make ambitious emissions reductions are not some kind of expression of goodwill: they carry legal, political and moral significance[278] Meeting these obligations matters: emissions are reduced and environments are more resilient, creating the financial, technological and political space for poorer countries to pursue development whilst also responding to Earth system instability[279]

Money for stabilisation research must be additional to that already promised by wealthy countries for climate finance and for loss and damage. Those obligations still remain unmet, and research cannot become another claim on the same resources or an excuse to fail in relation to existing pledges. Research and loss and damage address fundamentally different needs and require distinct budgets. If Earth system knowledge is a global public good, every nation with the economic capacity to invest in it has an obligation to do so.





As part of the development wins of the last 40 years, the developing South has seen its institutional capacity to act and implement change consolidated and deepened. University research, economic development plans, regional cooperation and planning, all have emerged as deep-rooted functional capabilities. However, the poorest countries have depended the most on development agreements and funding from the wealthier countries of the North. Most wealthy countries have cut back on their contributions, and future promises. This has been visible in sudden disruptions. There has been rollback of important assistance programmes in the US. There have also been funding cuts in the UK, across the EU and in Australia.

For poorer countries, therefore, the challenge is not political willingness – it is the undermining of institutional capacity through poverty. Demands for adaptation, resilient infrastructure, public health, and environmental surveillance are made on resources already stretched by the escalation of Earth system instability[280] International support is needed to strengthen national capacity in poorer countries, restoring and extending their ability to act and plan for themselves. This goes beyond the funding of individual, externally initiated and managed projects[281]

Funding promises in the field of climate and system stabilisation must be delivered by wealthy countries. Data sharing, access to intellectual property and ongoing knowledge sharing and collaboration will yield adaptation responses that make people safer, and communities more resilient.

What comes next

Unchecked Earth system instability threatens the development gains of recent decades, and the economies that depend on them. It also threatens the economies of even the wealthiest nations. Establishing scientific capacity to steady Earth systems equitably requires a fraction of the capital at risk, provided funds are added to existing climate commitments rather than carved out of them. Part 5 sets out what that investment must buy first.

Part 5: Mobilising the research

The Research Agenda: seeing the danger and managing the risk

The systems examined in Part 1 point to urgent research gaps and practical opportunities across the globe. Some – like sharing satellite warnings, regenerating soils and restoring forests – are straightforward to promote now; others involve more sensitive 'frontier science', where governance and ethics must move in lockstep with discovery. Emissions reduction to net zero remains critical, but it is no longer enough on its own to secure a safer future: we must do more to stabilise the different systems of the Earth and make sure they continue to function within safe limits.

Closing these gaps requires limiting the overshoot of 1.5°C and returning warming below 1.5°C by removing as much excess carbon dioxide from the atmosphere as possible: supporting, restoring and extending natural carbon sinks through forest management and regeneration, reversing desertification, and extending regenerative soil management; and researching natural means that require support, such as ocean biomass regeneration, alongside direct air capture and marine carbon dioxide removal.

Part 1 explores each of these in more detail (see The Amazon basin: from global carbon sink to source; Reversing desertification at scale; Soil regeneration and food security for the most vulnerable; and Seagrass and whales: marine life in the carbon cycle).

At the same time, it means protecting, repairing and supporting vulnerable or degraded, systemically important parts of the Earth system: monitoring, measuring and reporting transparently on the status of ecosystems; and protecting and extending forests, wetlands, tundra and other ecosystems for their capacity to store carbon as well as their value as biodiverse biomes. And where thresholds are approaching, it means researching interventions that retain or restore ice, stabilise glaciers, or protect coral reefs or other local systems close to collapse – to buy time while the Earth system is stabilised – and evaluating through research the possibility of protecting the Earth system from overheating further with the use of some kind of solar radiation modification (SRM).

These interventions are all important: there are no silver bullets, and no 'either/or'. SRM is a true 'frontier' option: research, transparency, ethics and governance all have to move together so that knowledge gained is demonstrably reliable and actionable; closing off unsafe or ineffective interventions is as important as finding effective and operable solutions. The purpose of understanding the potential of different SRM approaches is to explore the possibility of near-term cooling, to help shave the peak of the 1.5°C overshoot as fast as possible, and temporarily buying time to do everything else possible to achieve a stable, liveable Earth.

What this research effort needs to prioritise

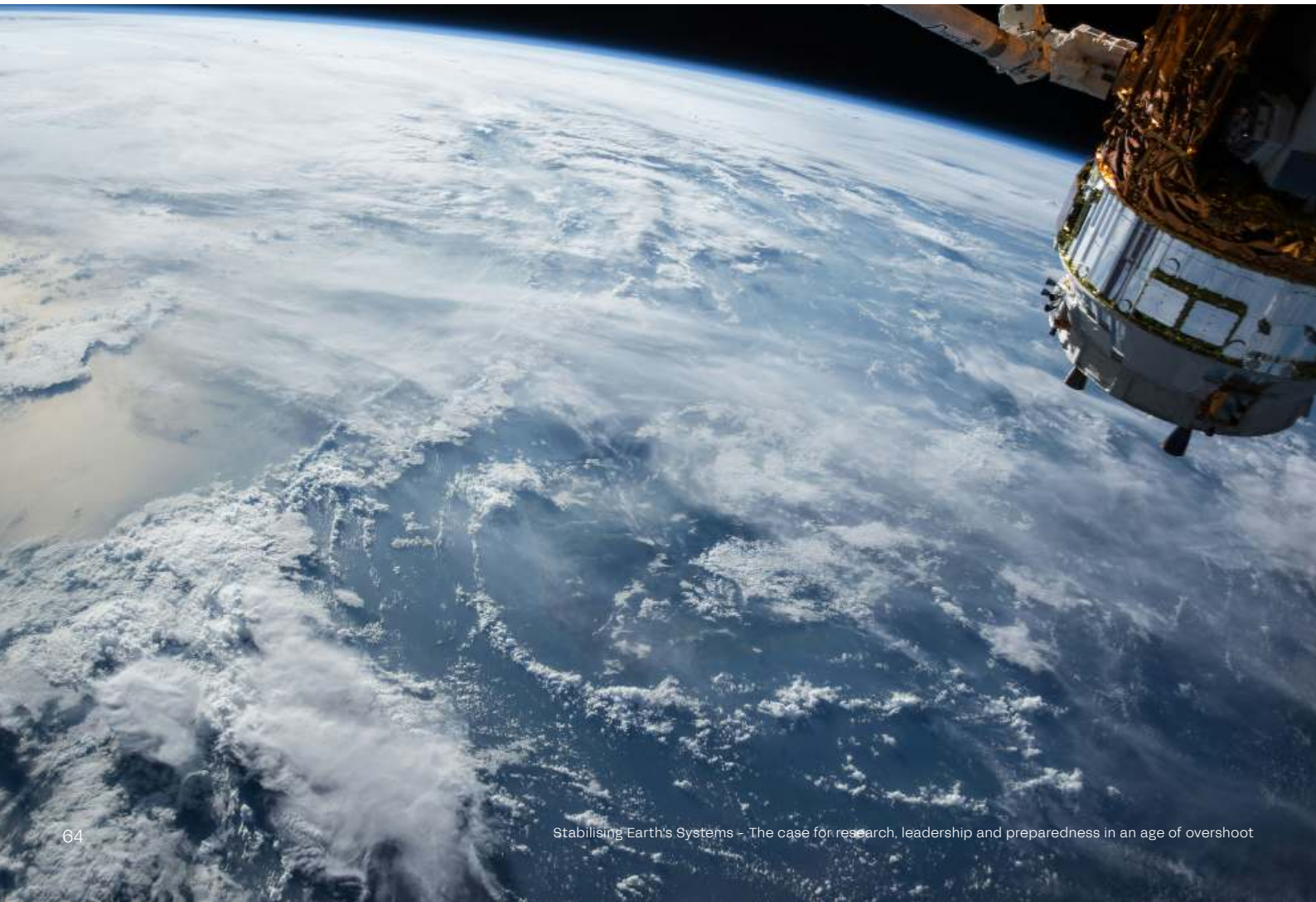
Secure the foundation research: monitoring, modelling and sharing information

Rebuild and expand monitoring and modelling capability over multiple scales and time frames, moving away from the modelling that stops at 2100, and understanding more about how close key systems are to tipping. In addition to research, we call for the management of information: the sharing, capturing, extending and deepening of knowledge is not difficult to support in theory, but it has costs and requires geopolitical engagement. All research efforts must encompass how information will be shared – and existing sharing gaps must also be addressed independently of the research agenda. Specific priorities and gaps include:

- **Long-term surveillance:** Gaps remain in satellite surveillance of clouds, ocean currents, emissions, sea-level change and other systemic changes. The capacity to capture baselines and to monitor change is conceptually simple even where technically challenging. Patient monitoring and reanalysing information from satellites and other information-gathering systems tells important stories about what is coming, what changes to prepare for, and what interventions might help to stabilise systems – helping us understand what is happening and how it feeds into wider Earth system change (see Part 1: Ice, clouds, reflectivity and absorption; Forests and clouds; The AMOC: the ocean's weakening conveyor belt; and Ocean acidification).

— **Early warning systems to help save lives:** We must build the capacity to capture, move and share new and existing information within meaningful timeframes. Floods and storms can be survived with even a few hours' notice, provided existing information gets to where it is needed. Communities in Nepal were failed by this gap (see Introduction sidebar: Nepal 2026: a mass-fatality climate event): a warning that could have saved lives never made it to the areas where glacier failure delivered devastating flash floods.

— **Simple information exchange:** Less crisis-focused, but with high impact, is the need for systematically gathering and sharing inventories of existing experience and information relating to farming, restoring soil or repairing landscapes to stabilise livelihoods at local scale. As communities all over the world manage the natural resources that support their livelihoods, databases and inventories of lived experience and outcomes from research trials are basic resources for accelerating change and increasing resilience (see Part 1: Soil regeneration and food security for the most vulnerable; and Reversing desertification at scale). There is no one-size-fits-all, but all shared experience and information speeds up effective action.





Strengthen the frontier response

Rapidly increase investment in research in frontier areas, funding it at the scale of the challenge: the more we know, the better equipped the world will be to make the judgement calls that lie ahead. Work must move through research phases from modelling and lab studies to controlled trials using transparent and ethically robust existing systems; research outcomes now will define responsible options for excess carbon removal and for SRM in coming decades.

Stay focused on the basics as well

Invest in every aspect of emissions reduction: the energy transition, monitoring leaks, and research into enhancing and stabilising infrastructure.

The immediate aim is deep and rapid cuts to emissions of SLCPs, methane above all: the quickest route to slowing near-term warming and lowering the overshoot peak while other interventions and solutions take effect. Alongside reaching global net zero, these are the foundations of a possible stable future for Earth systems. Whilst we engage in frontier research to discover what else, if anything, is possible for safe and effective intervention, the rapid emissions reduction of SLCPs is the only tool we have to act on near-term warming. There is no argument against the immediate deep SLCP emissions cuts, and they are critical for stabilising parts of the Earth systems that are moving towards their tipping points: immediate action can really make a difference.

Decision-making structures

All research is to be carried out responsibly. Investment to support structures and systems for legal frameworks, social deliberation, political science, collective action on problem-solving and other governance concerns as they arise must be available in parallel with, not bolted on after, the science experiments and monitoring systems, so the research produces institutions and not just papers.

Fund the most vulnerable so they can take the lead

Local communities and Indigenous peoples hold a lot of the knowledge needed now, and they experience the impacts of change: we must make sure they lead on creating solutions. Likewise, the nations of the developing South must lead on the protection of their own livelihoods, development and ecosystems, backed by funding for Southern-led capacity and South-South and North-South collaboration as a first charge, not an afterthought. This requires investing in ensuring that all available knowledge is seen, inventoried, shared, deployed and acted upon. Indigenous knowledge has been overlooked in the past, and is a missing element of a great deal of climate research. Separately, technical fixes that work in one place must be shared in case they offer help to communities in other areas.

The calls to action

— **Fund at the scale of the challenge:** Start now with a 'Mission Innovation' effort for stabilisation, scaling up public funding models such as ARIA. This will be a new research fund of billions per year from public sources, framed, managed and distributed as a coordinated risk management research fund for the world – strictly additional to climate finance and never carved from mitigation, adaptation, loss and damage or development. This is the insurance policy that pays out by preventing disaster instead of simply responding to the damage once it has happened.

— **Make stabilisation someone's job in government:** Each government should be required to identify and name the senior public servant or Minister with responsibility for Earth system stabilisation, giving explicit executive power and cross-departmental capacity that acknowledges links to treasury, national security, food, health, water, energy and economic growth. This needs no new institution, and countries such as Iceland and the UK are already moving.

— **Insist on open, accountable research:** Support and promote only research that is transparent and accountable; bring private sector research efforts into compliance with publicly funded research ethics, codes of practice, peer review and formal stage-gating controls in specific frontier areas – requiring independent oversight, public disclosure, intellectual property in the public interest, and free, prior and informed consent where communities are affected.

— **Lock every action to emissions cuts:** Increase efforts, incentives, regulation and penalties to support mitigation to reduce emissions much more rapidly; without this, the impacts of other efforts are compromised. Every stabilisation commitment must be tied explicitly to deep and rapid emissions cuts from the outset.

— **Build a coalition of the willing now:** Work with those who are ready to be part of this – others will join in when the effects are seen. In any coalition agreement a critical clause will be commitment to existing mitigation and finance pledges.



The coalition of the willing: start today

The willing members will include nations from the North and South, with participation of Indigenous leadership from the start, building on the Climate Vulnerable Forum's new climate-interventions workstream as the nucleus, and widening to willing G20 and first-mover governments. There is no requirement for pre-agreement on a final structure: governments can work with what we have to develop vision, guidance and governance, funding and investment. The final shape will emerge from this iterative process. As at Santa Marta and in the Climate and Clean Air Coalition, we must not be distracted from action by making demands for a new global body, or a fresh global consensus: work with the agreement of the nucleus, and build from there.

Outputs will be an expanded and deepened research base; evolving global and sector-specific governance mechanisms; and funding and investment calls with assurance of ethical, transparent, accountable research. To support this, members can engage a small secretariat to provide or facilitate grant-awarding capacity, accountability for research investment, compliance with peer review and stage-gated review within research programmes, and transparency of information and outcomes from research.

Milestones

At launch: Founding the stabilisation research mission coalition, with a founding declaration committing to a common risk assessment, shared research principles, existing mitigation and finance commitments, and a future roadmap.

Year one: Establishing the stabilisation research mission secretariat; publishing a destabilisation risk assessment and frontier research risk assessment with benchmarks to identify risk management opportunities and costs of research; agreeing research principles and funding structures; funding Global South-led capacity; and committing to individual country roadmaps.

Years two to three: Accelerated, coordinated research across geographies, sectors and scales.

Throughout: Review and feedback at every stage.

The coalition's job in this phase is not to decide whether to deploy anything. It is to produce the public, vetted knowledge and the networked institutions that let the right bodies decide well later.

GHGs - a manageable level?

The main GHGs: in order of longevity in the atmosphere

GHG	Chemical symbol	Duration in atmosphere	Mass in atmosphere	Potency at 20 year Global Warming Potential	Parts per Million or Billion in atmosphere	Historic levels Parts per Million or Billion
TOTAL (effective radiative forcing)					550 pp million CO_2 equivalent	280 pp million
Fluorinated Gases	HFCs,PFCs, SF6, NF3	Millennia	Less than 1% of GHG	Tens of thousands times CO_2	Few pp trillion	0
Carbon dioxide	CO_2	Average 100 years	3,380 gigatonnes	1 (baseline)	432 pp million	280 pp million
Nitrous Oxide	N_2O	109 – 121 years	3 gigatonnes	273	340 pp billion	270 pp billion
Methane	CH_4	10 – 12 years	6 gigatonnes	80+	1,900 pp billion	730 pp billion
Water vapour	H_2O	Hours to days	12,900 gigatonnes	Climate feedback	Varies very widely by altitude temperature etc	Varied very widely by altitude temperature etc

GHG removal at scale will focus mainly on CO_2. It exists in high volume and endures for centuries to millennia if not removed.

Human activity has already increased global atmospheric GHG levels to the point that, the atmosphere has excess GHGs beyond a safe level, especially with all amplifying feedbacks accounted for. Since the lifetime of CO_2 is measured in centuries, it is imperative that CO_2 emissions cease, and that direct removal of the excess in the atmosphere is ramped up to bring levels down to, say, 350 ppm or less. Methane with a shorter lifetime measured in decades, is best treated with a focus on ending emissions.

We must reduce GHG levels significantly. This means reducing emissions deeply and rapidly, and also removing excess GHGs already there. Removal rates at scale will need to exceed tens of billions of tons of CO_2 removal per year.

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AI tools were used in the preparation of this report, but were not used to generate any original analysis or conclusions drawn. AI use was limited to supporting specific aspects of the research (Google Search AI Overviews) and editing process (Claude) - locating some relevant source materials and providing editorial refinement.

All those involved developing the report's content have ensured it has been reviewed and verified and take responsibility for its accuracy and the recommendations presented.

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Endnotes

1. For a clear discussion of the breadth of response required from human society in response to the pressure on planetary boundaries imposed by human activity, see Nature NPJ Urban Sustainability, McPhearson et al (2021) 'Radical changes are needed for transformations to a good Anthropocene' https://www.nature.com/articles/s42949-021-00017-x .
2. The capacity for restoring forests is not unlimited. If allowed to deteriorate beyond a certain point – a point of no return, or tipping point, a forest system cannot be put back to its original condition simply with restoration efforts, even if the global temperature were to be stabilised at a suitable level. See for example, SIMACLIM, Rodrigues et al (2025) 'The Amazon Forest Tipping Point' ISBN: 978-65-988223-1-6 https://www.researchgate.net/publication/395353012_THE_AMAZON_FOREST_SYSTEM_TIPPING_POINT .
3. The persistence of carbon dioxide in the atmosphere and its capacity to linger for millennia is explained in Nature, Inman (2008) 'Carbon is forever' https://www.nature.com/articles/climate.2008.122 .
4. For an explanation of the impacts of these short-lived climate pollutants, and the potential strategies for tackling them, see the first global scientific report on the topic: Climate Clean Air Coalition (2011) 'Integrated Assessment of Black Carbon and Tropospheric Ozone' https://www.ccacoalition.org/resources/integrated-assessment-black-carbon-and-tropospheric-ozone .
5. For the current state of the 1.5°C limit, and thinking about the overshoot, see UNEP (2026) 'Limiting Overshoot: Navigating exceedance of 1.5°C and pathways towards its return' https://www.unep.org/en/publications/report/limiting-overshoot-navigating-exceedance-15degc-and-pathways-towards-return .
6. For the announcement of the end of the search and rescue phase, see Reuters, Sharma (2026) 'Nepal ends search and rescue after flood, focuses on rehabilitation' https://www.reuters.com/world/china/nepal-ends-search-rescue-after-flood-focuses-rehabilitation-2026-10-05/ .
7. See press release, UNDP Crisis (2026) 'Nepal floods hit vulnerable communities as UNDP estimates 2.2 million tonnes of debris' https://www.undp.org/crisis/press-releases/nepal-floods-hit-vulnerable-communities-undp-estimates-2point2-million-tonnes-debris
8. Previous floods were from the same tributary system. The first was in May 2025, when two glacial lakes burst, and the second in July 2025, when a super glacial lake flooded, killing nine people. Linked In, Tazvinzwa (2026) 'Nepal flood toll crosses 1450; over 6,000 still missing' https://www.linkedin.com/pulse/nepal-flood-toll-crosses-1450-over-6000-still-missing-tazvinzwa-vbape The UN Assistant Secretary-General and UNDP Regional Director for Asia and the Pacific, Kanni Wignaraja, told Reuters that the population at risk of future glacial floods across the Himalayan region 'goes into the millions'. See Reuters, Noack (2026) 'Himalayas face severe glacial flood risks in years ahead, UN official warns' https://ca.news.yahoo.com/himalayas-face-severe-glacial-flood-132404726.html ; A further flash flood in early October 2026, probably caused by a landslide, washed away houses, bridges and damaged a power project. Five people are missing. See BBC News (2026) 'Buildings swept away as flash floods hit central Nepal' https://www.bbc.co.uk/news/videos/cwzrdnljedx0o
9. There are two kinds of glacier collapse. The first, as has just happened in Nepal, is when a mass of ice shears off and triggers floods and landslides downstream. The other is a glacial lake outburst flood (GLOF) where meltwater builds up behind a natural barrier until it bursts. Both threats are rising in the Himalayan region. For explanation of GLOFs. See ICIMOD, 'Glacial Lake Outburst Floods' https://www.icimod.org/mountain/glacial-lake-outburst-flood/
10. Of the 47 places at risk for glacial lake outburst floods (GLOFs). 42 are within the Koshi river basin; 21 are within Nepal. See UNDP Climate Change Adaptation (2020) 'Report by ICIMOD and UNDP identifies potentially dangerous glacial lakes in river basins of Nepal, the Tibet Autonomous Region of China, and India' https://www.adaptation-undp.org/report-icimod-and-undp-identifies-potentially-dangerous-glacial-lakes-river-basins-nepal-tibet To see the ICIMOD/UNDP report, go to ICIMOD, Bajracharya et al (2020) 'Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India' https://lib.icimod.org/records/p869r-n4132
11. See, again, the Reuters report for this figure: Reuters, Sharma (2026) 'Nepal ends search and rescue after flood, focuses on rehabilitation' https://www.reuters.com/world/china/nepal-ends-search-rescue-after-flood-focuses-rehabilitation-2026-10-05/ .
12. An agreement to share data has been suggested several times by China, but Nepal has been slow to follow up, according to its own disaster authority. The Diplomat, Telor (2026) 'Who is to blame for the massive death toll in the Nepal floods?' https://thediplomat.com/2026/09/who-is-to-blame-for-the-massive-death-toll-in-the-nepal-floods/ See also Linked In, Tazvinzwa (2026) 'Nepal flood toll crosses 1450; over 6000 still missing' https://www.linkedin.com/pulse/nepal-flood-toll-crosses-1450-over-6000-still-missing-tazvinzwa-vbape
13. For a discussion about the usefulness, or otherwise, of the term 'tipping point', given its wide and often imprecise use, see Nature Climate Change, Kopp et al (2024) ''Tipping points' confuse and can distract from urgent climate action' https://www.nature.com/articles/s41558-024-02196-8
14. For a detailed definition of the scientific use of 'tipping point' and the phenomena that fall within that definition, see Science, McKay et al (2022) 'Exceeding 1.5°C global warming could trigger multiple climate tipping points' https://www.science.org/doi/10.1126/science.abn7950 In this 2022 paper the authors exclude melting sea ice as a potential tipping point, whereas in an earlier paper (and Lenten and Rockstrom are authors in both) melting sea ice is explicitly one of the tipping points of concern. This shows that the definition is contested, or shifting, even amongst those scientists for whom tipping points are a central focus of research. See Nature, Lenten et al (2019) 'Climate tipping points – too risky to bet against' https://www.nature.com/articles/d41586-019-03595-0
15. For the doubling of the energy imbalance, see Geophysical Research Letters, Loeb et al. (2021) 'Satellite and Ocean Data Reveal Marked Increase in Earth's Heating Rate' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL093047 and Loeb et al (2024) 'Observational Assessment of Changes in Earth's Energy Imbalance Since 2000' https://link.springer.com/article/10.1007/s10712-024-09838-8. Observations from

space of the energy imbalance show that by 2023 it was more than twice that of the best estimate of the IPCC scenarios. The need to understand the energy imbalance better, and to be able to make robust predictions, is made clear. Satellites that assist in the process of observing the energy imbalance are being decommissioned, potentially increasing the research gap in this area. See AGU Advances, Mauritsen et al (2025) 'Earth's Energy Imbalance More Than Doubled in Recent Decades' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024AV001636

16. The stable energy balance held true for 10,000 to 12,000 years, leading up to the 20th Century. This is the Holocene epoch. For a discussion of the naming of the Holocene, and of sub-divisions within the epoch, see Journal of Quaternary Science, Walker et al (2012) 'Discussion Paper – Formal subdivision of the Holocene Series/Epoch: a Discussion Paper By a Working Group of INTIMATE 9Integration of ide-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy)' Introduction, Page 649 https://leilan.yale.edu/sites/default/files/publications/article-specific/walker_et_al_2012_formal_subdivision_holocene_jqs.pdf
17. The exact percentage of reflectivity will vary. If the ice or snow are not fresh or clean the percentage of energy reflected will be lower. The surface characteristics of ice are important. See for example, the impact of the 'surface scattering layer' described in Geophysical Research Letters, Smith et al (2022) 'Sensitivity of the Arctic Sea Ice Cover to the Summer Surface Scattering Layer' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL098349 See also the albedo of glaciers (another reflective area of the Earth's surface) discussed in Earth-Science Reviews, Zhang (2021) 'Albedo reduction as an important driver for glacier melting in Tibetan Plateau and its surrounding areas' https://www.sciencedirect.com/science/article/abs/pii/S0012825221002361 The albedo of the Earth is constantly monitored by satellite because of its importance as part of the climate system. See for example EU Climate Data Store live status 'Surface albedo 10-daily gridded data from 1981 to the present' https://cds.climate.copernicus.eu/datasets/satellite-albedo?tab=overview NASA says that 'the open ocean tends to have an albedo lower than 0.1, absorbing more than 90% of incoming sunlight and reflecting less than 10%.' See NASA Earth Data 'Albedo' https://www.earthdata.nasa.gov/topics/land-surface/albedo
18. 'Within the last 40 years' in this report refers to data from the mid-1980s. For an overview of the loss of both summer and winter sea ice in the Northern Hemisphere see European Environment Agency (2025) 'Arctic and Baltic sea ice' https://www.eea.europa.eu/en/analysis/indicators/arctic-and-baltic-sea-ice See also NOAA, Lindsey et al (2022) 'Climate Change: Arctic sea ice summer minimum' https://www.climate.gov/news-features/understanding-climate/climate-change-arctic-sea-ice-summer-minimum
19. After an apparent pause in ice loss in the early 2020s, the 20 year decline trend is found to be significant again, and consistent with ongoing winter sea ice reduction. See Earth, Atmospheric and Planetary Sciences, Chan et al (2026) 'Record-low 2025 and 2026 ice extents restore Arctic winter sea-ice decline' https://www.pnas.org/doi/10.1073/pnas.2614134123
20. See IPCC (2021) 'AR6 – Climate Change 2021: The Physical Science Basis Chapter 7 Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity' https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/ For experimental evidence of the impact on albedo of black carbon, see for example: Nature Climate Change, Hadley et al (2012) 'Black carbon reduction of snow albedo' file:///Users/admin/Downloads/HadleyandKirchstetterBCsnowalbedoreductionNatureClimateChange2012.pdf For exploration of variable concentrations of black carbon around the globe, see Liu et al (2025) 'A Global Black Carbon Dataset of Column Concentration and Microphysical Information Derived from MISR Multi-band Observations and Mie Scattering Simulations' (Manuscript version) https://essd.copernicus.org/preprints/essd-2025-593/essd-2025-593-manuscript-version3.pdf Also, Environmental Pollution, Zhang et al (2025) 'Black carbon in major global source areas from 2000 to 2023: Spatiotemporal variation, vertical distribution, and extreme case analysis' https://www.sciencedirect.com/science/article/abs/pii/S0269749125003021 For a study of black carbon in Beijing over time, see Nature Clean Air, Xie et al (2025) 'Long term trends oof black carbon levels, sources and radiative effects from 2013 to 2022 in Beijing, China' https://www.nature.com/articles/s44407-025-00010-z
21. For the high level of sensitivity of Tundra to climate change, see Tellus B: Chemical and Physical Meteorology, Stiegler et al (2015) 'Tundra permafrost thaw causes significant shifts in energy partitioning' https://www.tandfonline.com/doi/full/10.3402/tellusb.v68.30467
22. Tundra vegetation responds rapidly to climatic changes in the Arctic, creating feedbacks which may amplify or dampen permafrost thaw. See: Nature Reviews Earth and Environment, Heijmans et al (2022) 'Tundra vegetation change and impacts on permafrost' https://www.nature.com/articles/s43017-021-00233-0
23. The risk of releasing carbon in unknown quantities is discussed in a review article in Nature. It also flags the importance of further research, in particular more detailed monitoring via airborne and satellite observations. See Nature Reviews Earth & Environment, Miner et al (2022) 'Permafrost carbon emissions in a changing Arctic' https://www.nature.com/articles/s43017-021-00230-3
24. See Nature, Abrams et al (2025) 'Emerging evidence of abrupt changes in the Arctic environment' https://www.nature.com/articles/s41586-025-09349-5
25. See Nature, Purich et al (2023) 'Record low Antarctic sea ice coverage indicates a new sea ice state' https://www.nature.com/articles/s43247-023-00961-9 and for the seasonal timing changes, see National Science Review, Liang et al (2025) 'Delayed Antarctic melt season reduces albedo feedback' https://academic.oup.com/nsr/article/10/9/nwad157/7181506
26. For a discussion about the nature and risk of long-term Antarctic ice loss, see Nature Climate Change, Winkelmann et al (2026) 'Mapping tipping risks from Antarctic basins under global warming' https://www.nature.com/articles/s41558-025-02554-0 ; For a discussion of the uncertainties around Antarctic ice sheet instability, and the potential contribution to global sea-level rise by 2100, and beyond, see Science, Fricker (2025) 'Antarctica in 2025: Drivers of deep uncertainty in projected ice loss' https://www.science.org/doi/10.1126/science.adt9619

27. The full quote (from the Abstract): 'Amplifying feedbacks are common between these abrupt changes in the Antarctic environment, and stabilizing Earth's climate with minimal overshoot of 1.5°C will be imperative alongside global adaptation measures to minimise and prepare for far-reaching impacts of Antarctic and Southern Ocean abrupt changes.' See Nature, Abram et al (2025) 'Emerging evidence of abrupt changes in the Antarctic environment' https://www.nature.com/articles/s41586-025-09349-5
28. See European Space Agency (2023) 'Revealing invisible Himalaya glacier loss' https://www.esa.int/Applications/Observing_the_Earth/Revealing_invisible_Himalaya_glacier_loss Also, see ICIMOD Press Release (2026) 'Hindu Kush Himalaya glaciers losing ice at double the rate since 2000, new ICIMOD report confirm' The press release links to two ICIMOD reports with immense detail of the status of Himalayan glaciers. https://www.icimod.org/press-releases/hindu-kush-himalaya-glaciers-losing-ice-at-double-the-rate-since-2000-new-icimod-report-confirm/ A study of an ancient glacier close to Mount Everest records a collapse from 100km in length 60,000 years ago, to 5 km today. Heavy rainfall has not shielded the glacier from decline. See Nature India, Ghosh (2026) 'Tracing the collapse of a giant ancient Himalayan glacier' https://www.nature.com/articles/d44151-026-00101-0
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30. For a discussion of the importance of community led strategies, as well as the cascading physical science context, see ScienceDirect, Evolving Earth, Ahmed (2025) 'Decoding the Fate of Himalayan Glaciers under Climate Change: Impacts, Challenges, Research Gaps, and Policy Pathways' https://www.sciencedirect.com/science/article/pii/S2950117225000263
31. Since 1979 the rate of warming in the Arctic has been measured at four times the global rate. See Nature Communications Earth and Environment, Rantanen et al (2022) 'The Arctic has warmed nearly four times faster than the globe since 1979' https://www.nature.com/articles/s43247-022-00498-3
32. See Ambio, Naik et al (2026) 'A framework for assessing global health impacts of polar change: An urgent call for interdisciplinary research' https://link.springer.com/article/10.1007/s13280-025-02255-0 A life in close connection with nature is strongly impacted by climate change. Food is sourced from rivers and the ocean, pastures support reindeer herds, and these traditional food sources are being dangerously disrupted. The entire culture of Indigenous Peoples, directly bound up with the natural environment, is vulnerable to disruption. See for example Arctida (2025) 'When ice melts, life melts too: the impact of the climate crisis on Indigenous Peoples of the arctic' https://arctida.io/en/projects/climate-crisis-and-indigenous-peoples
33. The different projections and their various probabilities are not always consistent with one another, and none says that these levels of sea-level rise are the most likely (the central estimate) based on the information currently available. However, the IPCC, reported by the European Environment Agency, and a range of different studies tend to show that these levels are possible. In particular the probability increases if the world follows a 'high emissions' scenario between now and 2100. For the clearest framing of the risk of a 2 metre sea-level rise by 2100 at the upper end of uncertainty, in the face of unchecked emissions, see PNAS, Bamber et al (2019) 'Ice sheet contributions to future sea-level rise from structured expert judgement' https://www.pnas.org/doi/10.1073/pnas.1817205116 . The EEA projects a sea-level rise of 1.02 m, at the upper end of the 'likely' range in the face of very high emissions, relative to the 1995 – 2014 average. In the face of fast disintegration of the polar ice sheets, as well as very high emissions, the rise is projected to be up to 2.3 metres by 2100, and up to 5 metres by 2150. See EEA (2025) 'Global and European sea level rise' https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise . This report, as a matter of judgement given all of the uncertainty, is taking 1 metre of sea-level rise as a one-in-five risk, and over 2 metres as a one-in-twenty risk under high emissions.
34. The impacts of sea level rise have been underestimated in the past. One billion people are estimated to live less than ten metres above current sea level. See Nature Communications, Kulp et al (2019) 'New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding' https://www.nature.com/articles/s41467-019-12808-z
35. These risk categories - one-in-five by 2100, or one-in-twenty by 2100 - are this report's own. Support for the approach, as a minimum, is found in the 'Planetary Solvency' series of risk reports, which focus on tail risks. One summary notes that UK insurers are required to hold capital at a level designed to withstand losses that would occur only once in 200 years: this equates to an annual 0.5% chance of occurrence. This prudent risk management is more stringent than our approximation of one-in-20 'before 2100'. See Institute and Faculty of Actuaries and University of Exeter (2025) 'Planetary Solvency – finding our balance with nature: Global risk management for human prosperity' Page 15 https://actuaries.org.uk/planetary-solvency . Meantime, the UK Environment Agency is working on the assumption of over 1 metre of sea level rise by 2100 in its Thames Estuary planning. In 2026, the UK Environment Agency 15 year monitoring review of the Thames Estuary has shown that sea-level rise will be around 1.15 metres compared with 2000 levels based on current information. See Environment Agency (2026) 'Thames Estuary 2100: 15-year monitoring review (2026)' Section 'Critical indicators: overview' https://www.gov.uk/government/publications/thames-estuary-2100-15-year-monitoring-review-non-technical-summary/thames-estuary-2100-15-year-monitoring-review-2026#sea-level-and-extreme-water-levels . By way of further support, just over a metre is at the top end of the EEA's likely range of global sea level rise under very high emissions – without taking account of rapid ice destabilisation. See EEA (2025) 'Global and European sea level rise' https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise Under a high temperature rise scenario for 2100 (5°C), over 2 metres is within the 90% credible interval in the Bamber study. See PNAS, Bamber (2019) 'Ice sheet contributions to future sea-level rise from structured expert judgment' https://www.pnas.org/doi/10.1073/pnas.1817205116 .
36. The EEA (as above) supports anticipating high impact risks of up to about 5 metres by 2150, and the effect of delayed climate action on the extreme risks for 2300. See EEA (2025) 'Global and European sea level rise' https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise .

37. Global mean sea level projections vary substantially by emissions trajectory and by treatment of ice-sheet dynamics. Under an intermediate emissions scenario (SSP2–4.5), the European Environment Agency gives a likely (66% confidence) range of 0.44–0.76m by 2100 (EEA ranges are relative to 1995- 2014); under a very high-emissions scenario (SSP5–8.5), 0.63–1.02m. Scenarios that incorporate faster-than-central disintegration of the Antarctic ice sheet raise this considerably. Two different methods point the same way to a broadly similar high-end picture: Physically-based ice-sheet modelling puts sea-level rise with faster Antarctic disintegration at up to 2.3m by 2100 and 5.4m by 2150. See European Environment Agency, citing DeConto et al,(2021) and other studies at EEA (2025) 'Global and European sea level rise' https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise ; a structured expert-judgement assessment found total sea level rise exceeding 2m by 2100 within the 90% credible interval under high emissions and temperature rise of 5°C, more than double the upper estimate given by the IPCC Fifth Assessment Report at the time: see PNAS, Bamber et al (2019) 'Ice sheet contributions to future sea-level rise from structured expert judgment' https://www.pnas.org/doi/10.1073/pnas.1817205116 . The lower end of the overall published range (around 0.3m) assumes an emissions pathway consistent with rapid decarbonisation and warming held to about 1.5–2°C. Independent tracking of actual government policy commitments puts the world on a trajectory toward approximately 2.6°C of warming by 2100 under current policies; in a 'pledges and targets' scenario where full delivery of all current pledges and long-term net-zero targets are met, this reduces only to around 2.2–2.4°C. Both fall well above the pathway associated with the lowest published sea-level figures. An 'optimistic scenario' where all net zero targets in 140 countries are met, gives a median rise of 1.9°C, giving a possible pathway to the lower end of sea-level rise projections. See Climate Action Tracker (2025) 'Warming Projections Global Update' https://climateactiontracker.org/publications/warming-projections-global-update-2025/
38. See for example Geomar (2025) 'Sea Level Rise is Accelerating! Where is the End of the Line?' Summarising the IPCC figures published in 2021, the summary shows how sea-level rise could in theory be as low as 0.4 metres, where ambitious climate protection is pursued. This is not happening at the moment. https://www.geomar.de/en/discover/ocean-and-climate/climate-change-in-the-ocean/sea-level-rise
39. See Nature Reviews Earth & Environment, Hanna et al (2024) 'Short- and long-term variability of the Antarctic and Greenland ice sheets' https://www.nature.com/articles/s43017-023-00509-7 and Nature Climate Change, Darnell et al (2025) 'The interplay of future emissions and geophysical uncertainties for projections of sea-level rise' https://www.nature.com/articles/s41558-025-02457-0
40. See Nature Geoscience, Golledge et al (2026) 'Ice-sheet regime shifts with climate warming' https://www.nature.com/articles/s41561-026-02010-4 ; and Nature Communications, Zheng et al (2026) 'Expansion of Antarctic surface melt through the 21st century' https://www.nature.com/articles/s41467-026-71114-7 . For sharp updates on the continuing challenges of accounting for ice dynamics, see Science Daily (2026) 'Antarctica is melting from below and scientists say it's worse than expected' https://www.sciencedaily.com/releases/2026/05/260509210637.htm .
41. For the full explanation, see Nature, Seeger et al (2026) 'Sea level much higher than assumed in most coastal hazard assessments' https://www.nature.com/articles/s41586-026-10196-1
42. This uncertainty is recognised in many research papers, with recent publications showing the challenges still faced. For a recent example, see Nature npj Climate and Atmospheric Science, Ma et al (2026) 'An analytical framework reduces cloud feedback uncertainty by linking percentage cloud change to surface warming patterns' https://www.nature.com/articles/s41612-026-01339-2 Reanalyses and comparisons highlight the different conclusions between existing climate models about the impacts of clouds and sea ocean temperature changes in different regions within Earth's energy flows. See, for example, JGR Atmospheres, Loeb et al (2022) 'Evaluating Twenty-Year Trends in Earth's Energy Flows From Observations and Reanalyses' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022JD036686 . Clouds interact with aerosols in the atmosphere, and these interactions 'remain a major source of uncertainty'. See the opening words of the Abstract for Nature Communications, Wang et al (2026) 'Challenges in global climate models to represent cloud response to aerosols: insights from volcanic eruptions' https://www.nature.com/articles/s41467-025-67359-3 There is plenty of evidence for the need for research, and for the ingenuity with which investigations are undertaken – from using historic satellite records to observing volcano eruptions to try and understand the behaviour and impact of aerosols.
43. The evidence of the impact of cloud cover has been gathered from long-lived satellite data going back 20 years. Study suggests that cloud shrinkage, rather than cloud darkening, is the driver of accelerated warming. A plausible feedback process occurs whereby shrinking clouds accelerate warming, which in turn accelerates the shrinking. Science, Voosen (2025) 'Earth's clouds are shrinking, boosting global warming' https://www.science.org/doi/epdf/10.1126/science.adv6047 Later research finds the feedback is by no means straight forward. See Geophysical Research Letters, Cesana et al (2026) 'A reconciled Satellite Record Reveals a Negative Low Cloud Feedback Over the Past 47 Years' https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2026GL124158 .
44. A description of latest models, and the importance of tracking low cloud cover, is set out in: Geophysical Research letters, Loeb et al (2020) 'New Generation of Climate Models Track Recent Unprecedented Changes in Earth's Radiation Budget Observed by CERES' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019GL086705
45. NASA writers seem to have introduced the idea of Earth's '44' as part of their publicising the findings of Science, Mishchenko (2007) 'Long-Term Satellite Record Reveals Likely Aerosol Trend' – with the use focussed on aerosols in the atmosphere. https://www.williambrossow.com/wp-content/uploads/2022/08/2007_Mishchenko_Science.pdf or https://www.science.org/doi/10.1126/science.1136709 The popular take up of the 'sunscreen' analogy was widespread among broadcasters and media. See for example CBC News (2007) 'Earth's 'sunscreen' is thinning, NASA says.' https://www.cbc.ca/news/science/earth-s-sunscreen-is-thinning-nasa-says-1.644440 The NASA article containing the original usage is no longer available on line. For confidence in the origin of the expression see the references in NASA Earth Observatory (2007) 'Aerosol Blanket Likely Thinned During 1990s' https://science.nasa.gov/earth/earth-observatory/aerosol-blanket-likely-thinned-during-1990s-7532/ The 'sunscreen' idea is now frequently used in relation to clouds. See for example, 'By acting as the Earth's 'sunscreen', they [low-level clouds] keep the climate cooler than it would otherwise be.' Carbon Brief, Ceppi (2026) 'Guest Post: How declining cloudiness is accelerating global warming' https://www.carbonbrief.org/guest-post-how-declining-cloudiness-is-accelerating-global-warming

46. The decrease in low cloud seems to be caused by feedback from cloud reduction itself, coupled with a reduction in human-driven greenhouse gas and aerosol emissions. The analysis suggests that emissions reductions and cloud cover feedback account for about 74% of increased absorption of solar radiation. See Atmospheric Chemical Physics, Ceppi et al (2026) 'Emerging low-cloud feedback and adjustment in global satellite observations' https://acp.copernicus.org/articles/26/4153/2026/acp-26-4153-2026.pdf
47. The amount of low cloud cover over the relevant study period (2003 – 2024) decreased at the rate of about 0.05% per decade. This declining low-level cloud cover increased absorbed solar radiation by 0.22 ± 0.07 W/m² per decade, compared with an observed increase in Earth's energy imbalance of 0.44 W/m² per decade. Thus, the low-cloud decline accounts for approximately 50% of the increase in the energy-imbalance trend over that period. The author of the relevant cloud cover study summarises the findings in Carbon Brief, Ceppi (2026) 'Guest Post: How declining cloudiness is accelerating global warming' https://www.carbonbrief.org/guest-post-how-declining-cloudiness-is-accelerating-global-warming The Ceppi study is fully explained in Atmospheric Chemistry and Physics, Ceppi et al (2026) 'Emerging low-cloud feedback and adjustment in global satellite observations' https://acp.copernicus.org/articles/26/4153/2026/
48. A description of latest models, and the importance of tracking low cloud cover, is set out in: Geophysical Research letters, Loeb et al (2020) 'New Generation of Climate Models Track Recent Unprecedented Changes in Earth's Radiation Budget Observed by CERES' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019GL086705
49. The interaction between clouds and aerosols is a source of great uncertainty in climate modelling and prediction. For an up-to-date review and confirmation of the importance of further research to improve forecasting, see AGU Advances, Im et al (2026) 'Aerosol-Cloud Interactions: Overcoming a Barrier to Projecting Near-Term Climate Evolution and Risk' https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2025AV001872 . Aerosols have reduced the impact of greenhouse gases in the atmosphere, and Reducing aerosols from human activity could contribute to further warming – but the response of clouds to such a change is very uncertain. See Review of Geophysics, Bellouin et al (2019) 'Bounding Global Aerosol Radiative Forcing of Climate Change' https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019RG000660
50. See Geophysical Research Letters, Cesana et al (2026) 'A reconciled Satellite Record Reveals a Negative Low Cloud Feedback over the Past 47 Years'. Research into the impacts of low cloud prevalence on acceleration/deceleration of heating finds the opposite link to that predicted - low cloud cover seems to increase with background warming, thereby slowing the immediate rate of warming. However, behind the low-cloud information is a suggestion that future warming will be in line with the strongest increases predicted. This study reconciles modelling and atmospheric records with historical data from satellite records (observational data). The findings highlight how much there is still to learn about clouds and climate - a clear research gap. This is important for making accurate predictions about future temperature trends. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2026GL124158
51. The Ceppi study suggests that a reversal to cloud levels of the early 21sy Century would make a considerable difference to the Earth's energy imbalance. The relevant cloud cover study is summarised by the author in Carbon Brief, Ceppi (2026) 'Guest Post: How declining cloudiness is accelerating global warming' https://www.carbonbrief.org/guest-post-how-declining-cloudiness-is-accelerating-global-warming .The Ceppi study is fully explained in Atmospheric Chemistry and Physics, Ceppi et al (2026) 'Emerging low-cloud feedback and adjustment in global satellite observations' https://acp.copernicus.org/articles/26/4153/2026/
52. The foundational source for this idea was published in 1977. See AMS, Twomey (1977) 'The Influence of pollution on the Shortwave Albedo of Clouds' https://journals.ametsoc.org/view/journals/atsc/34/7/1520-0469_1977_034_1149_tiopot_2_0_co_2.xml
53. A clear overview of the SRM options is set out in a recent policy briefing. See The Royal Society (2025) 'Solar Radiation Modification – Policy Briefing' https://royalsociety.org/-/media/policy/projects/solar-radiation-modification/solar-radiation-modification-policy-briefing.pdf
54. In response to the research gap, the European Space Agency launched the EarthCARE Satellite in 2024, carrying instruments for the observation of clouds and aerosols. See European Space Agency website: 'The EarthCARE Satellite' https://www.esa.int/Applications/Observing_the_Earth/FutureEO/EarthCARE/The_EarthCARE_satellite For an overview of the techniques to be undertaken, see EGU, Atmospheric Measurement Techniques, Wehr et al (2023) 'The EarthCARE Mission – Science and System Overview' https://amt.copernicus.org/articles/16/3581/2023/ Early achievements and validation are discussed in The Journal of European Meteorological Society, Kubota et al (2026) 'Summary of the EarthCARE science and validation workshop 2025 - Early achievements and future perspectives for the Earth Cloud Aerosol and Radiation Explorer (EarthCARE) satellite mission' https://www.sciencedirect.com/science/article/pii/S2950630126000062
55. For the breadth of the impact that clouds have on vegetation, see Frontiers in Forests and Global Change, Hughes et al (2024) 'Clouds and plant ecophysiology: missing links for understanding climate change impacts' https://www.frontiersin.org/journals/forests-and-global-change/articles/10.3389/ffgc.2024.1330561/full ; and for the impact of land cover on cloud formation and behaviour, see Nature Communications, Duveiller et al (2021) 'Revealing the widespread potential of forests to increase low level cloud cover' https://www.nature.com/articles/s41467-021-24551-5
56. For the broader relationship between vegetation change, evapotranspiration and climate, see: Nature Reviews Earth & Environment, Yang et al (2023) 'Evapotranspiration on a greening Earth' https://www.nature.com/articles/s43017-023-00464-3 For research specifically examining the influence of boreal afforestation on clouds and Earth's energy system, see: Nature npj Climate and Atmospheric Science, Ofosu (2026) 'Boreal afforestation's underestimated cloud influence on Earth's energy imbalance' https://www.nature.com/articles/s41612-026-01365-0 and
57. For a summary of this issue, see PIK Institute News (2025) 'Land and ocean carbon sinks weakening, ad other new insights from climate science' https://www.pik-potsdam.de/en/news/latest-news/land-and-ocean-carbon-sinks-weakening-and-other-new-insights-from-climate-science For further detail, see Nature Communications Earth and Environment, Wang et al (2025) 'A new indicator can assess absorption capacity for carbon dioxide and ocean acidification' https://www.nature.com/articles/s43247-025-02380-4

58. There are several millions of square kilometres of open ocean, and hundreds of coastal sites now limiting animal life through low oxygen. See Science, Breitberg et al (2018) 'Declining oxygen in the global ocean and coastal waters' https://www.science.org/doi/10.1126/science.aam7240
59. A local stress event can push a specific system past a threshold, and it settles into a new self-sustaining state. Kelp forest collapse in 2014 – 2016 occurred in Northeast Pacific, for example. Sea urchins took over, creating the 'urchin barrens' which have persisted. See Nature Scientific Reports, Rogers-Bennett et al (2019) 'Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens' https://www.nature.com/articles/s41598-019-51114-y . Coral to algae tipping points have been linked to El Nino stress events in Costa Rica's Isla del Caño reefs. See IABO Aquatic Biology, Palmer et al (2025) 'El-Niño-driven phase shift to algal dominance on Isla del Caño's coral reefs: implications for urgent restoration' https://peerj.com/articles/20088/ .
60. See Lenton et al (2025) 'Global Tipping Points Report 2025' https://ore.exeter.ac.uk/articles/report/Global_Tipping_Points_Report_2025/31889365?file=63280330
61. For a clear explanation of the AMOC, especially in relation to heat transport, see Copernicus, 'Atlantic Meridional Overturning Circulation' https://marine.copernicus.eu/explainers/phenomena-threats/atlantic-meridional-overturning-circulation .
62. 'The AMOC has exhibited a declining trend since the 1990s.' See Introduction to Nature Communications, Mimi et al (2026) 'Atlantic meridional overturning circulation slowdown modulates atmospheric rivers in a warmer climate' https://www.nature.com/articles/s41467-026-72555-w?fromPaywallRec=false The recent (August 2026) study examining the AMOC, and how it might be stabilised, confirms that overturning is slowing down. See Nature Climate Change, van Westen et al (2026) 'Failure to track a stable AMOC state under rapid climate change' Discussion section. https://www.nature.com/articles/s41558-026-02730-w .
63. For a detailed explanation and analysis of these mechanisms see Ocean Science, Roewer et al (2026) 'Nordic overturning increases as AMOC weakens in response to global warming' https://os.copernicus.org/articles/22/1195/2026/
64. See for example the study which finds that a key component of the AMOC, the Florida Current, has remained stable between Florida and the Bahamas since 1982. This follows a re-evaluation of motion-induced voltage measurements. Nature Communications, Volkov et al (2024) 'Florida Current transport observations reveal four decades of steady state' https://www.nature.com/articles/s41467-024-51879-5
65. An evaluation of Meridional ocean heat transport (MHT) from 17 global reanalyses show a trend indicating a 'broad reduction of northward Atlantic heat transport across most gateways since the early 1990s although substantial uncertainties remain prior to the Argo era.' See preprint EGUsphere, Winkelbauer et al (2026) 'Atlantic Meridional Heat Transports from Ocean Reanalyses, monitored Sections and Heat Budget Constraints' https://egusphere.copernicus.org/preprints/2026/egusphere-2026-5435/ . For modelling that shows the tipping point could be reached even earlier this century (from 2026 to 2095 under intermediate emissions scenarios – SSP2 - 4.5; or from 2023 to 2076 under a high-end emissions scenario – SSP5 - 8.5), See JGR Oceans, van Westen et al (2025) 'Physics-Based Indicators for the Onset of an AMOC Collapse Under Climate Change' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025JC022651
66. For a recent overview of the likelihood of collapse and the timescales involved, see The Guardian, Carrington (2026) 'Critical Atlantic current significantly more likely to collapse than thought' https://www.theguardian.com/environment/2026/apr/15/critical-atlantic-current-significantly-more-likely-to-collapse-than-thought .
67. The timing and pace of an AMOC collapse are uncertain – 'with a timescale ranging from 15 to 300 years (Armstrong McKay et al., 2022).' Cited in Nordic Council of Ministers (2026) 'A Nordic Perspective on AMOC Tipping: Impacts and Strategies for Prevention and Governance' page 8. https://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A2035531&dswid=-7840
68. For the implications of the AMOC slowing down and shutting down, see Oceanography, Rahmstorf (2024) 'Is the Atlantic Overturning Circulation Approaching a Tipping Point?' https://tos.org/oceanography/article/is-the-atlantic-overturning-circulation-approaching-a-tipping-point . For more about the cooling of the Arctic region if the AMOC collapsed, see Nature Communications Earth and Environment, Da Nian et al (2026) 'Collapse of the Atlantic Meridional Overturning Circulation would lead to substantial oceanic carbon release and additional global warming' https://www.nature.com/articles/s43247-026-03427-w .
69. A 2026 study used observations and modelling to determine what processes best explain the Cold Blob phenomenon. The conclusion is that ocean heat transport changes, rather than heat loss changes from the ocean surface, are the dominant explanation. The study interprets the Cold Blob as a sign of weakening of the AMOC. See Geophysical Research Letters, Rahmstorf et al (2026) 'Multidecadal Atlantic "Warming Hole" Heat Content Variations Are Caused by Ocean Heat Transport, Not by Surface Fluxes' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025GL118383
70. See Nordic Council of Ministers (2026) 'A Nordic Perspective on AMOC Tipping: Impacts and Strategies for Prevention and Governance' page 13. https://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A2035531&dswid=-7840
71. See Nordic Council of Ministers (2026) 'A Nordic Perspective on AMOC Tipping: Impacts and Strategies for Prevention and Governance' page 13. https://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A2035531&dswid=-7840 The sea level rise does not depend on Northern Europe experiencing cooling. Ibid page 14. For further detail, and an analysis of AMOC global sea-level rise continuing slowly over millennia, see JGR Oceans, van Westen et al (2025) 'Physics-Based Indicators for the Onset of an AMOC Collapse Under Climate Change' https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025JC022651 For the estimate of 50cm rise over the long term, see Ocean Science, van Western (2026) 'Dynamic and steric sea-level changes due to a collapsing AMOC in the Community Earth System Model' https://os.copernicus.org/articles/22/1353/2026/
72. The 'dynamic sea level responses' are described in Climate Dynamics, Levermann et al (2005) 'Dyhamic sea level changes following changes in the thermohaline circulation' https://www.pik-potsdam.de/~anders/publications/levermann_griesel05.pdf ; And an updated overview is contained in Oceanography, Rahmstorf (2024) 'Is the Atlantic Overturning Circulation Approaching a Tipping Point?' https://tos.org/oceanography/article/is-the-

atlantic-overturning-circulation-approaching-a-tipping-point

73. See IPCC AR6 (2021) Chapter 8: Water Cycle Changes https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/
74. This is the essential characteristic of systems that have passed their tipping point. There is no way back, even if original conditions are restored. See Global Tipping Points, Lenton et al (2023) 'Report 2023' Introduction, page 9 https://report-2023.global-tipping-points.org/section1/1-earth-system-tipping-points/
75. The fact that temperature increase is the driver of the weakening AMOC is widely discussed. For a discussion of the need for 'accelerated GHG emissions reductions' as the central strategy to reduce AMOC tipping risks, see Nordic Council of Ministers (2026) 'A Nordic Perspective on AMOC Tipping: Impacts and Strategies for Prevention and Governance' page 19. https://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A2035531&dswid=-7840
76. 'Eventually' is unspecified because precise warming levels and timescales at which the tipping threshold would be crossed and lead to collapse, remain highly uncertain. It may be beyond 2100. There is a complex interaction between the AMOC and the NOC which adds to the uncertainty of the timing of the tipping point. See ibid, Section 5 'Conclusions' page 1204.
77. The ocean has absorbed roughly a quarter of all carbon dioxide emitted by human activity since the industrial revolution, substantially slowing the pace of atmospheric warming. See European Environmental Agency (2025) 'Ocean acidification' https://www.eea.europa.eu/en/analysis/indicators/ocean-acidification .
78. See Annual Review of Environment and Resources, Doney et al (2026) 'The impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities' https://www.annualreviews.org/content/journals/10.1146/annurev-environ-012320-083019
79. Average surface ocean pH has fallen by about 0.1 units since pre-industrial times, from around 8.2 to 8.1. Because the pH scale is logarithmic, this corresponds to an increase in acidity of roughly 30%. Long-term monitoring at a fixed Pacific station records a decline from pH 8.11 in 1985 to 8.04 in 2024. See European Environmental Agency ibid
80. See NOAA Ocean Acidification Program (2025) 'Study finds ocean acidification is more pervasive than previously thought' https://oceanacidification.noaa.gov/study-finds-ocean-acidification-is-more-pervasive-than-previously-thought/
81. Parts of the Southern Ocean are projected to cross aragonite undersaturation by around 2050, with most of the wider Southern Ocean surface following by 2100. Separately, an estimated 70% of the world's deep-sea coral reefs are projected to fall below the aragonite saturation horizon — the depth below which reef skeletons dissolve rather than form — by the end of the century. See PNAS, McNeil et al (2008) 'Southern Ocean acidification: a tipping point at 450-ppm atmospheric CO2' https://pmc.ncbi.nlm.nih.gov/articles/PMC2596239/; For a summary of acidification impacts in the North Pacific, see the Abstract for a poster Kassem et al (2024) 'Ocean acidification impacts on deep-sea coral aragonite saturation, in the North Pacific' https://ui.adsabs.harvard.edu/abs/2024AGUOSCC14A1181K/abstract
82. For example, in west US Pacific, shellfish disease in commercial hatcheries was found to correlate closely with the aragonite saturation state of in-flowing sea-water. See Emerging Themes in Ocean Acidification Science, Barton et al (2015) 'Impacts of Coastal Acidification on the Pacific Northwest Shellfish Industry and Adaptation Strategies Implemented in Response' https://www.jstor.org/stable/24861877?seq=1
83. See Communications Biology, Noonan et al (2025) 'Progressive changes in coral reef communities with increasing ocean acidification' https://pmc.ncbi.nlm.nih.gov/articles/PMC12644485/
84. See IPCC WGII (2022) 'Climate Change 2022: Impacts, Adaptation and Vulnerability' – 'Chapter 3 – Oceans and Coastal Ecosystems and their Services' Page 381. https://www.nature.com/articles/d41586-019-03595-0. For the link between monitoring and assessing vulnerability to ocean acidification, see PLoS One, Zulian et al (2025) 'Assessing benthic invertebrate vulnerability to ocean acidification and de-oxygenation in California: The importance of effective oceanographic monitoring networks' https://pubmed.ncbi.nlm.nih.gov/39965026/. For insights into the work of a global research network, see IAEA – 'Global Ocean Acidification Observing Network (GOA-ON)' https://www.iaea.org/services/oa-icc/science-and-collaboration/global-ocean-acidification-observing-network-goa-on . For the current state of agreement on the needs for a research and governance programme on ocean acidification, see ARCHIMER, Newton et al (2015) 'Global Ocean Acidification Observing Network: Requirements and Governance Plan' https://archimer.ifremer.fr/doc/00651/76343/ . And for efforts to shift from 'piecemeal' to more systematic monitoring, see Science Progress, Taylor-Burns et al (2020) 'Locating gaps in the California System ocean acidification monitoring network' https://journals.sagepub.com/doi/full/10.1177/0036850420936204
85. Ocean alkalinity enhancement — adding alkaline material to seawater to increase its capacity to absorb CO_2 and locally counteract acidification — is an active area of research, with field trials under way including NOAA-funded work on coral reefs in the Pacific. See NOAA Ocean Acidification Program funding years 2023 – 2026 'Assessing the effects and risks of ocean alkalinity enhancement... in the Pacific' https://oceanacidification.noaa.gov/funded-projects/assessing-the-effects-and-risks-of-ocean-alkalinity-enhancement-on-the-physiology-functionality-calcification-and-mineralogy-of-corals-and-crustose-coralline-algae-in-the-pacific/; and also see Biogeosciences, Grosselindemann et al (2026) 'The efficiency and ocean acidification mitigation potential of ocean alkalinity enhancement on multi-centennial timescales' https://bg.copernicus.org/articles/23/3299/2026/
86. A realistic-scale addition of alkalinity was found to restore species-specific calcification rates by between 0% and 52%, with the largest benefit in the most acidification-sensitive species — a partial rather than complete reversal even where deployed. Separately, modelling over multi-centennial timescales finds that while ocean alkalinity enhancement lowers atmospheric CO_2, its net efficiency declines over time owing to carbon-cycle feedbacks. See Environmental Science and Technology, van de Mortel et al. (2025) 'Substantial Limitations of Ocean Alkalinity Enhancement in Mitigating the Negative Impacts of Ocean Acidification on Marine Calcifiers' https://pubs.acs.org/doi/10.1021/acs.est.5c09298; and see also Biogeosciences, Grosselindemann et al (2026) as above

87. Large-scale ocean alkalinity enhancement raises separate environmental questions beyond its effectiveness at restoring calcification. These include the impacts of mining and processing the alkaline material itself, uncertain effects of altered water chemistry on marine life beyond the calcifying species it targets, and the practical difficulty of monitoring and verifying its effects once deployed at scale. See Project Drawdown, 'Deploy Ocean Alkalinity Enhancement' https://drawdown.org/explorer/deploy-ocean-alkalinity-enhancement; van de Mortel, Bednaršek, Feely et al. (2025) 'Substantial Limitations of Ocean Alkalinity Enhancement in Mitigating the Negative Impacts of Ocean Acidification on Marine Calcifiers' Environmental Science & Technology 60(1), 622–641 https://pubs.acs.org/doi/10.1021/acs.est.5c09298
88. The original three-pump framework for marine systems was outlined by Volk and Offert in 1985. It has been discussed over the years, with modifications and additions. For an analysis of the magnitude of the dissolved ocean carbon effect, and the interaction between the different pumps, see Progress in Oceanography, Legendre et al (2015) 'The microbial carbon pump concept: Potential biogeochemical significance in the globally changing ocean' https://www.sciencedirect.com/science/article/abs/pii/S0079661115000105
89. For the explanation of the solubility and carbonate pumps, see Volk et al (1985) 'Ocean Carbon Pumps: Analysis of Relative Strengths and Efficiencies in Ocean-Driven Atmospheric CO_2 Changes'
90. For an explanation of the biological pump, see Annual Review of Marine Science, Siegel et al (2024) 'Quantifying the Ocean's Biological Pump and its Carbon Cycle Impacts on Global Scales' https://www.annualreviews.org/content/journals/10.1146/annurev-marine-040722-115226
91. The microbial pump is described well in Progress in Oceanography, Legendre et al (2015) 'The microbial carbon pump concept' https://www.sciencedirect.com/science/article/abs/pii/S0079661115000105?via%3Dihub
92. The migration-driven pump is also described in Annual Review of Marine Science, Siegel et al (2024) 'Quantifying the Ocean's Biological Pump and its Carbon Cycle Impacts on Global Scales' https://www.annualreviews.org/content/journals/10.1146/annurev-marine-040722-115226
93. For the importance of Marine Protected Areas in principle, and as a strategy for protecting biodiversity, see Oceans Research Institute (2026) 'Marine Protected Areas (MPAs): Importance & Benefits' https://www.oceans-research.com/importance-of-marine-protected-areas/; for 'fast facts' about the importance of protecting sea grass and its capacity for storing carbon, in the face of its current decline, see also NOAA National Ocean Service 'Coastal Blue Carbon' https://coast.noaa.gov/states/fast-facts/blue-carbon.html
94. For evidence and discussion of the importance of the quality of management and protection of areas of the ocean, rather than rapidly designating areas that become simply 'paper parks', see Nature, npj Ocean Sustainability, Stephenson et al (2025) 'Quality of marine protected areas is critical to achieving global biodiversity targets' https://www.nature.com/articles/s44183-025-00169-8 and also ScienceDirect, Trotman et al (2026) 'A roadmap for effective and sustainable marine protected areas: Beyond paper parks' https://www.sciencedirect.com/science/article/pii/S0301479726004160
95. For evidence of the value of sea grass for carbon sequestration, see PLOS One, Greiner et al (2013) 'Seagrass Restoration Enhances "Blue Carbon" Sequestration in Coastal Waters' https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0072469 and for an analysis of impacts of restoration of sea grass on carbon sequestration over time, see Nature, npj Ocean Sustainability, Ward et al (2025) 'Management approach matters: meeting seagrass recovery and carbon mitigation goals' https://www.nature.com/articles/s44183-025-00111-y
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99. For a discussion of the impact on prey (including krill) of losing whales from the ecosystem, see Nature, Savoca et al (2021) 'Baleen whale prey consumption based on high-resolution foraging measurements' https://www.nature.com/articles/s41586-021-03991-5
Baleen whales support an estimated 10% of net primary production in offshore areas during the summer. See North Atlantic Marine Mammal Commission (2025) '15 December 2025: A new study on the impact of baleen whales on ocean primary production across space and time' https://nammco.no/topics/15-december-2025-a-new-study-on-the-impact-of-baleen-whales-on-ocean-primary-production-across-space-and-time/ ; see also Nature Portfolio Collection (2026) inviting submissions on 'Whale-driven nutrient transport in marine eco-systems'. This call for contributions captures the different ways in which whales are understood to be 'ecosystem engineers'. https://www.nature.com/collections/hcabdihieh ; For the impact on biodiversity, a study found that the capacity for marine mammals to move nutrients decreased to 6% of past values across ocean and land. The decrease – across fish and bird species in the transport of nutrients – disrupted the efficient nutrient pump that existed 'from the deep sea to the continental interiors'. See The Proceedings of the National Academy of Science USA, Doughty et al (2015) 'Global nutrient transport in a world of giants' https://pmc.ncbi.nlm.nih.gov/articles/PMC4743783/
100. The discussion about the 'carbon value of whales', whilst recognising their importance in their own right, concludes that the impact of whales on 'deep carbon exports' remains largely unknown, flagging the need for further research here. See Trends in Ecology & Evolution, Pearson et al. (2023) 'Whales in the carbon cycle: can recovery remove carbon dioxide?' https://www.cell.com/trends/ecology-evolution/fulltext/S0169-5347(22)00279-8
101. For a science-journalism discussion of the status of synthetic whale waste research (in early stage) see The Brighter Side of News (2024) 'Whale faeces could be the solution to climate change, study finds' — reporting on WhaleX Foundation research led by Edwina Tanner https://www.thebrighterside.news/post/whale-feces-could-be-the-solution-to-climate-change-study-finds/

102. The WWF Living Planet Report (2022) captures the current loss of biodiversity, with a 69% drop in the abundance of monitored wildlife across the world. The drivers of the loss are land-use change and, increasingly, global warming. The losses are not shared equally around the world, with Latin America severely hit (94% loss of abundance) and freshwater species globally (83% loss of abundance). See WWF (2022) Executive Summary, Living Planet Report 2022 page 4 https://www.wwf.org.uk/our-reports/living-planet-report-2022 For an estimate of the rates of extinction of species today, compared with pre-human times, see The Royal Society, Johnson (2026) 'Past and future decline and extinction of species' https://royalsociety.org/news-resources/projects/biodiversity/decline-and-extinction/ The IPCC's IPBES report says it is 'well-established' that 'The rate of species extinction is already at least tens to hundreds of times higher than it has averaged over the past ten million years, and it is set to rise sharply still further unless drivers are reduced.' IPBES (2019) 'Global Assessment Report on Biodiversity and Ecosystem Services: Summary for Policymakers' Executive Summary, Key Message A5 page 11 https://ict.ipbes.net/ipbes-ict-guide/data-and-knowledge-management/citations-of-ipbes-assessments/global-assessment
103. For further thinking about how ecosystems move towards thresholds beyond which their previous condition may no longer be recoverable, see 'Ecosystems are in transition'
104. For a clear and vivid explanation of how important this risk is, perhaps even more so than financial volatility or war, see Mongabay, Muggah (2026) 'Tipping points and ecosystem collapse are the real geopolitical risk' https://news.mongabay.com/2026/02/tipping-points-and-ecosystem-collapse-are-the-real-geopolitical-risk-commentary/
105. For example, the degradation of the Southeastern Amazon rain forest has already caused parts of it to emit CO_2 when it has always been an important carbon store. The current level of human pressure will prevent the forest from recovering, and as a new source of carbon emissions, the forest will contribute to global warming – adding another local and global pressure. See Nature, Florres et al (2024) 'Critical transitions in the Amazon rain forest system' https://www.nature.com/articles/s41586-023-06970-0 Similar feedbacks in dryland areas expand the threat of desertification, causing ever increasing areas of farmland to be lost. A controlled field study tried to tease out the relative impacts of different pressures on land that lead to desertification. All of the pressures contributed, and a self-reinforcing feedback was also identified as important: degraded drylands reduce vegetation cover and moisture recycling, and in turn that reduces rainfall. The reinforced dryness adds further pressure towards desertification. See Nature, Burrell et al (2020)'Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification' https://www.nature.com/articles/s41467-020-17710-7 For examples of one species loss triggering another, there is evidence showing that cascades of extinction as one loss leads to loss of ecological interactions for others. See Science Advances, Strona et al (2022) 'Coextinctions dominate future vertebrate losses from climate and land use change' https://www.science.org/doi/10.1126/sciadv.abn4345
106. Since the Cenozoic era the past dynamics of the Amazon Rain Forest have been relatively stable, including through significant climate shifts. Even when draining of massive wetlands began 7 million years ago, and then humans appeared, the forests persisted. The new stresses from rapidly warming temperatures, combined with extreme drought, deforestation and fires, have placed the forest system under threat. See Nature, Flores et al (2024) 'Critical transitions in the Amazon forest system' page 556. https://www.nature.com/articles/s41586-023-06970-0
107. The Amazon supports connectivity patterns that move water, minerals and organisms from one location to another. This connectivity supports ecological functions and stabilises carbon and hydrological cycles on regional and global scales. See: Science Panel for the Amazon (2025) 'The Amazon Assessment Report 2025: Connectivity of the Amazon for a Living Planet' Box 1.1 Page 68. The 'ecological integrity is tightly linked to global climate stability, biodiversity preservation, and the well-being of people world-wide.' Ibid Page 49. https://www.sp-amazon.org/ar2025
108. The Amazon is home to about one in ten known species on Earth. The Amazon basin covers about 40% of South America and the landscape contains about 20% of Earth's liquid fresh water. See WWF website: Places – Amazon https://www.worldwildlife.org/places/amazon/
109. A study, using satellite images, shows how the transpiration of the rainforest is important for initiating the transition from dry to wet season over the southern Amazon. In this way the forest is a driver of seasonal cycles of rainfall. See PNAS Environmental Sciences, Wright et al (2017) 'Rainforest-initiated wet season onset over the southern Amazon' https://www.pnas.org/doi/10.1073/pnas.1621516114 The 2017 work builds on the understanding of a mechanism whereby the Amazon seeds rainfall with potassium salt particles. See Science, Pöhiker et al (2012) 'Biogenic potassium salt particles as seeds for secondary organic aerosol in the Amazon' https://pubmed.ncbi.nlm.nih.gov/22936773/
110. The moisture recycling of the amazon 'contributes 20% - 50% of the rain that falls in the region and regulated continental and global weather through sea-surface temperatures, rain and cloud.' See: Science Panel for the Amazon (2025) 'The Amazon Assessment Report 2025: Connectivity of the Amazon for a Living Planet' Page 52 https://www.sp-amazon.org/ar2025
111. See Nature, Flores et al (2024) 'Critical transitions in the Amazon forest system' page 555 https://www.nature.com/articles/s41586-023-06970-0
112. The Amazon forest faces extreme stresses on multiple fronts, and there is a danger it will reach a tipping point (from which it will be unable to recover whatever remedial steps are then taken) as early as 2050. Ibid. See Abstract. For a summary, see CarbonBrief, Dwyer (2024) 'Unprecedented stress in up to half of the Amazon may lead to tipping point by 2050' https://www.carbonbrief.org/unprecedented-stress-in-up-to-half-of-the-amazon-may-lead-to-tipping-point-by-2050
113. For a recent analysis of the status of the amazon forest system and the dangers of reaching a tipping point, see Ibid pages 556, 562. Separate discussion about water stress and the possibility of tipping points is found Ibid, pages 559, 560. Existing deforestation is shifting the Amazon forests towards climate similarities with areas in transition to savanna. See Nature Communications, Earth & Environment, Silveira et al (2025) 'Observed shifts in regional climate linked to Amazon deforestation' https://www.nature.com/articles/s43247-025-02900-2?fromPaywallRec=false There is a positive feedback that accelerates the decline towards a tipping point. The

reduction in moisture caused by deforesting also lowers the global temperature rise threshold to 1.5°-1.9° of warming when 'near system-wide transition' of the Amazon will occur, if it takes place in combination with deforestation of 22–28%. See Nature, Wunderling et al (2026) 'Deforestation-induced drying lowers Amazon climate threshold' https://www.nature.com/articles/s41586-026-10456-0

114. Ibid for evidence that forest loss contributes to higher land temperatures, lower evapotranspiration and dry season rainfall, and fewer rainy days where cover falls below 60%. For impacts further afield, a connection is detected between Amazon fires and deforestation, and the weather in the US Midwest. See for example, 'The Amazon is definitely a weather engine' WWF quoted in NBC News, Ortiz (2019) 'How the Amazon 's fires, deforestation affect the U.S. Midwest' 'https://www.nbcnews.com/news/world/how-amazon-s-fires-deforestation-affect-u-s-midwest-n1045886 A detailed Amazon Assessment report sets out the current understanding of how the Amazon systems interplay with weather and climate, affect health, production, biodiversity with global impacts. See Science Panel for the Amazon (2025) 'Connectivity of the Amazon for a Living Planet' https://www.sp-amazon.org/ar2025
115. For the tendency to underestimate the impact of deforestation on the Earth system; and for the importance of analysing the interactions between oceanic-driven and terrestrial-recycled precipitation, see Nature Communications, Cui et al (2026) 'Historical deforestation drives strong rainfall decline across the southern Amazon basin' https://www.nature.com/articles/s41467-026-68361-z . If the Amazon rainforest was to be completely cleared, extreme weather events would become more frequent and more extreme – including through extreme precipitation. See Max-Planck-Gesellschaft, Yoon et al (2026) 'Amazon rainforest: More Extreme Weather Events after Deforestation' https://www.mpg.de/26203124/deforestation-leads-to-more-extreme-weather-events-in-the-amazon-region
116. For example, simulations show a 10% - 20% reduction in precipitation in important agricultural areas of the western US if the Amazon rainforest is deforested. See Journal of Climate, Medvigy (2013) 'Simulated Changes in Northwest US Climate in Response to Amazon Deforestation' https://journals.ametsoc.org/view/journals/clim/26/22/jcli-d-12-00775.1.xml The interplay between deforestation and regional and global impacts is complex – but inevitably places agricultural production at risk. See Nature, Lawrence et al (2015) 'Effects of tropical deforestation on climate and agriculture' https://www.nature.com/articles/nclimate2430
117. This is substantiated by the World Bank, academic researchers and journalistic investigation. See World Bank, Margulis (2004) 'Working Paper No. 22: Causes of Deforestation of the Brazilian Amazon' https://documents1.worldbank.org/curated/en/758171468768828889/pdf/277150PAPER0wbwp0no1022.pdf ; Forest Policy and Economics, Diaz Parra et al (2026) 'Pastures of power: A literature review on cattle ranching deforestation in the Amazon' https://www.sciencedirect.com/science/article/pii/S1389934126001577 ; and The Guardian, Wasley et al (2023) 'More than 800m Amazon trees felled in six years to meet beef demand' https://www.theguardian.com/environment/2023/jun/02/more-than-800m-amazon-trees-felled-in-six-years-to-meet-beef-demand .
118. For a recent report showing the drop in deforestation, see Observatorio do Clima (2026) 'Amazon deforestation alerts hit all-time low in 2026' https://oc.eco.br/en/amazon-deforestation-alerts-hit-all-time-low-in-2026/ . However, the impact of fires on the amazon's ability to absorb carbon has not been fully understood. Fires elevate ozone in the atmosphere and this stops carbon dioxide absorption, in addition to the impact of the fires themselves. See Communications Earth and Environment, Brown et al (2026) 'Fire derived ozone intensifies carbon loss in Amazon forests under drought conditions' https://www.nature.com/articles/s43247-026-04047-0 . Fires in the Amazon forest system during 2024 triggered record-breaking CO2 releases, with 'a sevenfold increase on the average of the previous two years.' See European Geosciences Union (2025) 'Record-breaking 2024 Amazon fires drive unprecedented carbon emissions and ecosystem degradation' https://www.egu.eu/news/1509/record-breaking-2024-amazon-fires-drive-unprecedented-carbon-emissions-and-ecosystem-degradation/ .
119. 'Almost all fires in the amazon are started by people, mainly to clear land...' See EarthSky, Ortiz (2026) 'Amazon wildfires hide another threat to the rainforest' https://earthsky.org/earth/amazon-wildfires-hide-another-threat-to-the-rainforest/ .
120. For a detailed explanation of the natural mechanism of fire control, see Ecological Applications, Ray et al (2005) 'Micrometeorological and Canopy Controls of Fire Susceptibility in a Forested Amazon Landscape' https://esajournals.onlinelibrary.wiley.com/doi/10.1890/05-0404 .
121. See Environmental Research Letter, Cooley et al (2025) 'Thermal stress in degraded forests in Brazilian Amazon Arc of Deforestation' https://iopscience.iop.org/article/10.1088/1748-9326/adea98
122. A study modelling the potential across the globe for forests to regenerate naturally found that there is great potential in tropical regions across Brazil and other countries. However, the proximity to existing forest is essential because self-regeneration depends on the climate modification provided by the existing forest, as well as for seed dispersal. The quality of soil available to the regenerating forest is also important. A history of intensified use of land for farming can prevent self-regeneration. See Nature, Williams et al (2024) 'Global potential for natural regeneration in deforested tropical regions' https://www.nature.com/articles/s41586-024-08106-4
123. Brazil provides some evidence that national policy and political commitment can make a substantial difference to forest protection: stronger environmental policies and enforcement were associated with falling deforestation during the earlier Lula administrations, while the weakening of environmental protections under Bolsonaro was followed by a marked increase in deforestation. CCAG (2022) 'Brazil CCAG Country Report' https://www.ccag.earth/reports/brazil---ccag-country-report
124. The rate at which forests regenerates varies across the world, influenced by temperature, water deficit and disturbance. In a study looking at a twenty year period, Amazon forest regenerates more slowly than in Central Africa or Borneo. Even with slower recovery rates, natural regeneration is relatively efficient and effective. The importance of protecting recovering forest areas, and preventing harm to remaining forests is clear. Forest regeneration across the world currently offsets about a quarter of the carbon

emissions caused by the forests' initial destruction or degradation. See Nature, Heinrich et al (2023) 'The carbon sink of secondary and degraded humid tropical forests' https://www.nature.com/articles/s41586-022-05679-w

125. The classic text on the complexity and diversity of soils is Weil and Brady (2017) 'The Nature and Properties of Soils – 15th Edition' The Abstract and a PDF of the full text can be found at ResearchGate: https://www.researchgate.net/publication/301200878_The_Nature_and_Properties_of_Soils_15th_edition
126. Carbon sequestration is supported by 'no-till' farming, cover cropping and agroforestry; all help to draw down carbon dioxide and store it as soil organic carbon. The IPCC estimates that between 0.4 and 8.6 gigatons a year of CO_2 equivalent can be captured through agricultural soil carbon sequestration. The IPCC estimate of carbon sequestration is found in IPCC (2022) 'Climate Change and Land: An IPCC Special Report on climate change, desertification, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems': https://www.ipcc.ch/srccl/ .Note, the WEF, Strauss (2024) 'How regenerative agriculture can make climate solutions more resilient' gives a useful summary, but mis-attributes one figure to IPCC – saying in error that the sequestration of 23 gigatons is found in the IPCC report. https://www.weforum.org/stories/food-water-and-clean-air/regenerative-agriculture-climate-solutions-resilient .
127. For a review of regenerative farming and its central features, see AATCC, Bindu et al (2025) 'Regenerative Agriculture: A Sustainable Solution to Combat Climate Change and Restore Ecosytems' https://aatcc.peerjournals.net/wp-content/uploads/2025/08/Regenerative-Agriculture-A-Sustainable-Solution-to-Combat-Climate-Change-and-Restore-Ecosystems.pdf .
128. See, for example, Growing Africa, Kihara et al (2023) 'Soil Health Challenges in Sub-Saharan Africa: Status and Solutions https://growingafrica.pub/soil-health-challenges-in-sub-saharan-africa-status-and-solutions/
129. See, for example, Afro Agricultural Network, Tumushabe (2026) 'Africa's Soil Crisis and the Regenerative Response' https://africaagriculturalnetwork.com/africas-soil-crisis-and-the-regenerative-response/
130. For numbers of farms around the world, and their relative scales, see World Development, Lowder et al (2016) 'The number, size, and distribution of farms, smallholder farms, and family farms worldwide' https://www.sciencedirect.com/science/article/pii/S0305750x15002703
131. See IPCC (2022) 'Climate Change 2022: Mitigation of Climate Change' Chapter 7 – Section 7.4.3.1 page 788
132. See Growing Africa, Kihara et al (2023) 'Soil Health Challenges in Sub-Saharan Africa: Status and Solutions page 16 https://growingafrica.pub/soil-health-challenges-in-sub-saharan-africa-status-and-solutions/
133. See, for example, Alliance Biodiversity and CIAT, Bolo et al (2025) 'The cost of soil erosion in sub-Saharan Africa: Why the time to act is now' https://alliancebioversityciat.org/stories/soil-erosion-costing-africa-numbers
134. See European Journal of Soil Science, Mesele et al (2025) 'Current Problems Leading to Soil Degradation in Africa: Raising Awareness and Finding Potential Solutions' https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70069 ; and Harper Collins, Iyer et al (2026) 'Water Nature, Progress' in which co-management of water and landscapes is proposed, aligning nature-based thinking with strategic crop selection, forest protection and water conservation. https://harpercollins.co.in/announcements/water-nature-progress/ .
135. For a discussion of the importance of policy and its implementation, awareness, education and community engagement, see Mesele et al. Ibid.
136. See IUCN Issues Brief (2017) 'Drylands and land degradation' https://iucn.org/resources/issues-brief/drylands-and-land-degradation
137. For the impact of desertification on farming, see IPCC Special Report on Climate Change and Land – Chapter 3. For example, Section 3.5.1.1 Integrated crop-soil-water management https://www.ipcc.ch/srccl/chapter/chapter-3/
138. For amplification of floods, see Ibid Section 1.4.2.5; for the projected increase in the severity of droughts across some dryland areas, see, for example, Ibid Summary for Policymakers Section 3.1.4 and 3.1.4.3
139. See, for example, Potsdam institute for Climate Impact Research, Tomalka et al (2024) 'Stepping back from the precipice: Transforming land management to stay within planetary boundaries' Page 37 https://doi.org/10.48485/pik.2024.018
140. See UN FAO (2026) 'SDG Indicators Data Portal – Indicator 15.3.1 Proportion of land that is degraded over total land area' https://www.fao.org/sustainable-development-goals-data-portal/data/indicators/1531-proportion-of-land-that-is-degraded-over-total-land-area/en Also, see UNCCD (2025) 'Desertification and Drought Day 17 June 2025 Factsheet' https://www.unccd.int/sites/default/files/2025-05/DDD%20factsheet%20EN.pdf
141. Ibid
142. Like soil loss generally, the complex ecosystems within dry lands prone to desertification are not always capable of being rebuilt; they may pass a point of no return. However, rehabilitation remains important for returning some functional capability to the soil, and for slowing down or preventing the ongoing erosion and desertification. For an understanding of the characteristics of drylands, see, again, Weil and Brady (2017) 'The Nature and Properties of Soils – 15th Edition' The Abstract and a PDF of the full text can be found at ResearchGate: https://www.researchgate.net/publication/301200878_The_Nature_and_Properties_of_Soils_15th_edition For a discussion about the specifics of tipping points in Drylands, see University of Exeter, Lenton et al (2023) 'Global Tipping Points' Chapter 1.3 Tipping points in the biosphere Page 78. And especially Section 1.3.2.5 Drylands Page 96. https://report-2023.global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/1-3-2-current-state-of-knowledge-on-tipping-points-in-the-biosphere/1-3-2-5-drylands/
143. See, for example, Smale et al (2018) 'Fostering transformation and growth in Niger's agricultural sector – Chapter 1 Farmer-managed restoration of agroforestry parklands in Niger' https://brill.com/edcollchap-oa/book/9789086868735/BP000002.xml
144. See World Bank (2004) 'The Loess Plateau Watershed Rehabilitation Project' – Impact Analysis' page 7 onwards https://documents.worldbank.org/en/publication/documents-reports/documentdetail/142661468762366534
145. Ibid

146. By 2017, an estimated 7 million hectares in Niger were affected by FMNR, with earlier research estimating that around 5 million hectares had been improved, producing more than 500,000 additional tonnes of food each year. In the Maradi and Zinder regions, more than one million rural households have managed trees across over 4 million hectares. The additional tree cover has improved soil fertility, provided fodder and other products, and increased agricultural production. In Burkina Faso, similar farmer-led techniques rehabilitated between 200,000 and 300,000 hectares and increased food production. See Smale et al (2018) 'Fostering transformation and growth in Niger's agricultural sector – Chapter 1 Farmer-managed restoration of agroforestry parklands in Niger' https://brill.com/edcollchap-oa/book/9789086868735/BP000002.xml ; USGS, Reij et al (2007) 'Re-greening the Sahel: Farmer-led innovation in Burkina Faso and Niger https://pubs.usgs.gov/publication/70157359 and WRI, Weber et al (2016) 'Restoring Africa's Degraded Lands by Improving Farmers' Rights' https://www.wri.org/insights/restoring-africas-degraded-lands-improving-farmers-rights ;
147. The IPCC's IPBES report considers the importance of supporting local efforts of Indigenous Peoples in a number of sections. See Key Message D5 for one example, on page 18. IPBES (2019) 'Global Assessment Report on Biodiversity and Ecosystem Services: Summary for Policymakers' Executive Summary https://ict.ipbes.net/ipbes-ict-guide/data-and-knowledge-management/citations-of-ipbes-assessments/global-assessment
148. See discussions about vulnerability in IPCC AR6 (2022) 'WGII - Climate Change 2022: Impacts, Adaptation and Vulnerability' – especially the chapters on cities, health and vulnerability. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/
149. See PNAS Sustainability Science, Xu et al (2020) 'Future of the human niche', with the quotation from the 'Significance' summary. https://www.pnas.org/doi/10.1073/pnas.1910114117
150. Those most exposed to the dangers of heat stress work in construction, baggage handling or agricultural – all low-pay occupations where there are no real opportunities for adaptation to reduce heat stress impacts. ILO estimates that more than 2% of global working hours will be lost to heat effects. 60% will be lost to agriculural workers, and 19 per cent to construction workers. See ILO, Kjellstrom et al (2019) 'Working on a warmer planet: The impact of heat stress on labour productivity and decent work' Page 14 https://www.preventionweb.net/publication/documents-and-publications/working-warmer-planet-impact-heat-stress-labour-productivity .
151. The critical limit used to be fixed at 35°C wet bulb temperatures. However empirical studies show that this was too high a threshold, with vulnerable human beings being fatally affected at temperatures as low as 24° wet bulb measurements. See PNAS Journal of Applied Physiology, Vecellio et al (2022) 'Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project)' https://journals.physiology.org/doi/full/10.1152/japplphysiol.00738.2021 and Nature Communications, See also Nature Communications, Vanos et al (2023) 'A physiological approach for assessing human survivability and liveability to heat in a changing climate' https://www.nature.com/articles/s41467-023-43121-5
152. See Science Advances, Raymond et al (2020) 'The emergence of heat and humidity too severe for human tolerance' https://www.science.org/doi/10.1126/sciadv.aaw1838
153. The healthy young adults threshold is, again, found in Journal of Applied Psychology, Vecellio et al (2022) 'Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project)' https://journals.physiology.org/doi/full/10.1152/japplphysiol.00738.2021 ; the discussion about thresholds in the Gulf coast stations is found in Science Advances, Raymond et al (2020) 'The emergence of heat and humidity too severe for human tolerance' https://www.science.org/doi/10.1126/sciadv.aaw1838
154. There are impacts on neurological and psychological health. See The Lancet, Sisodiya et al (2024) 'Climate change and disorders of the nervous system' https://www.thelancet.com/journals/laneur/article/PIIS1474-4422(24)00087-5/abstract .
155. For the limit to heat tolerance, see PNAS, Sherwood et al (2010) 'An adaptability limit to climate change due to heat stress' https://www.pnas.org/doi/10.1073/pnas.0913352107 .
156. Copernicus recorded that, in 2025, average global warming was 2.37°C above pre-industrial levels, with 1.5°C expected to be surpassed within four years. See Earth System Science Data, Forster et al (2026) 'Indicators of Global Climate Change 2025: Annual update of key indicators of the state of the climate system and human influence' https://essd.copernicus.org/articles/18/3889/2026/ . The World Meteorological Office confirmed that 2025 was one of the three warmest years on record, that the preceding 11 years had been the 11 warmest on record, and that the global average temperature rise was now 1.44°C above pre-industrial levels. This information is summarised in the press release at WMO (2026) 'WMO confirms 2025 was one of the warmest years on record' https://wmo.int/news/media-centre/wmo-confirms-2025-was-one-of-warmest-years-record?access-token=6ULhYwBphbE9qriKJKbQMVQKArS8riMAs3G_v730YgU .
157. See, again, Science Advances, Raymond et al (2020) 'The emergence of heat and humidity too severe for human tolerance' https://www.science.org/doi/10.1126/sciadv.aaw1838 . In 2016, regional climate models suggested that 35°C events would be regular decadal event by 2071. This is further support, dating back over a decade, for the expectation that life-threatening heat in the Persian Gulf area will become a recurring threat. See Nature Climate Change, Pal et al (2016) 'Future temperature in southwest Asia projected to exceed a threshold for human adaptability' http://www.nature.com/nclimate/journal/v6/n2/full/nclimate2833.html In a NASA feature article Alan Buis reported on Colin Raymond's expert view that 35°C will be exceeded in the Red Sea area by around 2050, in eastern China and parts of Southeast Asia by 2070; and in Brazil by around 2070. See NASA, Buis (2022) 'Too Hot to Handle" How Climate Change May Make Some Places Too Hot to Live' https://science.nasa.gov/earth/climate-change/too-hot-to-handle-how-climate-change-may-make-some-places-too-hot-to-live/

158. US agricultural workers have a heat-related mortality rate 20 to 30 times higher than other industries. See EDF (2023) 'Heat stress threatens agricultural workers' health as US temperatures rise' https://www.edf.org/report/heat-stress-threatens-agricultural-workers-health-us-temperatures-rise ; and FAS (2025) 'Heat Hazard and Migrant Rights: Protecting Agricultural Workers In A Changing Climate' https://fas.org/publication/heat-hazards-and-migrant-rights/
159. See IPCC for heat related mortality and morbidity. IPCC AR6 (2022) 'Impacts, Adaptation and Vulnerability' Chapter 7: Health, Wellbeing and the Changing Structure of Communities' https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/
160. Global synthesis shows wealthier neighbourhoods consistently have higher-quality accessible green space. See Nature Communications, Li et al (2024) 'Green spaces provide substantial but unequal urban cooling globally' https://pmc.ncbi.nlm.nih.gov/articles/PMC11369290/ . Trees within a neighbourhood translate directly into protection from heat mortality. In US urban tree canopy has been calculated to prevent 1200 deaths a year – with this protection unevenly distributed roughly according to neighbourhood wealth or poverty. Nature npj Urban Sustainability, McDonald et al (2024) 'Current inequality and future potential of US urban tree cover for reducing heat-related health impacts' https://www.nature.com/articles/s42949-024-00150-3
161. For an estimate built from statistical modelling showing half a million people a year dying from heat stress, see Lancet Romanello et al (2025) 'The 2025 Lancet Countdown on health and climate change: climate change action offers a lifeline' https://lancetcountdown.org/2025-report/ . India is the the country with sharpest evidence of undercounting. India's National Crime Records Bureau (NCRB) counted 116 heat stroke deaths in Telangana in 2024. For the same year, Telangana's own Heatwave Action Plan showed only 10 deaths. Narang and Gadgil have tried to show how far short official tallies fall. See Frontiers in Environmental Health, Narang et al (2026) 'Estimating heatwave-induced excess mortality in India's districts' https://www.frontiersin.org/journals/environmental-health/articles/10.3389/fenvh.2026.1789071/full
162. See Lancet, Romanello et al (2025) 'The 2025 Lancet Countdown on health and climate change: climate change action offers a lifeline' See in particular the sections on heat-related health impacts and adaptation, planning and resilience for health. https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(25)01919-1/abstract
163. See United Nations Department of Economic and Social Affairs (2025) 'World Urbanization Prospects 2025: Summary of Results' https://www.un.org/development/desa/pd/world-urbanization-prospects-2025
164. The FAO summarises relevant data from ILO. See FAO (2025) Highlights: Employment indicators 2000–2023 (July 2025 update) https://www.fao.org/statistics/highlights-archive/highlights-detail/employment-indicators-2000-2023-(july-2025-update)/en .
165. For the proportion of people living in urbanised areas, see UN DESA (2025) 'World Urbanisation Prospects'. This methodological update to splits populations three ways: 45% live in cities; 36% live in towns. Only 19% live in rural areas. The proportion in cities has roughly doubled since the 1950s, and the rural proportion has roughly halved. Around 1975 the number of city dwellers overtook the number in the rural population.. This methodological update to splits populations three ways: 45% live in cities; 36% live in towns. Only 19% live in rural areas. The proportion in cities has roughly doubled since the 1950s, and the rural proportion has roughly halved. Around 1975 the number of city dwellers overtook the number in the rural population. https://www.un.org/development/desa/pd/world-urbanization-prospects-2025 For the number of people exposed to flood risk, see Kulp et al (2019) 'New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding' https://www.nature.com/articles/s41467-019-12808-z
166. This figure, based on high emissions continuing, is C40's warning. In fact it is possible that C40 underestimate what is likely in this scenario because the updating of elevation models carried out in the Nature, Kulp et al paper mentioned above took place after the C40 report was published. For C40 article, summarising their 'The Future We Don't Want' report, see C40 (2018) 'Sea Level Rise and Coastal Flooding' https://www.c40.org/what-we-do/scaling-up-climate-action/water-heat-nature/the-future-we-dont-want/sea-level-rise/
167. For South East Asia's vulnerabilities, note that 19 of the 25 of its cities fall into the category 'most exposed to sea level rise.' 77% of its population live in coastal areas. It is the location of over 42% of Asia-Pacific's coastal flooding damage. For a single source for South East Asia's particular exposure, see Frontiers in Climate, Putra (2024), 'ASEAN's climate change mitigation and adaptation measures' https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2024.1488560/full
168. For evidence of Vietnam's status as the third largest rice exporter in the world, see OEC (2024) 'Rice in Vietnam' https://oec.world/en/profile/bilateral-product/rice/reporter/vnm?selector2787id=trade_i_baci_a_17 ; see also MDPI Sustainability, Maitah et al (2020) 'Rice as a Determinant of Vietnamese Economic Stability' Section: 3 'Production and Export' 10.3390/su12125123 .
169. For the extent of Vietnam's rice production, and the adaptation efforts there to cope with increased (but still partial and temporary) salination of crop lands, see PLOS One, Paik et al (2020) 'Salt tolerant rice variety adoption in the Mekong River Delta: Farmer adaptation to sea-level rise' https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0229464 For Vietnam's export details, and the area threatened by flood with sea level rise, see Asian Impact Management Review, Phung Phi Tran (2024) ' Climate Change Impacts on Food Security in Vietnam: A Comprehensive Review' https://www.aimr.asia/environmental-impact/climate-change-impacts-on-food-security-in-vietnam-a-comprehensive-review/ ; For wider impacts, showing the systemic nature of global food security and its vulnerability to climate change, and also that river flooding is a widespread hazard affecting the world, see also King, Schrag, Zhou Dadi, Ye Qi and Ghosh (2015) 'Climate Change: A Risk Assessment' Page 110 and Page 88. https://www.csap.cam.ac.uk/media/uploads/files/1/climate-change--a-risk-assessment-v10-spreads.pdf
170. For Vietnam's own assessment of the impact of 1 meter of sea level rise, see Ministry of Natural Resources and Environment, Thuc et al (2016) 'Climate Change and Sea Level Rise Scenarios for Vietnam' – for inundation maps, Page 26. https://imh.ac.vn/files/doc/KichbanBDKH/CCS_SPM_2016.pdf
171. This study, published only in September 2026, exposes Vietnam's extreme vulnerability. See Science Direct Environmental Challenges, Kompas et al (2026) 'The severe economic impacts from sea level rise and storm surge with global warming: The case of Vietnam' https://www.sciencedirect.com/science/article/pii/S2667010026001666 .

172. For discussion of flood defences, see IPCC AR6 WGII, Cross-Chapter Paper 2: 'Cities and Settlements by the sea' on coastal systems and adaptation. The paper notes the need for approaches using hard and soft protection, nature based measures and more, with a need for an integrated, sequenced portfolio. Section CCP2.4.4 'Enabling Climate Resilient Development for Cities and Settlements by the Sea' The need for both nature based and hard defences is explored further in sections CCP2.3.2.3 'Nature Based Measure' and CCP2.3.2.1 'Hard Engineering Measures' https://www.ipcc.ch/report/ar6/wg2/chapter/ccp2/ . For a discussion of the value of mangrove as a flood defence measure, and the advantages of conservation rather than losing and restoring mangrove forest, see World Bank (2022) 'The Economics of Large-scale Mangrove Conservation and Restoration in Indonesia' https://www.worldbank.org/en/country/indonesia/publication/the-economics-of-large-scale-mangrove-conservation-and-restoration-in-indonesia
173. For the design and objectives of the silvofisheries project, see World Bank Project Appraisal Document (2022) 'Mangroves for Coastal Resilience Project' page 29. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/793041653404341879 For a broader overview of the role of Mangroves for strengthening livelihoods and increasing resilience in the face of climate change, see Indonesia Sustainable Landscapes Management Programme (SLMP) 'Critical role of mangroves for livelihoods, resilience and climate' https://www.worldbank.org/en/programs/indonesia-sustainable-landscapes-management-program/practice For evidence of protection being derived from the newly restored mangroves, see UNDP Climate Change Adaptation (2025) 'in Indonesia, Mangrove restoration is protecting the coastline against rising sea levels' https://www.adaptation-undp.org/indonesia-mangrove-restoration-protecting-coastline-against-rising-sea-levels
174. In Shanghai an adaptive pathway has been developed in which flood defences and drainage are strengthened as risks evolve, rather than relying on a single fixed response in the face of the uncertain risks of sea level rise. See Nature Water, Tian et al (2023) 'Dynamic adaptive engineering pathways for mitigating flood risks in Shanghai' https://www.nature.com/articles/s44221-022-00017-w
175. This is according to the new UN harmonised definition of cities/urban areas. See UN Department of Economic and Social Affairs (2025) 'Latest urbanization data reveals world's most populous cities' https://www.un.org/en/desa/latest-urbanization-data-reveal-world%E2%80%99s-most-populous-cities Jakarta illustrates the interaction between sea-level rise and existing human pressures. The city is experiencing severe land subsidence, reaching up to 15cm a year in some places, and around 40% of the city is now below sea level. See NASA Earth Observatory (2024) 'Nusantara: A New Capital City in the Forest'. Note that this NASA source cites a population figure for Jakarta of 30 million, based on the older 'metro definition' as opposed to the UN's newer 'harmonised urban-area definition' Jakarta illustrates the interaction between sea-level rise and existing human pressures. The city is experiencing severe land subsidence, reaching up to 15cm a year in some places, and around 40% of the city is now below sea level. See NASA Earth Observatory (2024) 'Nusantara: A New Capital City in the Forest'. Note that this NASA source cites a population figure for Jakarta of 30 million, based on the older 'metro definition' as opposed to the UN's newer 'harmonised urban-area definition' https://science.nasa.gov/earth/earth-observatory/nusantara-a-new-capital-city-in-the-forest-152471/
176. The assessment of the causes of subsidence in Jakarta has not changed for many years. As far back as 2011 the dangers of groundwater extraction and the weight of construction were well studied and reported. See for example, Springer Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards, Abidin et al (2011) 'Land subsidence of Jakarta (Indonesia) and its relation with urban development' https://ideas.repec.org/a/spr/nathaz/v59y2011i3p1753-1771.html
177. See NASA Earth Observatory (2024) 'Nusantara: A New Capital City in the Forest'. As before, note that this NASA source cites a population figure for Jakarta of 30 million, based on the older 'metro definition' as opposed to the UN's newer 'harmonised urban-area definition' https://science.nasa.gov/earth/earth-observatory/nusantara-a-new-capital-city-in-the-forest-152471/ ; For the extent of the problem for Jakarta, and throughout Java, see Science Advances, Ohenhen et al (2026) 'Land subsidence on Java Island and its contributions to relative sea level change' https://www.science.org/doi/10.1126/sciadv.aec0172 ; For some of the impact of planning failure, see City and Environment Interactions, Hasibuan et al (2023) 'Policymaking and the spatial characteristics of land subsidence in North Jakarta' https://www.sciencedirect.com/science/article/pii/S2590252023000053
178. For a summary of the situation, see PBS News (2023) 'Why Indonesia is moving its capital from Jakarta to Borneo' https://www.pbs.org/newshour/world/why-indonesia-is-moving-its-capital-from-jakarta-to-borneo
179. A lack of funding or political commitment, combined with construction delays can undermine confidence in such a large project. See for example Guardian, Nielson (2025) 'Indonesia's new capital, Nusantara in danger of becoming a 'ghost city' https://www.theguardian.com/world/2025/oct/29/indonesia-new-capital-city-nusantara
180. For a review of how unexpected the 2008 crisis was, and an argument that the warnings were however there, see CEPR/Vox EU, Bezemer (2009) 'No one saw this coming – or did they?' https://cepr.org/voxeu/columns/no-one-saw-coming-or-did-they For a more complete and well known report on the crisis, see EconStor, Colander et al (2009) 'The Financial Crisis and the Systemic Failure of Academic Economics' https://www.econstor.eu/bitstream/10419/24885/1/593508424.PDF
181. This is the assessment of the UN Office for Disaster Risk Reduction. (UNDRR). See UNDRR (2025) 'Global Assessment Report on Disaster Risk Reduction – Resilience Pays: Financing and Investing for our Future – Executive Summary Page xi https://www.undrr.org/gar/gar2025#download
182. See Hindustan Times, Koll and Ghosh (2026) 'The case for a climate risk budget for India' in which the authors argue for climate risk to become a central consideration in all government budgeting decisions, in an attempt to get ahead of risks and disasters. https://www.hindustantimes.com/opinion/the-case-for-a-climate-risk-budget-for-india-101788194944486.html

183. For an overview of the climate-finance 'doom loop' see Finance Watch, The Blog (2025) 'Unprepared, the financial system will triple people's bills for climate change' https://www.finance-watch.org/blog/unprepared-the-financial-system-will-triple-peoples-bills-for-climate-change/
184. This is clearly argued, taking a 'systems' approach, in Earth System Dynamics, Laybourn et al (2023) 'Derailment risk: A systems analysis that identifies risks which could derail sustainability transition' https://esd.copernicus.org/articles/14/1171/2023/esd-14-1171-2023.html?ref=technosphere.earth .
185. In his speech to the BIS (which 'supports central banks' pursuit of monetary and financial stability through international cooperation') the President of De Nederlandsche Bank sets out how the use of 'scenarios' helps to address risk from climate change to the economic system. See BIS (2026) 'Climate change – the economic reality we can no longer ignore' https://www.bis.org/speeches/20261007-climate-change-economic-reality-we-can-no-longer-ignore . For a rapid overview of the gap between traditional economic modelling and the demands of climate impacts, see Oxford Martin School, Tetelboyn et al (2016) 'Climate economic models are broke, but there may be a way to fix 'em' https://www.oxfordmartin.ox.ac.uk/blog/climate-economic-models-are-broke-but-there-might-be-a-way-to-fix-em . For the importance of including potential tipping points in IAMs modelling, to challenge the discrepancies between IAMs models (which look at very high temperature change as the main possible driver of climate catastrophe) and climate science models that build in impacts of tipping points, see Climatic Change, Lenton et al (2013) 'Integrating tipping points into climate impact assessments' https://ideas.repec.org/a/spr/climat/v117y2013i3p585-597.html . Also, for an analysis of economic assessments of climate risk and policy insights into under-represented risks, see LSE Grantham Research Institute, DeFries et al (2019) 'The Missing Economic Risks in Assessment of Climate Change Impacts' Working paper https://www.lse.ac.uk/granthaminstitute/publication/the-missing-economic-risks-in-assessments-of-climate-change-impacts/ .
186. NGFS is the Network for Greening the Financial System, a group of Central Banks and supervisors seeking to capture and share best practice in the development of risk-management approaches for climate- and environment – related risk. See NGFS – 'About Us' https://www.ngfs.net/ngfs-scenarios-portal/about/ .
187. If conditions degrade further, that loss of life could reach 25% of humans, and in the extreme 50% - meaning 4 billion deaths. See risk matrix in appendix and its explanatory pages: Institute and Faculty of Actuaries and University of Exeter (2025) 'Planetary Solvency – finding our balance with nature' Page 32. For the summation of the risk in 2025, see Page 28 https://actuaries.org.uk/news-and-media-releases/news-articles/2025/jan/16-jan-25-planetary-solvency-finding-our-balance-with-nature/
188. Ibid. Page 13.
189. For data about the Great Depression, showing the US suffered levels of GDP loss in the region of 30% (at its peak), but GDP in 'advanced countries' dropped roughly 17%, see Oxford Journals, Crafts et al (2010) 'Lessons from the 1930s Great Depression' https://cooperative-individualism.org/crafts-nicholas_lessons-from-the-1930s-great-depression-2010-autumn.pdf ; for information about the 2008 global financial crisis, and its enduring impacts, see IMF Blog, Chen et al (2018) Lasting Effects: The Global Economic Recovery 10 Years After the Crisis' https://www.imf.org/en/blogs/articles/2018/10/03/blog-lasting-effects-the-global-economic-recovery-10-years-after-the-crisis
190. Again: Institute and Faculty of Actuaries (2026) 'Parasol Lost: Global Risk Management for Human Prosperity' Page 9. https://actuaries.org.uk/news-and-media-releases/news-articles/2026/jan/14-jan-26-parasol-lost-recovery-plan-needed/
191. See PNAS, Dietz et al (2021) 'Economic impacts of tipping points in the climate system' in which the authors note that climate tipping points have not generally been incorporated into climate economics. The study looks at eight potential climate tipping points and their likely economic impact. Climate tipping points increase the social cost of carbon and therefore increase global economic risk, with economic losses increased almost everywhere. https://www.pnas.org/doi/10.1073/pnas.2103081118 NOTE: Keen et al (2022) argued the Dietz et al. estimates "cannot be reconciled with the scientific literature". See PNAS, Keen et al. (2022) 'Estimates of economic and environmental damages from tipping points cannot be reconciled with the scientific literature' https://www.pnas.org/doi/10.1073/pnas.2117308119 Dietz et al. published a direct reply defending their approach as 'informative even if estimates are a probable lower bound See PNAS, Dietz et al (2022) 'Reply to Keen et al' https://www.pnas.org/doi/10.1073/pnas.2201191119
192. See, for example, how the simulated effect of climate change on sovereign credit ratings for 109 countries has shown the likelihood of credit downgrades by 2030: Management Science, Klusak et al (2023) 'Rising Temperatures, Falling Ratings' https://research-portal.uea.ac.uk/en/publications/rising-temperatures-falling-ratings-the-effect-of-climate-change-/ The ECB and EU insurance regulator have warned that the insurance gap poses risks to the economy and financial stability. See discussion paper ECB and EI & OPA (2023) 'Policy options to reduce the climate insurance protection gap' https://www.ecb.europa.eu/press/pr/date/2023/html/ecb.pr230424~a242491813.ga.html . In his 'Linked In' essay, Gunther Thallinger pulled the argument together to show how urgently speed and scale are needed in the fight against global warming. He says that 'the idea that market economies can continue to function without insurance, finance and asset protection is a fantasy. There is no capitalism without functioning financial services.' Once a critical threshold of heating is reached, he argues, risk cannot be transferred, absorbed or adapted to. See LinkedIn, Thallinger (2025) 'Climate, Risk, Insurance: The Future of Capitalism' https://www.linkedin.com/pulse/climate-risk-insurance-future-capitalism-g%C3%BCnther-thallinger-smw5f .
193. See ICE (2025) 'Ice Mortgage Monitor: Property Insurance Costs Grow 11.3% over the Last Twelve Months' https://ir.theice.com/press/news-details/2025/ICE-Mortgage-Monitor-Property-Insurance-Costs-Grow-11-3-over-the-Last-Twelve-Months/default.aspx
194. Up more than 6% from 2023, this has the hallmarks of 'quiet withdrawal'. See LendingTree, reported by NPR (2026) '2025 saw relatively fewer natural disasters. Will you get a break on home insurance?' https://www.npr.org/2026/03/09/nx-s1-5734455/home-insurance-risk-disasters-climate-change-extreme-weather
195. See Consumer Federation of America (2024) 'EXPOSED: A Report on 1.6 Trillion Dollars of Uninsured American Homes' https://consumerfed.org/news/reports/exposed-a-report-on-16-trillion-dollars-of-uninsured-american-homes/

196. In the UK, the government backed (temporary – it is meant to end in 2039) Flood Re scheme is actually a reinsurer, rather than an insurer of last resort. Insurers can pass the flood risk element of insurance cover to Flood Re in order to obtain cover for a fixed premium. See the Flood RE website for general details: FloodRe https://www.floodre.co.uk/ . In the US NFIP flood policies provide direct cover to the public, so they are insurers of last resort, although they are generally linked to the sale of private insurance policies, with the government taking responsibility for paying out the relevant losses. For general information see FEMA: Flood Insurance https://www.fema.gov/flood-insurance .
197. See for example the behaviour of insurers in The Guardian, Anonymous (2026) 'I work for a major insurer. Much of my industry is fudging the numbers in the face of the climate crisis' https://www.theguardian.com/commentisfree/2026/oct/14/climate-crisis-insurance-risk-disaster-catastrophe
198. Since 2023, insurance firm State Farm has withdrawn entirely from new property insurance in California. See State Farm (2023) 'State Farm General Insurance Company: California New Business Update' https://newsroom.statefarm.com/state-farm-general-insurance-company-california-new-business-update/
199. There is a significant insurance protection gap in developing countries. An estimated 60% to 90% of all losses arising from catastrophe are not insured. The highest rates of absent insurance are within emerging markets. See Swiss re Institute (2026) 'Sigma: Natural catastrophes in 2025: the persistent rise of wildfire and storm risk' https://www.swissre.com/institute/research/sigma-research/sigma-2026-01-natcat-2025-wildfire-storm-risk/adaptation-insurance-narrow-protection-gap.html
200. In the context of climate risk, traditional macro-financial stress testing 'based on estimated GDP impacts, may underestimate losses in adverse climate-related scenarios'. There are limitations in conventional economic modelling and specifically 'the potential for unknown and highly non-linear 'tipping points' occurring.' For this discussion, see Science Direct, Reinders et al (2025) 'Climate risk stress testing: A critical survey and classification' Introduction Page 2. https://www.sciencedirect.com/science/article/pii/S2949728025000021 There is some evidence of institutions starting to respond to the need for climate specific stress testing. The World Bank is supporting climate risk assessments in over 40 emerging/developing economies. See Financial Stability Board (2025) 'Roadmap for Addressing Financial Risks from Climate Change: 2025 update'. The report was delivered to the July 2025 meeting of the G20. https://www.fsb.org/2025/07/fsb-roadmap-for-addressing-financial-risks-from-climate-change-2025-update/
201. For example, in part 1 of this report we show how cloud research has revealed the unexpectedly large impact on the rate of global warming from modest reduction in low-cloud cover. See page X.
202. This tendency to underestimate the impact of interacting systems is captured well in Earth System Dynamics, Wunderling et al (Climate tipping point interactions and cascades: a review' https://doi.org/10.5194/esd-15-41-2024 .
203. For example, the IPCC show that almost all computations using the most advanced models end precisely in 2100; the simplified models for longer-term views allow some simulation of sea-level rise and atmospheric change. The IPCC calls 'near term' climate change as the period from 2021 – 2040. 'Long term' 2080 – 2100. Anything after that is 'very long term'. See IPPC AR6 WG1(2021) 'The Physical Science Basis' Chapter 4, especially Section 4.7, where a 'high-warming storyline' would bring about changes beyond those addressed in the longer term models. 'Irrespective of scenario, high-warming storylines imply changes in many aspects of the climate system that exceed the patterns associated with the best estimate of GSAT changes by up to more than 50% (high confidence).' Page 555 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter04.pdf .
204. The Trump administration 2026 budget request proposed cutting NASA science funding by nearly half and terminating dozens of operating Earth-science satellites. There were comparable cuts proposed to NOAA's research arm. Congress ultimately rejected most of these reductions, but the proposals show how fragile the US climate-monitoring infrastructure is to shifting political priorities. Similar proposals could happen again. For an overview of the proposed cuts, see Science (2025) 'Trump's proposed budget would mean disastrous cuts to science' https://www.science.org/content/article/trump-s-proposed-budget-would-mean-disastrous-cuts-science ; for a report of the Congress decision, see Sky and Telescope (2026) 'NASA's budget woes are over, for now' https://skyandtelescope.org/astronomy-news/nasas-budget-woes-are-over-for-now/
205. For a briefing on the state of knowledge and the need for research in relation to SRM to address 'many knowledge gaps', see The Royal Society (2025) 'Policy Briefing: Solar radiation management' – Executive Summary Page 8 https://royalsociety.org/-/media/policy/projects/solar-radiation-modification/solar-radiation-modification-policy-briefing.pdf .
206. See for example the recent assessment of Project Drawdown (2026) 'Deploy Direct Air Capture: Not Recommended' https://drawdown.org/explorer/deploy-direct-air-capture .
207. There is a recognised 'naturalness bias' when people are faced with choices. In some instances the less safe, but 'natural' option is preferred. This bias can align with science scepticism. See for example, Current Opinions in Psychology, Meier et al (2026) 'The naturalness bias' https://www.sciencedirect.com/science/article/pii/S2352250x25001563?via%3Dihub .
208. In its 2009 report on governance for geoengineering, for example, The Royal Society noted the importance of moral hazard, and the concern that 'the very discussion of geoengineering ... may weaken conventional mitigatoin efforts, or be seen as a 'get out of jail free' card by policy makers.' See The Royal Society (2009) 'Geoengineering the climate: Science, governance and uncertainty' Chapter 4 Page 37. https://royalsociety.org/-/media/policy/publications/2009/8693.pdf .
209. This idea is explored further in relation to SRM, and the conclusion is that some people will reduce and defer mitigation actions in the presence of SRM, and others will not. See Earth's future, McLaren (2016) 'Mitigation deterrence and the 'moral hazard' of solar radiation management' https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000445 .
210. For the derailment framing, asserting that 'the consequences of climate change ... and other changes to the Earth system will impact societies' ability to tackle the causes of those problems' see Earth System Dynamics (2023) 'Derailment risk: A systems analysis that identifies risks which could derail the sustainability transition' (Quote is from Abstract.) https://esd.copernicus.org/articles/14/1171/2023/ .

211. The IPCC modelling data, NASA Earth observation satellites, the UK's Met Office and British Geological Survey are all important in driving climate science, and all depend wholly or heavily on public finance. For the scope and funding of some of these, see Met Office – 'About Us' https://www.metoffice.gov.uk/about-us ; The British Geological Survey – 'About BGS' https://www.bgs.ac.uk/about-bgs/ . Until 2022, at least, public funding remained the primary driver of climate science in the US. See NCSES (2024) 'Analysis of Federal Funding for Research and Development in 2022: Basic Research' https://ncses.nsf.gov/pubs/nsf24332 .
212. In the UK there are 'UKRI Policy and Guidelines on Governance of Good Research Conduct' and the 'UK Research Integrity office (UKRIO) Code of Practice for Research'. These make standards for research explicit. See UKRI (2023) 'Review of peer review' https://www.ukri.org/publications/review-of-peer-review/ . For an overview of ethics in research (especially in medicine) in the US, see Ann Med Surg (Lond), Miteu (2024) 'Ethics in scientific research: a lens into its importance, history and future' https://pmc.ncbi.nlm.nih.gov/articles/PMC11060189/ . For a statement of agreed principles and responsibilites for fostering greater integrity in research worldwide, see World Conferences on Research Integrity (2010) 'Singapore Statement on Research Integrity' https://www.wcrif.org/guidance/singapore-statement .
213. For successful examples of collaborations, see The British Academy (2024) 'ODA Challenge-Oriented Research grants 2024: Climate Change Adaptation and Mitigation Led or Actively Involving Indigenous Peoples and Local Communities Projects' https://www.thebritishacademy.ac.uk/programmes/oda-challenge-oriented-research-grants-projects-2024-climate-change-adaptation-and-mitigation-led-by-or-actively-involving-indigenous-peoples-and-local-communities/ .
214. The World Economic Forum recently discussed the need for market incentives to be created if private sector investment is to be pulled in. See WEF White et al (2026) 'We can measure climate resilience. Why aren't we investing in it?' https://www.weforum.org/stories/climate-action-and-waste-reduction/climate-adaptation-resilience-finance
215. Make Sunsets (US founded in 2022) is actively releasing material into the atmosphere. It is exploring the use of 'cooling credits' as a commercial product. This highlights the risk of interventions to cool the Earth being seen as an alternative to managing climate change with fundamental changes human activity. Make Sunset activities have been banned in Mexico. https://makesunsets.com/?srsltid=AfmBOooIYO5f_6jsWnjnPXlcWwi2DoMPTaRNBSxbpjyqxkvwDOVP1R HJ . Stardust Solutions (US founded 2023) is explicitly seeking commercial implementation rather than experimental activities. For their plans and safety measures see https://stardustsrt.com/
216. MakeSunsets launched weather balloons that 'may have released sulfur particles in the stratosphere'. These would have been in very small quantities. Each flight carried less than 10 grammes of sulphur. By comparison a commercial flight can emit 100 grammes per minute. Mexico then moved to prohibit experiments linked to solar engineering and the company moved its launches to Nevada. The company did not engage in any public consultation. See MIT Technology Review, Temple (2022) 'A startup says it's begun releasing particles into the atmosphere, in an effort to tweak the climate' https://www.technologyreview.com/2022/12/24/1066041/a-startup-says-its-begun-releasing-particles-into-the-atmosphere-in-an-effort-to-tweak-the-climate/ ; CNBC, Clifford (2023) 'Mexico cracks down on solar geoengineering, forcing startup to pause operations' https://www.cnbc.com/2023/01/18/mexico-cracks-down-on-solar-geoengineering-stalling-make-sunsets.html ; and CNBC, Clifford (2023) 'After Mexican government cracked down on solar geoengineering, startup lets off balloons in Nevada' https://www.cnbc.com/2023/02/22/solar-geoengineering-startup-make-sunsets-lets-off-balloons-in-nevada.html
217. See, for example, SRM360 (2026) 'Beyond the Ban: A New Model for US State SRM Bills' https://srm360.org/news-article/a-new-model-for-us-state-srm-bills/ .
218. For public perception of these risks, and the influences in that thinking, see for example, Nature Communications Earth and Environment, Buck et al (2025) 'Public concerns about solar geoengineering research in the United States' https://www.nature.com/articles/s43247-025-02595-5 .
219. Mission Innovation has catalysed and coordinated funding from its 22 nation members plus the European Commission. It has supported over 1500 individual clean energy innovations, and if fully deployed these have the potential to reduce emissions by up to 21 Gigatons of CO2 per year by 2030. For overviews of Mission Innovation work, see EU (2022) 'Mission Innovation Missions' https://op.europa.eu/en/publication-detail/-/publication/d8ea93b2-b3bf-11ec-9d96-01aa75ed71a1/language-en ; and Mission Innovation (2025) 'Impact Statement from the 10th Mission Innovation Ministerial August 2025, Busan' https://mission-innovation.net/wp-content/uploads/2025/09/Impact-Statement-from-the-10th-Mission-Innovation-Ministerial_compressed-1_compressed.pdf. Also, see Mission Innovation website: https://mission-innovation.net/ .
220. The IPCC defines governance as 'a comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures'. IPCC (2022) Climate Change 2022: Mitigation of Climate Change, Annex I: Glossary. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Annex-I.pdf
221. Threat to capacity is the 'derailment risk' discussed in Part 2. For a careful guide to tackling the derailment risk so as to achieve a positive spiral, see for example, Strategic Climate Risks Initiative, Laybourn et al (2025) 'Derailment Risk: Why climate strategies might fail – and how to fix them' https://static1.squarespace.com/static/66fa5c9696c4073ff217b52f/t/68fb3e971399ce2d45eacf6b/1769699641470/Derailment+risk+report+v6.pdf.
222. Lawmakers in many US states have proposed bills that would make field research into solar radiation management or weather modification illegal. See University of Houston, Hester et al (2026) 'The Case Against Blanket Bans: A State Permitting Model for Solar Radiation Management' https://law.uh.edu/eenrcenter/SRM-Texas-White-Paper-final-20260630.pdf and SRM360, Vinders et al (2025) A Growing Number of US States Consider Bills to Ban Geoengineering' https://srm360.org/news-reaction/us-states-consider-bills-to-ban-geoengineering/ . In 2024 a Swiss proposal at the UN Environment Assembly for an expert review of the science was withdrawn after governments could not agree to it. Even a suggestion to create a repository for existing scientific information failed to find agreement. See Swissinfo, Bradley (2024) 'Nations fail to back Swiss proposal to examine solar geoengineering tech' https://www.swissinfo.ch/eng/climate-solutions/nations-fail-to-back-swiss-proposal-to-examine-solar-geoengineering-tech/73205591 In 2023 African environment

ministers expressed concern with the promotion of technologies, particularly SRM. They made a call 'for a global governance mechanism for non-use of solar radiation management.' See AMCEN 19/6 (2023) 'Report of the meeting of the nineteenth session of the African Ministerial Conference on the Environment' The relevant wording is in the Annex: Decision 19/5 Climate Change, para 15, Page 32. The decision did not reject research or funding. https://wedocs.unep.org/items/945139b0-e90d-4aa9-919c-e9c8da2d3e44 TIn 2025 the call for a governance mechanism was reiterated, by reference to the earlier decision. See AMCEN/20/Dec.9 (2025) 'Decision AMCEN/20/Dec.9: Africa's engagement at the seventh session of the United Nations Environment Assembly' Page 1. https://wedocs.unep.org/items/d0cab887-5dbc-4901-99d1-e96ec482a057 .

223. The programme sits within ARIA's 'Resilient Climate and Ecosystems' Opportunity Space, which also supports research in forecasting tipping points, accelerated adaptation and flexible funding for 'speculative and ambitious research aligned to the opportunity space.' See ARIA website: Advance Research and Innovation Agency - 'Resilient Climate and Ecosystems' – Exploring Climate Cooling https://aria.org.uk/opportunity-spaces/resilient-climate-and-ecosystems/opportunity-seeds

224. US public funding has addressed stabilisation research questions in the past, but under the current administration the shift has had to be made to private sector funding as government support has been withdrawn or dismantled. See, for example, Rethink Priorities, Clare et al (2026) 'Earth Systems Risks and the Case for Funding Stabilization Research' https://rethinkpriorities.org/research-area/earth-systems-risks-and-the-case-for-funding-stabilization-research/ ; for a review of EU engagement in stabilisation research, see EU, European Climate, Infrastructure and Environment Executive Agency (2025) 'EU Research on Earth system science' https://cinea.ec.europa.eu/publications/digital-publications/eu-research-earth-system-science_en ; for Iceland's view of the potential AMOC collapse as a security concern, see Iceland Review, Chapman (2025) 'Iceland Declares Potential Collapse of Atlantic Ocean Current a Security Threat' https://www.icelandreview.com/news/iceland-declares-potential-collapse-of-atlantic-ocean-current-a-security-threat/ ; and for the Australian efforts to stabilise the Great Barrier Reef, see for example, Reef Restoration and Adaptation Programme, Hardisty et al (2019) 'Reef Restoration and Adaptation Program – Investment Case' https://gbrrestoration.org/wp-content/uploads/2022/08/RRAP-Investment-Case_2022.pdf .

225. The report is summarised in coverage of the presentation of UK Foreign Minister to Foreign Ministers of EU and Kenya. The quote to the Guardian is also in this article. See Guardian, Harvey (2026) 'UK shares findings of damning climate crisis national security report suppressed under Starmer' https://www.theguardian.com/environment/2026/sep/23/uk-climate-crisis-national-security-report-suppressed-starmer-ed-miliband

226. In the UK, as an example, a task force was launched in 2026 to assess how climate change and nature loss might threaten national security and public preparedness. The Taskforce is led by the climate Minister and the Security Minister. See Gov.UK, Press Release (2026) 'UK launches first ever taskforce to strengthen climate security' https://www.gov.uk/government/news/uk-launches-first-ever-taskforce-to-strengthen-climate-security . The previous leader of the Ministry of Defence Climate Change and Sustainability Strategy has frequently criticised the narrow focus of defence institutions. There is a lack of imagination in understanding the severe impacts of climate change compared with standard military threats; these challenges help to push the threat of 'existential dangers' like global food supply collapse or biome failure, out of focus (and funding), whilst attention remains fixed on state-based threats and non-state terrorism. See, for example, Britain's World, Coxon (2024) 'Is climate change the most fundamental threat to British interests?' https://www.britainsworld.org.uk/p/is-climate-change-the-most-fundamental

227. For an example of a multi-country assessment of this kind, see King, D., Schrag, D., Zhou, D., Ye, Q. and Ghosh, A. (2015) 'Climate Change: A Risk Assessment', Centre for Science and Policy, University of Cambridge. It brought together institutes from China, India, the United States and the United Kingdom to assess climate risk as governments assess other national security threats. CCAG grew out of that collaboration. https://www.csap.cam.ac.uk/projects/climate-change-risk-assessment/ https://www.agu.org/ethicalframeworkprinciples

228. See World Bank Policy Research Working Paper, Ostrom (2009) 'A polycentric Approach for Coping with Climate Change' – Working Paper 5095 https://documents1.worldbank.org/curated/en/480171468315567893/pdf/WPS5095.pdf .

229. Climate and Clean Air Coalition, 'Our partners' https://www.ccacoalition.org/content/our-partners

230. For the 159 countries involved, together with European Commission, and the nature of their commitments, see Global Methane Pledge https://www.globalmethanepledge.org/

231. See Carbon Brief, Dunne (2026) 'Santa Marta: key outcomes from first summit on transitioning away from fossil fuels' https://www.carbonbrief.org/santa-marta-key-outcomes-from-first-summit-on-transitioning-away-from-fossil-fuels

232. The tripling of renewables and the doubling of energy efficiency were goals first cited in the Leaders' Declaration under India's G20 Presidency in September 2023, for example. This was before those targts were incorporated into the UAE Consensus on COP28 in Dubai in December 2023. For a press report on these targets and other outcomes of the G20 meeting, see Hindustani Times, Ghosh (2023) 'Green path to G20 development goals' https://www.hindustantimes.com/opinion/green-path-to-g20-development-goals-101694699072110.html .

233. See Nature Climate Change, Quagraine et al (2025) 'Africa must lead the governance of solar radiation management' https://www.nature.com/articles/s41558-025-02420-z

234. See The Degrees Initiative, 'Our approach' Since 2018 its funds have supported research teams in 27 developing countries: https://www.degrees.ngo/our-approach/.

235. In the field of infectious disease reliance is placed on a decentralised framework of guidelines, international law and national laws to govern research. The World Health Organisation, under the UN, sets global safety guidelines, issues frameworks for research, and also tracks global pathogens. The WHO is moving to create a 'Pandemic Agreement' to 'make the world safer and more equitable.' See WHO (2025) 'WHO Pandemic Agreement' https://www.who.int/health-topics/who-pandemic-agreement#tab=tab_1 . The nuclear energy sector is largely governed through global international frameworks: International Atomic Energy Agency for safety and safeguards; OECD Nuclear Energy Agency to facilitate and regulate legal collaboration across international research boundaries. For IAEA, see their website: https://www.iaea.org/ ; for OECD NEA, see their website: https://oecd-nea.org/.

236. See UK Research and Innovation – 'Framework for responsible research and innovation' https://www.ukri.org/who-we-are/epsrc/our-policies-and-standards/framework-for-responsible-innovation/

237. Research ethics governance is developing on a broadly similar model worldwide. Implementation varies to some degree according to the maturity of a system. For example, in South Africa the National Health Research Ethics Council (NHREC) was established under the National Health Act in 2003 (Section 72). It sets norms and standards for health research and clinical trials nationally. It registers and audits local ethics committees, and can take disciplinary action for breaches of research guidelines. 46 ethics committees are registered with the NHREC. For general overview see: BMC Medical Ethics, Moodley et al (2007) 'Health Research Ethics Committees in South Africa 12 years into democracy' https://pmc.ncbi.nlm.nih.gov/articles/PMC1794248/ and for number of committees, see: BMC Medical Ethics, Burgess et al (2023) 'Key ethical issues encountered during COVID-19 research: a thematic analysis of perspectives from South African research ethics committees' https://pubmed.ncbi.nlm.nih.gov/36793067/ In 2004 Kenya's National Council for Science and Technology issued national guidelines for the ethical conduct of biomedical research with human subjects. This was followed in 2005 with guidelines specifically for research into HIV/AIDS vaccines. See as example: Kenya Ministry of Health (2005) 'Guidelines for Research and Development of HIVAIDS Vaccines' https://www.globalgiving.org/pfil/1108/projdoc.pdf The Human Heredity and Health in Africa (H3 Africa) Consortium has worked with national ethics committees to develop a governance framework for genome research and biobanking. See: BMC Medical Ethics, Tindana et al (2019) 'Engaging research ethics committees to develop an ethics and governance framework for best practice in genomic research and biobanking in Africa: the H3Africa model' https://pubmed.ncbi.nlm.nih.gov/31623617/ . Meanwhile the Africa Centres for Disease Control and Prevention (Africa CDC) is working with AU member national ethics committees, proposing a continent-wide, Africa-centric research ethics framework. The specific arrangements for simplified multi-country research, where clearance is run at the continental level, is designed to produce consistency and nimbleness in response to public health emergencies. See: Science Direct, Fallah et al (2025) 'A call for an Africa-centric health research ethics framework: a way forward for shaping global health research' https://www.sciencedirect.com/science/article/pii/S2214109×2500097X Publicly funded research in the UK is now required to meet the requirements of the Framework for responsible research and innovation'. The framework applies the 'AREA' framework: requiring research proposals to 'Anticipate' (describing possible impacts, intended and otherwise), Reflect (think about the purposes and motivations for research – with a list of considerations including uncertainties), Engage (open up discussion, debate and dialogue about the research), Act ('Use these processes to influence the direction and trajectory of the research and innovation process itself'). See UKRI (2026) ' Framework for responsible research and innovation' https://www.ukri.org/who-we-are/epsrc/our-policies-and-standards/framework-for-responsible-innovation/. Although capacity and resources remain uneven, frameworks and processes are in place, and are rapidly evolving to meet perceived needs.

238. Wong, C.H., Siah, K.W. and Lo, A.W. (2019) 'Estimation of clinical trial success rates and related parameters', Biostatistics 20(2), 273–286: the overall probability that a drug entering phase 1 trials reaches approval is 13.8%. https://academic.oup.com/biostatistics/article/20/2/273/4817524

239. Global ambition for collective action is set out in the framework agreement of the UNFCCC: UNFCCC (1992) 'UN Framework Convention on Climate Change': https://unfccc.int/resource/docs/convkp/conveng.pdf and, in more detail, in The Paris Agreement: UNCC (2015) 'The Paris Agreement': https://unfccc.int/process-and-meetings/the-paris-agreement . The framework and agreement are built around national governments as the Parties responsible for making and implementing their climate commitments. Either in the role of coordinators or facilitators, or in the role of direct implementers, governments retain decisive levers over what happens within their borders to deliver on climate commitments.

240. See the website of Amazon Cooperation Treaty Organisation at https://otca.org/en/

241. As outlined above (Endnote 7) the African Ministerial Conference on the Environment makes collective decisions about environmental issues. A different example of a coordinated response to ethically challenging research is shown in the African Medicines Agency (AMA) Treaty. This Africa Union (AU) decision enables AU member states to coordinate joint reviews of clinical trials, building on the African Medicines Regulatory Harmonisation initiative. The Treaty came into force in 2021. See Africa Union (2021) 'Treaty for the establishment of the African Medicines Agency (AMA) enters into force' https://au.int/es/node/41138 .

242. See Article 2 'Objective' of the official UNFCCC treaty text. https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf For adoption of the objective in the Paris Agreement, see UNFCCC (2015) 'The Paris Agreement' Article 2.1 https://unfccc.int/sites/default/files/resource/english_paris_agreement.pdf .

243. As things stand, there are clear gaps in the governance structures when it comes to implementation of, for example, solar radiation modification. For research, the role of governance may be to enable and legitimise activities, and to ensure the quality and transparency of findings. See, for example, Carnegie Climate Governance Initiative, Reynolds et al (2022) 'Solar Radiation Modification: Governance gaps and challenges' https://www.c2g2.net/wp-content/uploads/202203-C2G-GovGaps.pdf .

244. Each has different reach and authority. For example, although the USA signed the 1996 London Protocol in 1998, the Senate has never ratified the provisions; nonetheless the US does implement most of its provisions. See EPA (2026) 'London Convention and London Protocol: International Treaties to Prevent Marine Pollution' https://www.epa.gov/marine-protection-permitting/london-convention-and-london-protocol-international-treaties-prevent .

245. For up to date information about SRM funding, see SRM360. They are a non-profit 'knowledge broker' gathering and publishing information about solar geoengineering. They publish information about SRM funding, most recently updated in September 2026. See SRM360 (2026) 'SRM Funding – 2026 Edition' https://srm360.org/funding-tracker/ and SRM360 (2025) 'SRM funding overview (2025)' https://srm360.org/article/srm-funding-overview/ . For an earlier (2018) funding overview, see Umweltbundesamt/German Environment Agency (2018) 'Factsheet - The research and funding landscape of solar radiation modification' https://www.umweltbundesamt.de/en/publikationen/the-research-funding-landscape-of-solar-radiation. For information

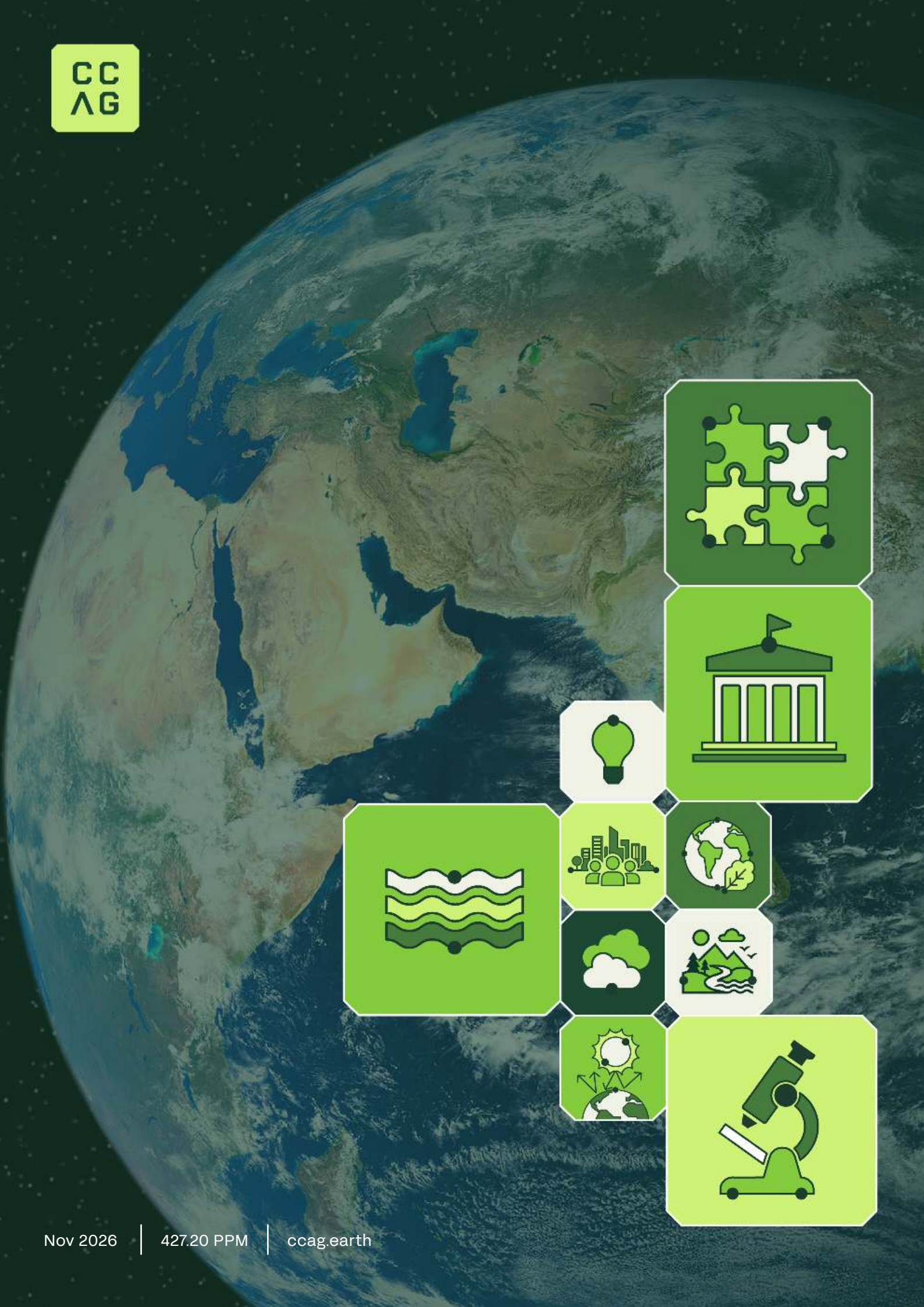
about GESAMP, see GESAMP – 'About': https://www.gesamp.org/about . For information about IPBES, see ipbes – 'About': https://www.ipbes.net/about .

246. For information about Future Earth, see futureearth – 'About': https://futureearth.org/about/ , for information about WCRP, see WCRP – 'About us': https://www.wcrp-climate.org/about-wcrp/wcrp-overview, and for information about GCOS, see GCOS – 'About' https://gcos.wmo.int/site/global-climate-observing-system-gcos .
247. Originally drafted and discussed in 2009 to 2010, the Oxford Principles were published in a journal for the first time in 2013. See Climatic Change, Heyward et al (2013) 'The Oxford Principles' https://link.springer.com/article/10.1007/s10584-012-0675-2 For the detail of the Tollgate Principles, see Ethics, Policy and Environment, Gardiner et al (2018) 'The Tollgate Principles for the Governance of Geoengineering: Moving Beyond the Oxford Principles to an Ethically More Robust Approach': https://www.tandfonline.com/doi/full/10.1080/21550085.2018.1509472 . For the position of the AGU, 'Advancing Earth and Space Science' see AGU (2024) 'Ethical Framework Principles for Climate Intervention Research': https://www.agu.org/ethicalframeworkprinciples . For their manifesto against geoengineering, see Home Alliance (2018) 'Hands Off Mother Earth (HOME) Manifesto': https://handsoffmotherearth.org/resources/hands-off-mother-earth-manifesto/
248. For the detail of these rights, see Articles 18, 19 and 32 of the UN Declaration on the Rights of Indigenous Peoples (2007). See UN Department of Social and Economic Affairs – 'United Nations Declaration On The Rights Of Indigenous Peoples' https://social.desa.un.org/issues/indigenous-peoples/united-nations-declaration-on-the-rights-of-indigenous-peoples .
249. This analysis and quote are taken from ICREA's work in local and Indigenous communities. See ICREA (2024) 'Climate change impacts on Indigenous Peoples and local communities. A global perspective through local studies.' https://www.icrea.cat/impact/outreach/scientific-highlights/944/climate-change-impacts-on-indigenous-peoples-and-local-communities-a-global-perspective-through-local-studies/ . Similarly, see Global Centre on Biodiversity for Climate (2026) 'Working with Indigenous Peoples and local communities: 8 lessons from GCBC Research' https://www.gcbc.org.uk/working-with-indigenous-peoples-and-local-communities-8-lessons-from-gcbc-research/ , https://climatepromise.undp.org/news-and-stories/indigenous-knowledge-crucial-fight-against-climate-change-heres-why
250. Ibid. Article 19 is specifically about consent
251. For a specific example, see the clash between a Harvard proposal for testing solar engineering and the Saami Peoples, over whose land the experiments were to take place. The story is summarised in: Inside Climate News, Dunleavy (2021) 'An indigenous Group's Objection to Geoengineering Spurs a Debate About Social Justice in Climate Science' https://insideclimatenews.org/news/07072021/sami-sweden-objection-geoengineering-justice-climate-science/
252. See Target 1A in UN (2015) 'Millennium Development Goals and Beyond 2015' https://www.un.org/millenniumgoals/poverty.shtml .
253. The coordination was carried out in pursuit of the UN Millennium Declaration. The way in which the Millennium Development Goals provided a shared framework for action is set out in the 'Global Summitry Project' analysis. For the Millennium Declaration, see UN (2000) 'United Nations Millennium Declaration' https://www.ohchr.org/en/instruments-mechanisms/instruments/united-nations-millennium-declaration ; for the analysis, see Global Summitry Project – 'Strengthening Global Governance Activity' https://globalsummitryproject.com/projects-home/strengthening-the-g20/ .
254. For poverty reduction, see UN (2104) 'The Millennium Development Goals Report 2014' Page 9. https://www.un.org/millenniumgoals/2014%20MDG%20report/MDG%202014%20English%20web.pdf . For child mortality reduction, see IGME/UNICEF (2025) 'Level and Trends in Child Mortality – Report 2025: Key facts and findings' Page 4. https://childmortality.org/wp-content/uploads/2026/05/UNICEF-2025-Child-Mortality-Report_Key-facts.pdf .
255. The UN Secretary General's Scientific Advisory Board warns that components of the Earth system are approaching tipping points. In 'a year of extreme events' pressure is rising across the planetary boundaries of the Earth system. See Stockholm Resilience Centre (2026) 'Planetary Health Check: Seven breached Planetary Boundaries continue to worsen, new report shows' https://www.stockholmresilience.org/research/research-stories/2026-09-21-seven-breached-planetary-boundaries-continue-to-worsen-new-report-shows.html .
256. For example, continued coastal development will worsen exposure. 7 – 14 trillion USD of coastal infrastructure will be exposed by 2100. See IPCC (2022) 'AR6 - Cross Chapter Paper 2: Cities and Settlements by the Sea' https://www.ipcc.ch/report/ar6/wg2/chapter/ccp2/ .
257. See World Bank Group (2016) 'Shock Waves: Managing the Impacts of Climate Change on Poverty' – there is a need for 'good, climate-informed development' Foreword Page xi. https://documents1.worldbank.org/curated/en/260011486755946625/pdf/Shock-waves-managing-the-impacts-of-climate-change-on-poverty.pdf .
258. See World Bank Blogs (2026) 'Who is most at risk? A global vision indicator to measure climate vulnerability' https://blogs.worldbank.org/en/developmenttalk/who-is-most-at-risk--a-global-vision-indicator-to-measure-climat .
259. This trend is long-standing. See for example the World Economic Forum noting that 'the economic injustice of climate change has already been operating for 60 years.' WEF (2019) 'Climate Action and Waste Reduction: Global inequality is 25% higher than it would have been in a climate-stable world' https://www.weforum.org/stories/climate-action-and-waste-reduction/global-inequality-is-25-higher-than-it-would-have-been-in-a-climate-stable-world . For a comparison of risk-level between wealthier countries and 46 poorest, see UNDRR (2022) 'Poorest countries at greatest risk of losses and damage from climate change' https://www.preventionweb.net/news/poorest-countries-greatest-risk-losses-and-damage-climate-change .

260. The UNEP Emissions Gap report restates the Paris Agreement aim, and says the world will exceed 1.5°C of warming for several decades. Deep cuts in emissions now could delay the overshoot, but cannot avoid it entirely. See UNEP (2025) 'Emissions Gap Report 2025' https://www.unep.org/resources/emissions-gap-report-2025 .
261. In summary, UN Trade and Development finds that 'Development is stalling. High and rising interest costs are putting the brakes on development.' See UNCTAD (2026) 'A World of Debt – Report 2026: Rising debt costs and stalling development' Overview, Slide 28. https://unctad.org/publication/world-of-debt .
262. IPCC AR6 WGII Chapter 8 found with 'high confidence' that many poor communities, especially in regions with high vulnerability and inequality, are less resilient to diverse climate impacts. These people are poor, have typically low carbon footprints but are disproportionately affected, lacking access to adaptation options. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-8/ . Climate change has already put about 9% of people (around 600 million) outside the temperature 'niche', with that number increasing as climate change progresses. The largest impact is in India, but others include Nigeria, Indonesia, the Philippines, Pakistan – and Burkina Faso and Mali. See Nature Sustainability, Lenton et al (2023) 'Quantifying the human cost of global warming' https://www.nature.com/articles/s41893-023-01132-6 .
263. These normative conclusions are reflected in the IPCC and Lenton et al sources cited above. The stability and resilience of earth systems are directly linked to human well-being in Nature, Rockström et al (2023) 'Safe and just Earth system boundaries' https://www.nature.com/articles/s41586-023-06083-8 .
264. See World Bank (2024) 'Poverty Prosperity and Planet Report' showing nearly 700 million people living in poverty. The baseline for extreme poverty was adjusted in 2025 from $2.15 US per day to $3 US per day, bringing an additional 125 million people into 'extreme poverty'. For the figures and an explanation, see Our World in Data, Hasell et al (2025) '$3 a day: A new poverty line has shifted the World Bank's data on extreme poverty. What changed, and why?' https://ourworldindata.org/new-international-poverty-line-3-dollars-per-day .
265. Most people in extreme poverty have carbon footprints under 1 tCO2 per year, compared with around 10 tCO2 per person each year, typically, in high-income countries. Lifting more than 1 billion people out of poverty leads to small increases in global emissions of 1.6%-2.1% or less. Nonetheless, carbon emissions in low- and middle-income countries in sub-Saharan Africa can more than double as an effect of poverty alleviation. See Nature Sustainability, Bruckner et al (2022) 'Impacts of poverty alleviation on national and global carbon emissions' https://www.nature.com/articles/s41893-021-00842-z . For a clear analysis of the link between extreme poverty alleviation and consumption (leading to emissions), see Nature Wollburg et al (2023) 'Ending extreme poverty has a negligible impact on global greenhouse gas emissions' https://www.nature.com/articles/s41586-023-06679-0
266. For a discussion about halving the uncertainty range of transient climate response, and how much better information about climate change is worth, see The Royal Society Philosophical Transactions A, Hope (2015) 'The $10 trillion value of better information about the transient climate' https://royalsocietypublishing.org/rsta/article/373/2054/20140429/114944/The-10-trillion-value-of-better-information-about . In a value-of-information analysis, a conference abstract concludes that every $1 invested in advanced climate observing systems returns roughly $50. See Cooke et al (2020) 'Market-based methods for monetising uncertainty reduction' https://ideas.repec.org/a/spr/envsyd/v40y2020i1d101007_s10669-019-09748-w.html . Finally, the classic valuation study estimates that early information is worth $1.5 – 2 billion for each year that resolution of uncertainty is brought forward and that damages and abatement costs account for about 75% of the value of improved knowledge. See The Energy Journal, Nordhaus et al (1996) 'What is the value of scientific knowledge? An Application to Global Warming Using the PRICE Model' – Cowles Foundation Discussion Paper https://ideas.repec.org/p/cwl/cwldpp/1117.html .
267. The initiative would 'explore the decision space.' See AIP Science Policy News, Schwarber (2021) 'Academies Panel Proposes Cautious Geoengineering Research Initiative' https://www.aip.org/fyi/2021/academies-panel-proposes-cautious-geoengineering-research-initiative ;
268. See CPD News, Swiss RE (2021) 'World Economy Set to Lose Up To 18% GDP From Climate Change if No Action Taken, Reveals Swiss RE Institute's Stress-Test Analysis' https://www.fanews.co.za/article/company-news-results/1/swiss-re/1254/world-economy-set-to-lose-up-to-18-gdp-from-climate-change-if-no-action-taken-reveals-swiss-re-institute-s-stress-test-analysis/31740 .
269. For an overview of 'sovereign risk pooling', see World Bank (2017) 'Sovereign Catastrophe Risk Pools: A World Bank Technical contribution to G20' https://www.gfdrr.org/sites/default/files/publication/WB%20DRFIP_Cat%20Risk%20Pool%20for%20G20_full%20report.pdf .
270. See WEF, Henry (2025) 'How catastrophe bonds help manage climate risks' https://www.weforum.org/stories/global-risks/catastrophe-bond-insurance-climate-crisis/
271. A proposed public backstop is explicitly framed as transforming climate risk 'from a largely unmanaged threat into a somewhat more predictable macroeconomic variable'. Bruegel, Grabbe et al (2026) 'Planning for the rising fiscal costs of climate disaster' Section 4.4 'Supranational coordination and risk pooling' https://www.bruegel.org/policy-brief/planning-rising-fiscal-costs-climate-disasters
272. See CCRIF (2025) 'CCRIF Provides US$91.9 Million in Payouts to Jamaica Following Hurricane Melissa' https://www.ccrif.org/ccrif-provides-us919-million-payouts-jamaica-following-hurricane-melissa-strengthening-recovery-and?language_content_entity=en .
273. See Global Commission on Adaptation (2019) 'Adapt Now: A Global Call for Leadership on Climate Resilience' Page 5. https://gca.org/about-us/the-global-commission-on-adaptation/
274. See Swiss Re (2021) 'World economy set to lose up to 18% GDP from climate chagne if no action taken, reveals Swiss Re Institute's stress-test analysis' https://www.swissre.com/media/press-release/nr-20210422-economics-of-climate-change-risks.html .
275. The International Court of Justice (ICJ) Climate Advisory Opinion confirms that states face legal consequences and potential reparations if they fail to protect the environment and mitigate climate change. The court validated the 1.5°C temperature target as a definitive legal benchmark under international law, and declared that the failure to regulate GHG emissions, the maintenance of harmful fossil fuel subsidies, or ignoring climate

due diligence was an internationally wrongful act. The court linked climate inaction directly to violations of fundamental human rights in the right to life, health and a clean environment. See ICJ (2025) 'Obligations of States in Respect of Climate Change' https://www.icj-cij.org/sites/default/files/case-related/187/187-20250723-adv-01-00-en.pdf . In May 2026, the UN General Assembly formally adopted a resolution that operationalises the ICJ decision within the UN framework, calling on all member states to comply with their international obligations. See UN News ((2026) 'General Assembly backs historic World Court climate ruling' https://news.un.org/en/story/2026/05/1167561 .

276. For an analysis showing that the least developed countries contributed less than 0.4% of historical CO2 emissions from fossil fuels and industry between 1850 and 2019, see IPCC AR6 WGIII (2022) 'Summary for Policymakers' – Section B3 https://www.ipcc.ch/report/ar6/wg3/chapter/summary-for-policymakers/ .
277. For example, The UN Framework Convention on Climate Change (1992) Article 3.1 talks about 'common but differentiated responsibilities and respective capabilities'. The Paris Agreement (2015) Article 2.2 adds 'in the light of different national circumstances'. See UN (2019) 'Framework Convention on Climate Change' https://unfccc.int/resource/docs/convkp/conveng.pdf ; and UNFCCC (2015) 'The Paris Agreement' https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf .
278. The specific commitments are in the Paris Agreement – finance at Article 9, loss and damage in Article 8, technology in Article 10 and so on. Developed countries take the lead in emissions cuts in Article 4.4. See UNFCCC (2015) 'The Paris Agreement' https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf . For the legal significance, and commitments to the global community, see International Court of Justice Advisory Opinion of 23 July 2025, adopted unanimously. The Court found that states have binding obligations under international law to protect the climate system. See ICJ (2025) 'Obligations of States in Respect of Climate Change – Advisory Opinion' https://www.icj-cij.org/sites/default/files/case-related/187/187-20250723-adv-01-00-en.pdf .
279. The UN Framework Convention on Climate Change (1992) Article 4.7 makes the point that developing countries' ability to implement their commitments depends on developed countries meeting their commitments on finance and technology transfer, and that social development and poverty eradication are the first and overriding priorities of developing countries. See UN (1992) United Nations Framework Convention on Climate Change' - Article 4.7 Page 8: https://unfccc.int/resource/docs/convkp/conveng.pdf
280. The IPCC AR6 WGII Summary for Policymakers explains that adaptation gaps are largest among lower-income populations and that financial, governance, institutional and policy constraints limit what can be done: small fragmented programmes focus on conditions now or near-term risks. Planning is more prevalent than implementation. There is specific argument that implementation gaps are partially driven by disparities between costs of adaptation and finance allocated to adaptation. See IPCC AR6 WGII 'Summary for Policymakers' – Section C1 Page 20 https://www.ipcc.ch/report/ar6/wg2/chapter/summary-for-policymakers/
281. Capacity building for developing countries is expressly addressed in the Paris Agreement. Article 11 says capacity building should be country driven, respond to national needs and foster country ownership. See UNFCCC (2015) 'Paris Agreement' Page 15: https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf The Paris Declaration on Aid Effectiveness offers practical action-oriented roadmap to improve the quality of aid and its impact on development. Accountability is placed on both the donors and the recipients of support. See OECD (2005) 'Paris Declaration on Aid Effectiveness' https://www.oecd.org/content/dam/oecd/en/publications/reports/2005/03/paris-declaration-on-aid-effectiveness_g1g12949/9789264098084-en.pdf .
282. In the 1860s the Irish scientist Tyndall established that certain gases in the atmosphere trap energy radiated from the surface of the earth, preventing heat from escaping to space. The Greenhouse gases – GHGs - are carbon dioxide, methane and nitrogen oxides, with water vapour acting as a further powerful amplifier of warming. Of the GHGs, carbon dioxide and methane are directly produced by human activity. Since the industrial revolution fossil fuel use has increased levels of CO_2 in the atmosphere from the pre-industrial baseline of ~200–270 parts per million (ppm) that prevailed for the previous million years (oscillating between ~200ppm in ice ages to ~270 ppm in warm periods). CO_2 levels today are ~430ppm, and still rising rapidly. Methane levels from human activity have risen rapidly over recent decades. Methane per unit weight, or per molecule, is a considerably more powerful GHG than CO_2. To add GHGs together the convention is to convert gases to their potency relative to CO_2: methane is around 130 times more effective as a GHG than CO_2. The practice is usually to further modify this number to allow for GHG's lifetime in the atmosphere. Methane's lifetime averages 10 to 12 years, whilst CO_2 remains in the atmosphere for beyond 100 years. At any point in time, it is the existing level of GHGs in the atmosphere that determines the amount of energy captured, so the instantaneous level of GHG impact is more helpful than the notional level that would exist after a number of years from the moment when the measurement is taken. Methane levels in the atmosphere right now, combined with current CO_2 levels, give around 550 ppm CO_2eq in the atmosphere today. Human activity has doubled the amount of radiation captured by the atmosphere: this is the driver of global warming. Water vapour is also a very efficient GHG. The amount of water vapour in the atmosphere increases as the earth's temperature rises: and as ocean surface temperatures are increasing rapidly, water vapour pressure above the oceans (72% of the earth's surface) is also increasing. The increased humidity accelerates global warming further, in the form of a positive feedback from fossil fuel burning.



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