

CLIMATE ANALYTICS

Climate overshoot:

The way back below 1.5°C

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Authors

Bill Hare, Marcia Rocha, Richard Black, Gabriela Cangussu, Claudio Forner, Neil Grant, Johannes Honneth, Alicia Hou, Anna Kanduth, Zarrar Khan, Uta Klönne, Danial Riaz, Michiel Schaeffer, Dimitris Tsekeris, Lara Welder

About Climate Analytics

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

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Summary

Overshoot is unavoidable, but how high and how long is still in our hands. Human-induced warming reached 1.37°C in 2025. Unless there is a step change in action, the world is heading towards a permanent overshoot with global warming of at least 2.6°C by 2100. Decisions taken this decade will shape the size of the overshoot and how soon it ends.

Limiting how high and long the overshoot is and getting back below 1.5°C by 2100 has to be the goal. The Paris Agreement, the International Court of Justice and COP decisions give countries a clear basis for acting with the highest possible ambition.

No country is safe, and those who contributed least to climate change are hit first and hardest. Small island states already lose 1–9% of GDP a year to climate-related impacts, and an estimated 50,391 heat-related deaths occurred in 854 European cities in summer 2026.

Every tenth of a degree avoided protects lives. Record-breaking heat over land is already more than four times as frequent as in pre-industrial times; with warming at about 1.2°C by 2100, it would be less frequent than today.

A lower and shorter overshoot limits damage that builds over time. The rate of sea-level rise has more than doubled since satellite measurements began, and marine heatwave days have more than tripled since 1991.

Bringing warming back below 1.5°C by 2100 offers an escape window for some tipping points. Coral reefs, the West Antarctic ice sheet, the Amazon and the Atlantic overturning circulation are at risk, but the lower the peak and the faster warming falls, the better the chance of avoiding tipping.

Warming can still return below 1.5°C by 2100. If emissions fall as fast as is feasible – our highest possible ambition pathway – warming peaks at around 1.7°C around 2040 and falls to about 1.2°C by 2100. Eleven Very Low emissions pathways reach a median of about 1.3°C.

The next decade can set the course for the century. Cutting emissions by 49% by 2035, from 2025 levels, largely decides the peak warming. Reaching net zero CO_2 by mid-century or before would stop warming, and reaching net zero greenhouse gases around the 2070s or before, would bring it back below 1.5°C by 2100.

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1 Introduction

1.1 Where we are

Overshooting 1.5°C is now unavoidable (United Nations Environment Programme, 2026). In 2024, global mean temperature exceeded 1.5°C above pre-industrial levels over a full calendar year for the first time, and 2025 was the second or third warmest year on record, at around 1.43°C above pre-industrial levels (WMO, 2026b). Individual years are influenced by natural variability, such as El Niño; the Paris Agreement's 1.5°C limit refers to long-term warming, typically assessed as a 20-year average, and human-induced warming was estimated at around 1.37°C in 2025 (Forster et al., 2026). On current trends, long-term warming is expected to reach 1.5°C around 2030 or in the early 2030s (United Nations Environment Programme, 2026) (Climate Analytics, 2026c).

This situation is the result of political choices, not physical constraints. Global greenhouse gas (GHG) emissions in 2025 remained close to their 2019 level, roughly a quarter above the level assumed in the 1.5°C pathways assessed by the IPCC (Climate Analytics, 2026c). Yet the means to cut emissions much faster have been available throughout. In 2022, the IPCC found that mitigation options costing USD 100 per tonne of CO_2-equivalent or less could reduce global emissions by at least half of the 2019 level by 2030, with more than half of this potential available at under USD 20 per tonne (IPCC, 2022c). Since then, renewable energy and other zero-carbon technologies have become cheaper and more competitive than anticipated (Climate Analytics, 2026c). Yet emissions have barely fallen. Had globally coordinated action begun in 2020, as the AR6 pathways assumed, warming could have been held to 1.5°C with no or limited overshoot.

1.2 The 1.5°C limit endures — in law, in science, and in equity

The 1.5°C limit is anchored in the Paris Agreement, reinforced by key decisions of the Parties to the Agreement, by the International Court of Justice and by science.

Article 2.1 sets the goal of holding the increase in global average temperature to well below 2°C and pursuing efforts to limit it to 1.5°C, "recognizing that this would significantly reduce the risks and impacts of climate change." Article 2.1 sets **one integrated long-term temperature goal** – 1.5°C is the *limit*, while "well below 2°C" functions as the outer boundary that must *always* be respected.

Article 4.1 sets out how the long-term temperature goal is to be achieved: a global peaking of emissions as soon as possible, rapid reductions thereafter in accordance with the best available science, and a balance between emissions and removals in the second half of the century (Paris Agreement, 2015). Article 4.1 opens with the words "In order to achieve the long-term temperature goal," so the timing of that balance – net zero

greenhouse gas emissions globally – cannot be read in a way that puts the 1.5°C *limit* out of reach.

With overshoot of 1.5°C by around 2030 now unavoidable, this timing matters even more. Due to the lack of action in the last decades, limiting warming below ~1.7°C appears no longer feasible. In scientific terms, because holding warming "well below 2°C" means peak 21st century warming should be below 1.6°C (see Box 2), the overshoot situation means that the world is no longer able to hold warming below this level.

Nevertheless, as this report shows, it is still possible to limit warming below 1.5°C by the end of the century with a likely or greater probability, with warming falling from peak levels around 1.7°C in mid-century. It is hard to argue that this limit should not be achieved with a likely or greater probability to give substantive meaning to the Paris Agreement limit.

To bring this about, the earlier net zero greenhouse gas emissions are achieved globally in the second half of the century, the further warming can fall by 2100 (see Chapter 3).

In its 2025 advisory opinion, the International Court of Justice gave the 1.5°C limit new legal force. The Court identified the reports of the IPCC as the best available science on climate change (para. 74).

It accepted that anthropogenic GHG emissions are "unequivocally the dominant cause" of observed warming, and that significant harm to the climate system and other parts of the environment has already been caused as a result (para. 437) (International Court of Justice, 2025).

The Court found that decisions by the Parties, namely the Glasgow Climate Pact and the first Global Stocktake outcome, reinforcing the centrality of the 1.5°C limit, are crucial for understanding how the Paris Agreement should be interpreted, under Article 31(3)(a) of the Vienna Convention on the Law of Treaties. It concluded that "1.5°C has become the scientifically based consensus target under the Paris Agreement," and therefore considered the 1.5°C threshold to be the Parties' agreed primary temperature goal, an interpretation it found consistent with the requirement in Article 4.1 that mitigation be based on the best available science (para. 224) (International Court of Justice, 2025).

The Court also made clear that NDCs are not a matter of "unfettered discretion" (para. 239) and must together be capable of contributing to limiting warming to 1.5°C. In this context Parties have only "limited" discretion in preparing them (para. 245). NDCs must:

- become progressively "more demanding over time" (para. 241);
- reflect each Party's "highest possible ambition", capable of making an adequate contribution to limiting warming to 1.5°C (para. 242);
- be informed "by the outcome of the Global Stocktake" (para. 243); and
- taken together, be "capable of achieving the temperature goal of limiting global warming to 1.5°C" (para. 245).

Failure to meet these obligations is a breach of international law rather than a question of political choice.

The Court further stated that a State's failure to take appropriate action to protect the climate system, "including through fossil fuel production, fossil fuel consumption, the granting of fossil fuel exploration licences or the provision of fossil fuel subsidies," may constitute an internationally wrongful act (para. 427) (International Court of Justice, 2025).

Since the 2025 ICJ Advisory Opinion, Parties have continued to consolidate the understanding around the 1.5°C limit.

The COP30 Global Mutirão decision, adopted four months after the Court's opinion, reiterates their resolve "to pursue efforts to limit the temperature increase to 1.5°C, to limit both the magnitude and the duration of any temperature overshoot, and to close adaptation gaps" (para. 7) (UNFCCC, 2025).

The decision makes clear that 1.5°C is the limit against which overshoot is measured: it is the only temperature named in the passage, and the decision elsewhere refers to "1.5°C with no or limited overshoot" (see Box 1).

It also sets the direction after the peak: an overshoot is by definition temporary, so limiting its duration means bringing warming back below 1.5°C as soon as possible.

The legal and ethical case for keeping 1.5°C as the operative limit after it is exceeded has been set out by Rogelj and Rajamani (2025). They argue that its legal and policy implications apply continuously before, at and after the threshold is crossed, and that exceeding 1.5°C intensifies the obligations on States, because every 0.1°C of additional peak warming increases loss and damage and the risk of triggering major tipping points (Rogelj & Rajamani, 2025).

It is clear from the science and the law that States can and should continue to pursue 1.5°C-aligned emissions pathways after 1.5°C is exceeded, with the long-term focus shifting to a net-negative emissions economy that minimises both the magnitude and the duration of overshoot and brings temperatures back below 1.5°C within this century.

The 1.5°C limit was not defined based on feasibility, but on what was needed to minimise harm to the most vulnerable countries, and it was a central part of the equitable outcome of the Paris Agreement (Climate Analytics, 2025b).

The scientific case for it has since grown stronger.

As the Court noted, risks and related loss and damage "will escalate with every increment of global warming" (International Court of Justice, 2025), and 1.5°C is increasingly understood as a physical limit to avoid, or reduce the risk of, crossing major tipping points (Climate Analytics, 2025b) (see Chapter 2).

Limiting warming to 1.5°C with likely or greater probability therefore remains the benchmark for climate action, from the global to the local level. Whilst this limit may matter the most for the most vulnerable countries, including Small Island Developing States (SIDS) and Least Developed Countries (LDCs), as this report shows even the

largest emitters face extreme risks unless overshoot is strictly limited in magnitude and duration and warming brought back below 1.5°C by 2100.

Box 1: The Paris Agreement temperature goal: its precursors and what followed

The EU adopted 2°C as a goal in 1996, and in 2009 the G8 and the Major Economies Forum "recognised" the scientific view that warming ought not to exceed this warming level.

Based on the IPCC AR4, Small Island Developing States and Least Developed Countries considered that the risks identified at 2°C for them were existential, and hence 2°C was not a safe level.

At Poznan in 2008, the Alliance of Small Island States called for warming to be limited to 1.5°C, and by the Copenhagen climate conference in 2009 around 100 countries supported that call, under the banner "1.5 to stay alive." The Copenhagen Accord set out, and the Cancún Agreements (decision 1/CP.16) formally adopted, the goal of holding warming below 2°C, but critically mandated a review of whether to strengthen it in relation to 1.5°C.

The review's Structured Expert Dialogue (SED) concluded in 2015 that the view that 2°C is safe "is inadequate." On 1.5°C, the SED found that limiting warming to below that level "would come with several advantages compared with limiting it to below 2°C" and would "come closer to a safer guardrail" (UNFCCC, 2015).

In December 2015, the Paris Agreement included the long-term temperature goal with its 1.5°C limit, and the requirement to get to net zero in the second half of the century to operationalise this.

Along with the adoption of the Paris Agreement at COP21, Parties requested an IPCC Special Report on 1.5°C (Decision 1/CP.21) (Paris Agreement, 2015).

Published in 2018, the SR1.5 defined 1.5°C pathways as those that stay below it or return below it after a limited overshoot of ~0.1°C, consistent with holding warming well below 2°C (IPCC, 2018). The IPCC's Sixth Assessment Report built this into its scenario categories to include Paris-compatible pathways that limit warming to 1.5°C with no or low overshoot, achieve net zero GHGs before 2100 and have warming below 1.5°C in 2100 with a likely or greater probability (IPCC, 2022b).

In the Glasgow Climate Pact of 2021, Parties recognised that impacts would be "much lower" at 1.5°C than at 2°C and resolved to pursue efforts to limit warming to that level (decision 1/CMA.3) (UNFCCC, 2021).

The first Global Stocktake in 2023 set out what 1.5°C with no or limited overshoot requires: cuts of 43% by 2030 and 60% by 2035 from 2019 levels, and net zero CO_2 by 2050. It also encouraged Parties to align their NDCs with 1.5°C (decision 1/CMA.5) (UNFCCC, 2023).

Most importantly, the first Global Stocktake outcome called on Parties to transition away from fossil fuels in energy systems in a just, orderly and equitable manner, explicitly framing this as action required in line with 1.5°C pathways.

In 2024, the International Tribunal for the Law of the Sea took 1.5°C as its benchmark. In 2025, the International Court of Justice called it the Parties' primary temperature goal, relying in part on the Glasgow and Stocktake decisions.

At COP30 in 2025, the Global Mutirão decision addressed overshoot directly (see main text), resolving "to pursue efforts to limit the temperature increase to 1.5°C, to limit both the magnitude and the duration of any temperature overshoot, and to close adaptation gaps." It reiterated the first Global Stocktake's emissions cuts for "1.5°C with no or limited overshoot;" launched the Global Implementation Accelerator, to help "keep 1.5 °C within reach" (para. 41), and the Belém Mission to 1.5 (para. 42); and recalled with concern that the carbon budget consistent with the temperature goal "is now small and being rapidly depleted" (UNFCCC, 2025).

1.3 What rescuing 1.5°C means now

Articles 2.1 and 4.1 of the Paris Agreement were designed to work together: warming would peak close to 1.5°C around mid-century and then decline to below 1.5°C by 2100 (Climate Analytics, 2025b). The decline after the peak is therefore not an optional extra, but part of how the Agreement's temperature goal was meant to be achieved.

A decade of insufficient action has made overshooting 1.5°C unavoidable (Section 1.1; Climate Analytics, 2025c). Articles 2.1 and 4.1 continue to provide operational guidance on the level and rate of emission reductions needed to reduce the overshoot, and there is a strong legal argument that exceeding 1.5°C increases the obligation on all Parties to act with the highest possible ambition (Climate Analytics, 2025b), an emerging legal norm (Mayer, 2024). This is consistent with the finding of the International Court of Justice that NDCs must reflect each Party's highest possible ambition and, taken together, be capable of limiting warming to 1.5°C (Section 1.2).

In an overshoot world, acting consistently with these obligations means:

- keeping the peak as low as possible;
- keeping the time spent above 1.5°C as short as possible;
- bringing warming back below 1.5°C, and ideally well below, by 2100; and
- continuing to cool after 2100.

That last element matters. Sustained warming of 1.5°C is too high for the polar ice sheets: limiting the risk of multi-metre sea-level rise in the coming centuries requires warming to be brought back towards around 1°C (Stokes et al., 2025). Emissions to 2020 have already committed the world to around 29 cm of sea-level rise; continuing current policies to 2090 would lock in an additional 79 cm by 2300, whereas reducing emissions in line with 1.5°C would cut this to around 15 cm (Nauels et al., 2025). This report does not model the period after 2100, but the long-term direction of travel is clear.

1.4 About this report

This report sets out what it would take to rescue 1.5°C, and why it matters more than ever. Chapter 2 reviews the latest science on rising impacts and risks, from tipping points and sea-level rise to the impacts facing major emitters and the most vulnerable countries, and shows why the height, length and rate of the overshoot all matter. Chapter 3 draws on the latest pathways, including Climate Analytics' Highest Possible Ambition scenario and a new generation of Very Low pathways, to show how warming can still be brought back below 1.5°C and what sets the peak and the decline. Chapter 4 turns to the solutions, centred on a rapid phase-out of fossil fuels through electrification, renewables and efficiency, together with faster methane cuts, carbon dioxide removal and finance, and to the real-world progress already under way.

2 Overshoot brings higher impacts and risks

Overshooting 1.5°C leads to many impacts escalating and risks triggering catastrophic events and tipping points, and these increase with both the magnitude and duration of the overshoot. Increasing damages will continue to happen at an accelerating rate throughout the globe, but are especially acute for vulnerable countries and communities, particularly SIDS and LDCs.

Overshoot has deleterious effects on human health, productivity and livelihoods. Ecosystems and biodiversity are also affected. Every additional 0.1°C of warming increases heat exposure, heat extremes, sea levels and tipping point risks, for example (Lenton et al., 2025); (Möller et al., 2024). Many of the impacts are irreversible or show no sign of reversibility within multi-centennial timescales. Ice sheets and glaciers, for example, will only have a chance of recovering once warming approaches 1°C in the 22nd century.

Every increment of warming above 1.5°C adds to the damage, and returning to 1.5°C after the overshoot will not be enough. Sustained warming at 1.5°C would keep ice sheets exposed to conditions at or near their critical thresholds (Stokes et al., 2025). It would also hold the Amazon at the limit of its suggested safe boundary for warming, when deforestation has already passed the 10% suggested as safe (Flores et al., 2024). Meanwhile, damage to the ocean keeps building for centuries (Morée et al., 2025). Temperatures therefore need to keep falling, to below 1.5°C this century and towards 1°C thereafter (Ritchie et al., 2026).

Human-induced warming triggers positive carbon cycle feedbacks from permafrost, wetlands, boreal forests and wildfires, which emit further carbon dioxide and methane and amplify the warming itself. There is already an observed weakening of the land sink, principally forests, which appears to be driven by heat, drought and fire. These feedbacks are likely to scale directly with the level and duration of warming.

Every year of earlier peak temperature and every fraction of a degree of faster decline after that peak reduces carbon cycle feedbacks and stabilises them. Meanwhile, stabilising warming at 1.5°C sustains and compounds them indefinitely.

Urgent mitigation action can minimise risks and make adaptation possible in the first place, substantially reducing its costs (Theokritoff et al., 2025) and maintaining the effectiveness of adaptation strategies. Adaptive capacity erodes during overshoot (Al Khourdajie et al., 2026). Overshoot might drive hard limits to be reached (C.-F. Schleussner et al., 2024), making adaptation more difficult, costlier and less effective.

This chapter sets out the evidence for why limiting the magnitude and duration of overshoot, together with bringing warming below 1.5°C, and ideally well below, by the

end of the century, is essential. It does so drawing on the latest science on heat extremes, sea-level rise and ocean impacts, tipping points, and impacts on major emitters and the most vulnerable countries.

2.1 Heat extremes

Every increment of warming sharply increases deadly heat, and overshooting 1.5°C is projected to add substantially to the toll (Lüthi et al., 2023). The frequency of a one-in-a-hundred-year monthly temperature extreme at 1.5°C of warming would increase by a factor of ten at 2°C, to become a one-in-ten-year event. Heat-mortality extremes will eventually become the norm if no adaptation occurs. Already at close to 1.5°C warming, we are seeing ever more heat records broken: August 2026 was the joint warmest month ever recorded, tied with July 2023. Monthly global average temperature reached 1.65°C above pre-industrial levels (Copernicus, 2026).

SIDS are among the most exposed to the health impacts of heat. During the record-breaking summer heat of 2023 alone, infants (i.e., aged 1 year or younger) experienced 48 times more heatwave days than the annual averages for 2000–2004 (Gordon-Strachan et al., 2025).

Across Asia and the Americas, historical climate change has increased dengue incidence by 18% (11 - 27%) on average, and future warming could further increase it by 49% (16-136%) to 76% (27-239%) by mid-century for low or high emissions scenarios, respectively, compared to a pre-industrial baseline (Gordon-Strachan et al., 2025).

If global warming is not halted, large parts of the world's population will face heat beyond the limits of human survival. At 1.5°C, nearly 25% of the world's population, including much of South Asia, parts of sub-Saharan Africa, Latin America, and northern Australia, would be exposed to combinations of heat and humidity at which humans cannot survive without cooling assistance such as air conditioning. Exposure increases rapidly with further warming, so periods of lethal heat would occur even more often and could overtake more than half the world's population at 3°C (Fischer et al., 2025).

Heat also amplifies other extremes. When flash droughts are accompanied by extreme heat, they exhibit 6.7–90.8% higher severity and 8.3–114.3% longer recovery time than flash droughts without extreme heat (Gu et al., 2025).

Children born today, and the most vulnerable, will bear the greatest burden. Under a 2°C pathway, around 80% of people born in 2020 will experience unprecedented lifetime exposure to heatwaves, compared to 52% under a 1.5°C pathway (L. Grant et al., 2025). Heat already affects health from the start of life: a cumulative increase of 150°C in extreme heat exposure during the nine-month pregnancy period is associated with two additional neonatal deaths per thousand live births (T. Wang et al., 2025). This particularly affects mothers of low socioeconomic conditions. Heatwaves are also associated with accelerated ageing, with more pronounced impacts for manual workers,

rural residents and participants from communities with less access to air conditioners, and thus less ability to adapt (Chen et al., 2025).

The magnitude of overshoot matters greatly for heat. For example, warming of 1.7°C rather than 1.5°C by 2050 could increase the number of people exposed to heatwaves by around one third in a number of different countries across the world. Warming of 1.8°C in 2050 increases these numbers by a further 10% or more (CONSTRAIN, 2022).

Limiting peak warming to 1.5°C will limit the increase in heat exposure to a minimum and, importantly, as global warming drops from peak levels in Paris-aligned pathways, this exposure will decline towards the end of the century. Peaking warming before mid-century is needed to reduce unprecedented heat exposure (Fischer et al., 2025).

The current level of global warming of about 1.3-1.4°C has made record-breaking daily maximum temperatures over land more than four times more frequent (2016–2024) compared to the pre-industrial period. Under a warming scenario close to current policies that warms by 2.7°C by 2100 (SSP2-4.5), such extreme heat records could occur 7.3 times more frequently. In contrast, limiting 2100 warming to 1.2°C as in the SSP1-1.9 scenario is projected to reduce exposure to levels lower than those observed today, about 1.8 times the pre-industrial baseline (Fischer et al., 2025).

A very strong finding from Fischer et al. (2025) is that the probability of record-shattering heat extremes is highly dependent on the rate or speed of warming. Slowing the warming trend leads to a reduction in the frequency of record-breaking heat events, and stabilisation of temperatures leads to a rapid reduction. This means that benefits in terms of reduced frequency of record-breaking heat extremes could be observed relatively quickly if the rate of warming is slowed, as would be expected under a Paris-aligned pathway.

2.2 Sea-level rise and ocean impacts

2.2.1 Sea-level rise

Sea-level rise is not a distant projection, but an accelerating reality. The higher the peak warming and the longer the duration of overshoot, the worse it will be. The rate of rise has more than doubled since satellite measurements began, reaching 4.5 mm per year in 2024 compared to 2.1 mm per year in 1992, averaging 3.94 mm per year over 2005–2023 (Zheng et al., 2026).

Around 75% of the current acceleration in sea-level rise is attributable to the loss of ice mass from Greenland, Antarctica, and mountain glaciers, with thermal expansion of warming ocean waters accounting for the remaining quarter (Dangendorf et al., 2024). Mountain glaciers and ice caps are exhibiting particularly sharp and recent acceleration.

Since 2000, the observed loss in mountain glacier ice mass is globally about 5%, with regional losses ranging from 2% to 39% (Zemp et al., 2025). Around 2% of mountain glacier mass is lost, effectively permanently, for each 0.1°C of overshoot (Zekollari et al., 2025) and glacier mass preservation is doubled on a Paris-aligned pathway, at 54%

instead of 27% under current policies (Zekollari et al., 2025) (Van Tricht et al., 2026). Regrowth can only happen with lower levels of warming by the end of the century (Schuster et al., 2025).

If the presently observed acceleration continues, sea-level rise rates are projected to reach 5.0 mm per year by 2030, 5.8 mm per year by 2040, and 6.5 mm per year by 2050 — with a rate of over 10 mm per year possible by 2100. With this acceleration, a sea-level rise of approximately 66 cm above 1993 levels can be expected (Hamlington et al., 2024). This is well within the range of the sea-level rise expected under a pathway similar to current policies that warms the world by about 2.7°C above preindustrial by 2100 (SSP2-4.5), which leads to 60 cm by 2100 relative to 1993.

An emission pathway similar to a Paris-aligned pathway that peaks global warming around 1.5-1.6°C by mid-century and has it back to about 1.2°C by 2100 (SSP1-1.9) is projected to lower 2100 sea-level rise by about 18 cm to ~42 cm, compared to current policies (SSP2-4.5).

Polar ice sheets (Greenland and West Antarctica) are already vulnerable at current levels of global warming (1.3°C)(Rosser et al., 2024). Sustained warming even at the current level is likely to generate several metres of global mean sea-level rise over coming centuries. This means that warming stabilised at 1.5°C is already too high for them (Stokes et al., 2025), and would lock in multi-metre sea-level rise. This risk could be substantially reduced if warming is brought towards 1°C in the 22nd Century from peak levels this century.

Global Mean Sea Level: Observations vs. IPCC AR6 Scenarios.

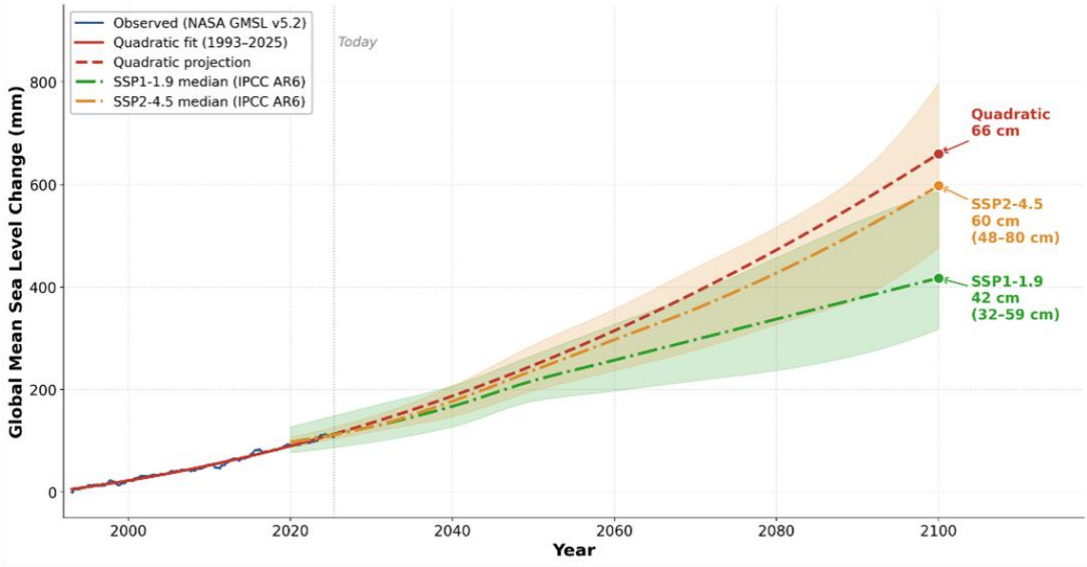


Figure 1: Observed global mean sea level compared with IPCC AR6 scenarios. Source: Climate Analytics.

Minimising the risk of multi-metre sea-level rise in the longer term requires bringing global warming back towards a maximum 1°C above pre-industrial times (Stokes et al.,

2025; Schuster et al., 2025). Sea-level rise also persists for centuries after temperatures stabilise, and continues even when warming declines. This means that overshooting 1.5°C carries direct and long-lasting consequences for sea-level rise that cannot be reversed on any humanly relevant timescale, but ambitious Paris-aligned mitigation can slow the rate of increase.

Accelerating global and regional sea-level rise rates represent an increasingly severe challenge for coastal adaptation, compressing the timescales available for planning, investment, and implementation (Hermans et al., 2023).

The costs are already materialising, and are greatest for atoll nations. By 2050, expected annual economic damages from sea-level rise alone are projected to reach between USD 143.7 billion and USD 197.8 billion. Atoll nations – including Kiribati, the Marshall Islands, Tuvalu, and the Maldives – face the most severe losses relative to GDP and might be rendered uninhabitable (Monioudi et al., 2025). The losses go beyond economics and encompass culture, livelihoods and heritage (Martyr-Koller et al., 2021).

2.2.2 Marine heatwaves

The ocean as a whole, which stores around 90% of excess heat content and 30% of carbon dioxide emissions (United Nations Environment Programme, 2026), suffers significant impacts as emissions and temperatures continue to rise. Since 1991, for example, the number of days experiencing marine heatwaves has more than tripled globally (Forster et al., 2026). These impacts outlast the overshoot period and affect human systems dependent on ocean services, including, for example, countries largely dependent on fisheries (discussed in more detail in the SIDS section).

Under current policy trajectories with approximately 2.5–3°C of warming by 2100, marine heatwave frequency is projected to increase several-fold above recent historical levels, with roughly half or more of the ocean – particularly in the tropics – approaching near-permanent marine heatwave conditions by the end of the century (Oliver et al., 2019); (IPCC, 2021b).

Limiting warming to around 2°C would substantially reduce this risk. The fraction of the ocean experiencing near-permanent marine heatwave conditions could be held to around one third, compared to roughly half or more under higher-warming trajectories, representing a meaningful reduction in risk, but still a substantial residual burden of marine heatwave risk (Oliver et al., 2019); (Frölicher et al., 2018)11/9/2026 6:23:00 PM.

Further reductions in warming below 2°C towards 1.5°C can be expected to reduce marine heatwave frequency and the extent of permanent heatwave conditions broadly in proportion to the degree of warming avoided, though the literature does not yet provide precise quantitative estimates for this.

Looking further ahead, even in a world where warming is stabilised at lower levels, preliminary modelling suggests that marine heatwave risks do not simply stabilise at their transient warming-level values. Marine heatwave patterns are projected to

continue reorganising for decades to centuries after temperatures stabilise, with a poleward shift in frequency and sustained intensity across much of the ocean, meaning that the long-term marine heatwave burden in a stabilised world is likely greater than near-term assessments would suggest (Bossert et al., 2026).

2.2.3 Ocean deoxygenation

Ocean deoxygenation is a slow, largely irreversible type of damage that keeps building for centuries after temperatures stabilise.

Projected habitat loss in the oceans from deoxygenation is severe and lags the global temperature by decades to centuries. Past CO_2 emissions have already committed the ocean to more than three times the oxygen loss seen so far (Oschlies, 2021), and ocean oxygen keeps declining to at least 2300, even where temperatures fall after an overshoot (Smith et al., 2026).

In a 1.5°C scenario, only about 41% of the eventual long-term habitat loss has happened by the time 1.5°C is first reached. The rest builds up over the following three centuries, for most species because oxygen keeps falling as ocean ventilation slows due to increased water temperatures. For species living on the sea floor, only 28% of the loss has happened at that point.

Stabilising at 1.2°C rather than 1.5°C would cut this long-term loss by around 40% (Morée et al., 2025).

2.2.4 Ocean acidification

Ocean acidification is driven by increased CO_2 concentration in the atmosphere, which is principally caused by fossil CO_2 emissions. How severe it gets depends on how high CO_2 concentrations get, for how long, and when they start to reduce.

Ocean acidification is driven primarily by cumulative ocean uptake of atmospheric CO_2, and its severity at any given temperature level depends directly on how much cumulative CO_2 has been emitted to reach and maintain that temperature.

Current policy pathways will continue to add CO_2 to the atmosphere and increase CO_2 concentrations, which means that ocean acidification will keep getting worse.

Surface pH largely tracks atmospheric CO_2 and can partly recover as CO_2 is drawn down. The deep ocean is another matter, as its waters take around 1000 years to circulate. After very high emissions, even removing CO_2 at 25 GtC a year, a rate considered probably unfeasible, does not bring whole-ocean pH close to pre-industrial levels by 2700. In the words of the authors, the deep ocean “remembers past human interference for several centuries, at least” (Mathesius et al., 2015).

To peak warming close to 1.5°C and have warming drop back below 1.5°C by 2100 means that CO_2 emissions have to drop and become negative so that CO_2 concentration will begin to decline. This brings less acidification (Terhaar et al., 2023). Even with warming stabilised at 1.5°C, the volume of ocean saturated in aragonite, a mineral many

marine organisms produce, is projected to shrink by 17–32% between 2002 and 2150 (Terhaar et al., 2023).

The 0.3°C difference between 1.5°C and 1.2°C stabilisation translates into materially less ocean acidification.

When marine heatwaves and ocean acidity extremes strike together, the harm to marine life can be greater than from either alone. These compound events already happen 1.8 times more often than chance would predict. Measured against a fixed pre-industrial baseline, they are projected to rise from 12 days a year to 265 days a year at 2°C, mainly because of long-term ocean warming (Burger et al., 2022). Every fraction of a degree of warming avoided therefore matters.

2.3 Tipping points

Overshoot raises the risk of crossing climate tipping points, some of which may already have been passed. A tipping point is a critical threshold beyond which a system reorganises, often abruptly or irreversibly.

Tipping elements of the Earth system, such as the ice sheets (which are actually multiple different systems), the Atlantic Meridional Overturning Circulation (AMOC), the Amazon rainforest and coral reefs, can undergo self-reinforcing transitions that are very hard or impossible to reverse once past a critical threshold. For some, crossing the threshold does not mean tipping immediately, which makes bringing temperatures back down critical. Multiple other tipping elements exist, but this section will focus particularly on those four. The latest evidence on each is summarised below. The comprehensive review by Ritchie et al. (2026) synthesises the evidence across all major tipping elements and reaches a common conclusion: global warming must peak below 2°C, return below 1.5°C as quickly as possible within this century, and continue declining towards approximately 1°C thereafter to limit long-term tipping risks (Ritchie et al., 2026). Further evidence shows that tipping risk increases with every additional 0.1°C of overshoot above 1.5°C, and accelerates sharply for peak warming above 2°C.

Stabilising temperatures at 1.5°C is not "safe" in terms of planetary stability. Keeping long-term tipping risk low requires achieving and maintaining net zero greenhouse gas emissions, so that temperatures decline below 1.5°C and towards 1°C. 1.5°C is therefore not a landing point: after the overshoot, warming needs to fall back below it and keep declining.

A foundational insight established by Ritchie, Huntingford and Cox (2025) is that climate tipping points are not instantaneous threshold crossings. Systems do not commit to tipping the moment they exceed a critical temperature level. Instead, tipping takes time to unfold, and for systems with slow response times a temporary exceedance of the critical threshold can be survived if the duration above is short enough (Ritchie et al., 2025).

This creates an escape window: the faster warming is reduced from its peak and brought below a critical threshold, the lower the probability that slow-responding systems will complete the transition to a tipped state. For the Greenland and West Antarctic ice sheets, that threshold is estimated at around 1.5°C, with ranges reaching down to 0.8°C and 1°C (Ritchie et al., 2026). Escaping their tipping points therefore means bringing warming below 1.5°C, and towards 1°C to be safe.

2.3.1 Coral reefs

Warm-water coral reefs are one of the elements most vulnerable to overshoot. Already at 1–1.5°C of global warming, they reach a "tipping point" of widespread dieback (Pearce-Kelly et al., 2025). This may have already been reached. Currently, the rise in average temperatures, ocean acidification, sea-level rise and storms are accelerating coral bleaching and reef weakening worldwide (Bhuyan et al., 2026). Global marine heatwaves, and the global bleaching events they drive, have also increased in frequency and severity (Forster et al., 2026).

This risk of a collapse of coral reef systems under global warming is reinforced by the recent IUCN Red List of Ecosystems assessment published in October 2026, which finds that 96% of all assessed shallow-water coral reef ecosystems are Critically Endangered under projected warming trajectories, covering all 127 tropical and subtropical ecoregions including the Great Barrier Reef, the Coral Triangle, the Mesoamerican Barrier Reef and the Red Sea. At present, based on observed changes and without a consideration of global warming, 24% of assessed ecosystems would be Critically Endangered (IUCN, 2026).

Overshoot will increase this risk, with the collapse of coral reefs threatening marine biodiversity and risking the livelihoods of hundreds of millions of people. Furthermore, loss of coral reefs compounds other impacts of overshoot, such as sea-level rise. This is because reefs act as natural coastline protectors, attenuating up to 98% of the incoming wave energy in the South Pacific (French Polynesia). Thus, if they are degraded, coastal flooding risk increases (Carlot et al., 2023).

Keeping global warming as close as possible to 1.5°C and bringing warming down from its peak to below 1.5°C while minimising other diverse interacting stressors (e.g., pollution) is the only long-term prospect for coral reefs to survive across their present range.

While some studies point out that management opportunities exist to promote adaptation in thermal refugia and warm spots (Vogt-Vincent et al., 2026) (Bozec et al., 2025), highlighting the key role of mitigation, others find already that warming of 1.5°C relative to pre-industrial levels will be catastrophic for coral reefs (Dixon et al., 2022), with loss of thermal refugia. This reinforces the need to bring temperatures below it by the end of the century.

2.3.2 Ice sheets

Critical thresholds for the major ice sheets of Greenland and Antarctica could be approaching, and a recent review finds that at 1.5°C warming, even a "best-case scenario will result in a steady increase in the rate of GMSL [global mean sea level], with no evidence to suggest it will halt or even slow the rate of SLR from the world's ice sheets" (Stokes et al., 2025). This review concludes that for a chance to prevent multi-metre sea-level rise in the longer term, global warming would need to be brought back towards maximum 1°C above pre-industrial levels.

The Greenland ice sheet will likely irreversibly decay if warming is maintained over centuries close to 1.5-1.6°C – if melted it would raise sea level by 7.4 metres (Morlighem et al., 2017). Recent modelling places its critical threshold at a regional summer air temperature anomaly of +1.2 to +1.8°C relative to present, within the lower range of previous estimates (Gutiérrez-González et al., 2026). The ice sheet also shows hysteresis: once it has retreated, it would not regrow simply by bringing temperatures back below the threshold. Timely action, however, can avoid a significant amount of the damage.

This is concerning, as we already see big losses materialising. Recent satellite imagery from Petermann Glacier in northwest Greenland, which connects the Greenland ice sheet to the Arctic Ocean, revealed that a 29 square mile (76 square km) section of the ice tongue has broken away (ESA, 2026).

Meanwhile, the West Antarctic ice sheet contains around 5.3 m of sea-level rise equivalent (Morlighem et al., 2020), and is long recognised as unstable (Mercer, 1978). This means it could have a collapse threshold close to 1.5°C of warming (Armstrong McKay et al., 2022), resulting in several metres of sea-level rise over a few centuries. Several authors have argued that the tipping point may have been crossed for at least part of this ice sheet and that the Antarctic Ice Sheet as a whole is committed to 21st-century mass loss (Naughten et al., 2023), even under aggressive emissions-reduction scenarios (Lin et al., 2026).

The East Antarctic ice sheet, which contains around 52.2 m of sea-level rise equivalent, is known to have unstable components vulnerable to collapse with warming of 2–3°C (Stokes et al., 2022). Pursuing efforts to reduce warming to well below 1.5°C is what would help prevent the polar ice sheets from tipping in the long term, even if some have already reached their tipping threshold (Ritchie et al., 2026).

2.3.3 Amazon rainforest

The Amazon is a unique ecosystem which has existed for the last 65 million years. It could rapidly die back if the combined effects of deforestation and global warming exceed its tipping points (Armstrong McKay et al., 2022), which are approaching. This would turn it into a drier, less productive savannah-like ecosystem with large adverse effects on the millions dependent on the rainforest, and which would have impacts for the hydrological cycle, influencing rainfall throughout the continent and globally (He et al., 2025).

A recent review of the risks identified 1.5°C as a safe boundary, and 2°C warming as a critical threshold for loss (Flores et al., 2024). Deforestation interacts with global emissions and further pushes the forest ecosystem to the limit. This means that 1.5°C, combined with deforestation, is already a threshold for widespread loss (Wunderling et al., 2021), which could tip the Amazon towards a savannah-like ecosystem. This reinforces the need to return global warming levels to below 1.5°C and halt deforestation.

Current deforestation levels are at 17% across the entire Amazon basin and approaching 20% in the Brazilian Amazon. This is close to the 22-28% threshold (combined with 1.5-1.9°C warming) for tipping. Over the past 35 years, deforestation has accounted for approximately 74% of the ~21 mm dry season decline and 16.5% of the 2°C rise in maximum surface air temperature (Franco et al., 2025). The recent success by the Lula administration of reducing deforestation rates – with satellite data (Wells & Guinto, 2026) showing that in the year to July 2026, the deforestation rate fell by 41.8% in the Amazon, the biggest drop since records began in 1988 – shows the power of ambitious policy.

2.3.4 Atlantic Meridional Overturning Circulation (AMOC)

The IPCC AR6 assessed with medium confidence that the AMOC would not undergo abrupt collapse before 2100, however, this assessment seems too conservative in retrospect. Post-AR6 observational and modelling evidence indicates this risk was substantially underestimated. The Global Tipping Points Report (2025) assesses AMOC collapse as a risk below 2°C of global warming, with risk beginning above 1.5°C; under realistic emission rates, recent modelling finds collapse could be triggered at warming levels of +2.2°C or lower (Lenton et al., 2025) (van Westen et al., 2024).

A collapse of the AMOC, which is already experiencing unprecedented, severe slowdown (Caesar et al., 2021), would be a very high consequence event globally. Unfortunately, evidence shows it is approaching, as recent studies project a ~50% weakening by the end of this century, above what climate models have historically suggested (Portmann et al., n.d.). The collapse could begin within the next 25 years and would be irreversible on human timescales even if temperatures return below current levels (van Westen et al., 2025).

Both theoretical modelling, going back to Stommel (1961), who proposed two stable equilibrium states driven by a positive salt advection feedback, and observational data suggest that the AMOC exhibits bistability – meaning it can exist in either an active (on) or inactive (off) state (STOMMEL, 1961). Its state depends on the prevailing boundary conditions as well as the system's past. As these boundary conditions change, for example due to rising temperatures, the circulation can become destabilised.

Recent modelling (Nian et al., 2026) indicates that above approximately 350 ppm CO_2 – a threshold already exceeded – the system becomes irreversibly bistable, such that once the AMOC collapses it cannot recover. Beyond a critical threshold, positive feedback mechanisms can amplify this destabilisation, leading to a collapse of the active state and

a transition to the inactive state. The AMOC is a key global mediator of tipping point interactions (STOMMEL, 1961). Most of those interactions are destabilising.

AMOC tipping depends on the rate of radiative forcing, implying that limiting the rate of emissions is critical for reducing the risk of an AMOC collapse (van Westen et al., 2026). Under slow warming, the AMOC may remain stable even at very high temperatures; under intermediate- and high-emission rates, collapse is projected at +2.2°C and +2.8°C respectively – well within current policy trajectories (van Westen et al., 2026).

A weakened AMOC may also strengthen El Niño–Southern Oscillation variability, increasing the frequency and intensity of extreme weather events across the globe (W. Liu et al., 2023).

Some non-exhaustive examples of the challenges an AMOC weakening and collapse bring are:

- In Europe, extremely cold temperatures across Britain, Scandinavia, and Iceland, with severe impacts for agriculture, potentially making it impossible in the UK (van Westen et al., 2025; Ritchie et al., 2020).
- Additional sea-level rise along the US coast, on top of global mean rise, as AMOC weakening reduces the dynamic effect that currently pulls water away from that coastline (Volkov et al., 2023).
- Sharp weakening of the West African monsoon, with projections showing severe multi-decadal drought across a region already food-insecure, home to several hundred million people (Ben-Yami et al., 2024).
- Adverse changes to South Asian monsoons, which would bring severe drying and shorter wet seasons under AMOC collapse with severe implications for agriculture and food security (Ben-Yami et al., 2024).
- AMOC weakening leads to increased precipitation in the Southern Amazon during the critical dry season - a 4.8% increase in mean dry season precipitation for every 1 Sv of AMOC weakening (Ben-Yami et al., 2024).
- The consequences of AMOC weakening extend well beyond the Atlantic and into Pacific marine ecosystems. North Atlantic temperature patterns are the dominant driver of oxygen variability in the tropical Pacific via their control on subsurface zonal circulation (Pichevin et al., 2024). Accelerating AMOC weakening would therefore compound Pacific deoxygenation beyond what warming-driven stratification alone projects. This has significant consequences for Pacific fisheries, biodiversity, and the livelihoods of SIDS and coastal communities across the region.
- AMOC collapse would also substantially reduce the North Atlantic's capacity to absorb CO_2, leaving more in the atmosphere and accelerating warming (Nian et al., 2026). This feedback loop is not fully captured in standard emissions pathway modelling, and it directly increases the carbon dioxide removal (CDR) burden required to compensate.

2.4 Impacts in countries: overshoot hits major emitters too

Vulnerable countries, particularly SIDS and LDCs, bear little responsibility for historical climate change, yet are severely affected and are already experiencing damages at current temperature levels. However, the impacts are global, and major emitters are progressively experiencing growing damages and risks. A better understanding of these impacts around the globe and in major emitters strengthens the case for urgent mitigation in these countries' own interests, as losses will increase across multiple sectors if emissions are not cut. This section sets out the impacts already hitting China, the United States, the EU, India, Brazil, the Middle East and Australia, what overshoot adds to them, and what each gains if overshoot is kept as low and short as possible. For these countries too, the costs keep growing for as long as warming stays high. Bringing warming back to below 1.5°C and keeping it falling is therefore directly in their own interest.

2.4.1 Impacts in major emitters

China

China is the world's largest emitter. Climate change affects it across the economy, with particularly severe impacts in the health sector through increases in air pollution interactions. Agriculture, ecosystems, and labour productivity are also severely impacted.

Heat has already taken a toll on the economy over the past two decades: between 2001 and 2019, heat-induced productivity loss in China increased six- to ninefold, with the southeast and secondary industries such as construction and manufacturing being the most affected (Chu et al., 2024). These losses are projected to affect regions in China unevenly, with low-income southwestern provinces (e.g. Guangxi, Guizhou) facing 3.4–7.1× higher losses than wealthier regions by 2100 under SSP2-4.5, widening income inequality and productivity gaps (M. Zhao et al., 2024). Population exposure to heatwaves is projected to increase eightfold under a 1.5°C warming scenario and fourteenfold under a more extreme 2°C warming level by the 2100s relative to the baseline (1985–2014)(J. Liu et al., 2024).

Impacts on agriculture and health are also present. Air pollution vulnerability is heightened by climate change and compounds inequality (H. Wang et al., 2025). Increases in maximum daily temperature in spring and autumn are projected to reduce crop net revenue, with impacts varying greatly across seasons, crop type and farm size, requiring significant resources to be invested in adaptation planning (Feng et al., 2025). As food security becomes a great concern, China has also seen an impact on vegetation growth associated with heatwave occurrence (Xu et al., 2024).

The Climate Impact Explorer finds that a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the number of days with high heat risk by 2100 in China to 29, compared to 47 under current policies (Climate Analytics, 2026a).

Days per year with high heat risk in China

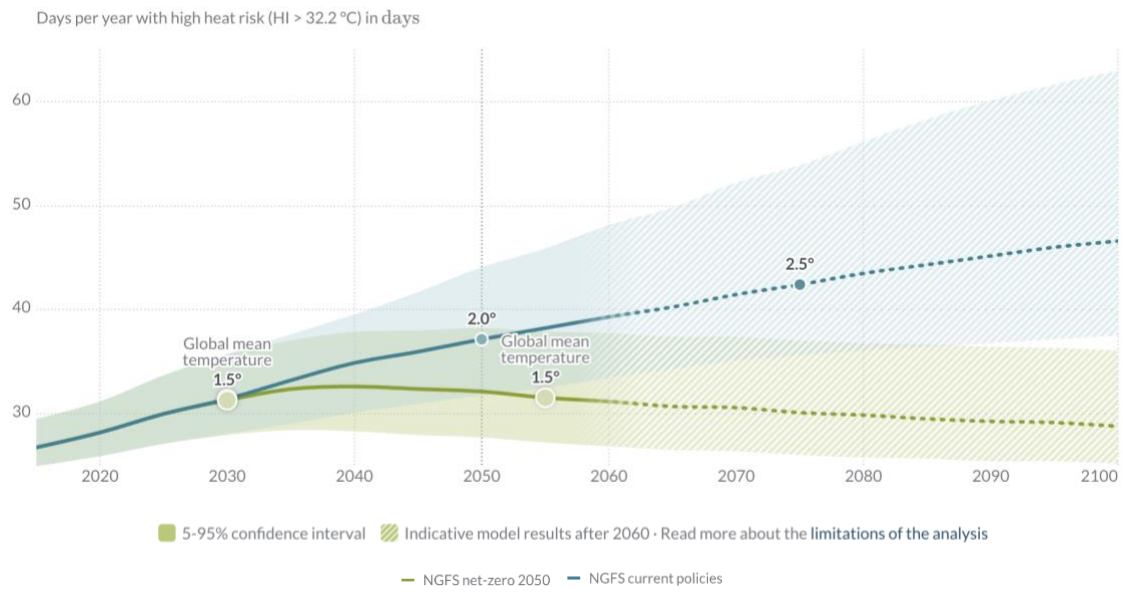


Figure 2: Days per year with high heat risk (HI > 32.2 °C) (expressed in days) will change over time in China at different global warming levels, based on the NGFS net-zero 2050 and NGFS current policies scenarios. Climate Impact Explorer, Source: ISIMIP

United States

The United States, the world's second-largest current and largest historical emitter, is highly exposed to climate-driven disasters, including hurricanes, wildfires, droughts, and heat extremes (NOAA, 2020). Hazards are increasingly translating into severe economic losses, rising health burdens, and deepening social inequalities. Emerging scientific evidence shows that climate change is already reducing annual US income by 0.32%, by altering counties' current, local temperatures, with losses concentrated in the Great Plains and Midwest (Lemoine, 2025).

Recent events in 2025 illustrate how warming is amplifying both the frequency and intensity of climate extremes across sectors – from insurance markets to agriculture and public health. 2025 ranks as the third-highest year (after 2023 and 2024) for billion-dollar weather and climate disasters – with 23 such events costing a total of $115 billion in damages (Climate Central, 2026). Climate change is also directly responsible for almost half the cost of the damages caused by hurricanes Milton and Helene in Florida, having increased Helene's wind speeds at landfall by about 11 mph (11%), and Milton's by almost 13 mph (10%).

The Climate Impact Explorer finds that a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the number of days with high heat risk by 2100 in the United States to 39, compared to 61 under current policies (Climate Analytics, 2026a).

Days with high heat risk in the United States by 2100

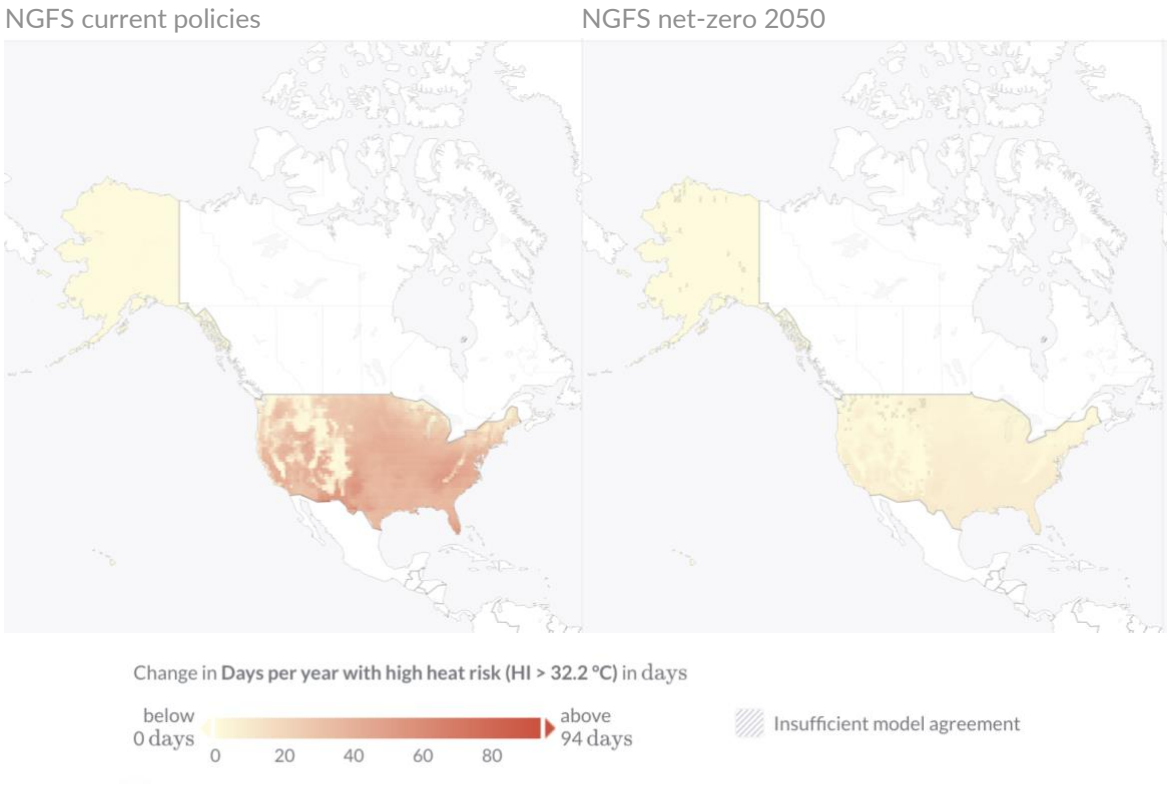


Figure 3: Days with high heat risk in the United States by 2100, NGFS current policies vs Net-Zero 2050. Climate Impact Explorer

European Union

The European Union, collectively the world's fourth-largest emitter, is highly vulnerable to compound climate impacts, in particular heatwaves, droughts, and air pollution episodes, which are increasingly disrupting economies, stressing health systems, and undermining energy and food security across the continent.

The 2026 summer has highlighted this vulnerability, with record-breaking heat, mounting economic losses, and tens of thousands of excess deaths linked to extreme temperatures. It was confirmed as the third hottest on record over Europe, and the hottest ever for western Europe. August 2026 was the joint warmest month ever recorded, tied with July 2023 (Copernicus, 2026).

Research estimates 50,391 heat-related excess deaths across 854 cities in 30 European countries during summer 2025, around two thirds of them attributable to anthropogenic climate change (Barnes et al., 2025). This also comes with economic impact, as it is estimated that between June and August 2025, extreme weather events cost European regions nearly EUR 43 billion, which will grow to EUR 126 billion by 2029 (Usman et al., 2025). In addition, a substantially weaker AMOC would make European temperature extremes more intense (Van Westen & Baatsen, 2025).

Agriculture is also significantly affected. Some crops, including some wine grapes, could be rendered almost unviable (van Leeuwen et al., 2024). The Climate Impact Explorer finds that, for Europe, a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the area exposed to severe drought in 2100 by 30%, compared to current policies, with implications for food security, economic activity, and public health (Climate Analytics, 2026a).

Area under severe drought in the European Union by 2100

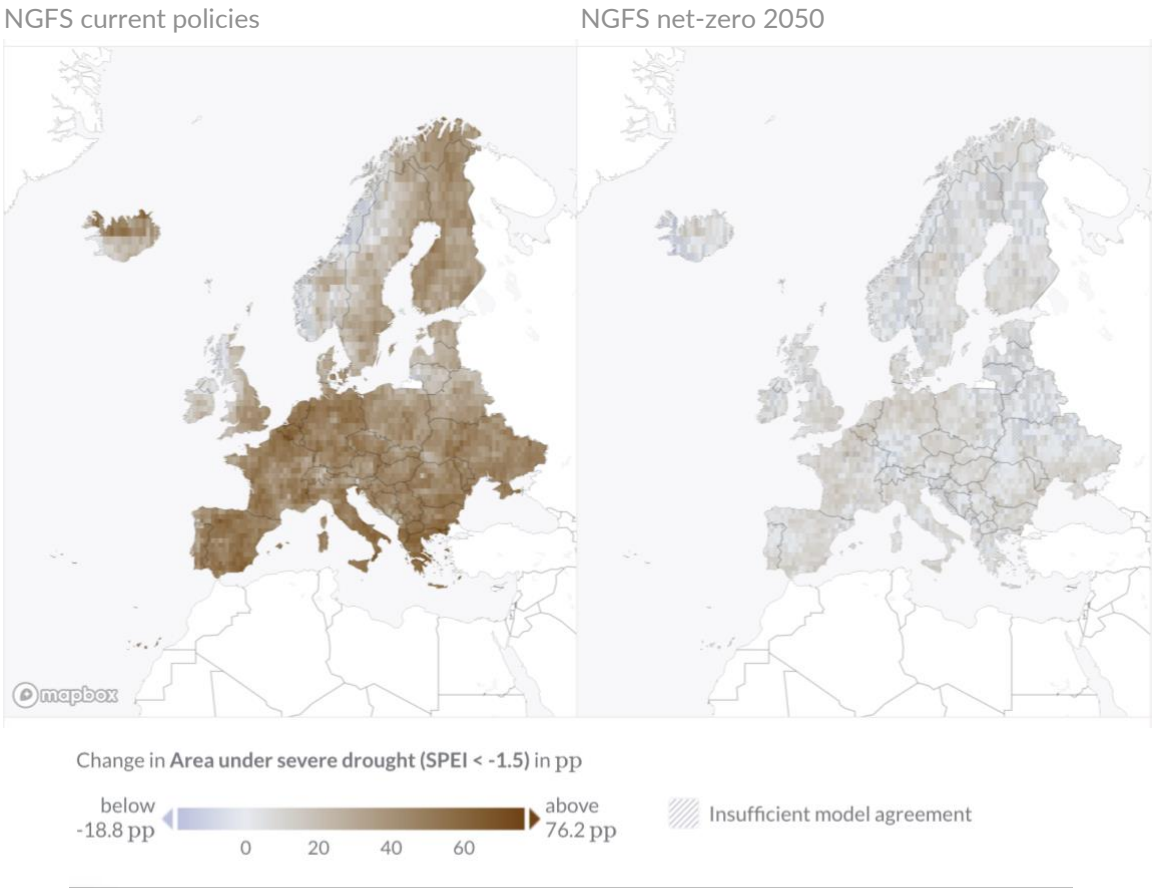


Figure 4: Area under severe drought in the European Union by 2100, NGFS current policies vs Net-Zero 2050. Climate Impact Explorer

India

India, the third-largest emitter globally despite its per-capita emissions being below the world average, faces rising temperatures, prolonged heatwaves, erratic monsoon rainfall, and worsening air pollution, which are driving water scarcity, crop losses, and health impacts (WMO, 2026a).

Agriculture is especially exposed: the 2022 heatwave was linked to a 4.5% decline in wheat production, with yield losses of up to 15% in some regions (Sidhu, 2023). Climate change made this heatwave at least 30 times more likely (World Weather Attribution, 2022). Risks to rice production, for which the country is the main exporter globally, are projected to increase at district level under future climate change across all emissions scenarios in the near (2025–2054) and far (2055–2084) future, with differences of

impacts becoming pronounced in the long term, highlighting the importance of mitigation measures to contain higher levels of damages in the future (Bowden et al., 2025). Agricultural labourers had the highest livelihood vulnerability to climate change, followed by cultivators, household industry workers and other workers (Kumari et al., 2025).

The Climate Impact Explorer finds that a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the number of days with high heat risk by 2100 in India to 182, compared to 223 under current policies (Climate Analytics, 2026a).

Days per year with high heat risk in India

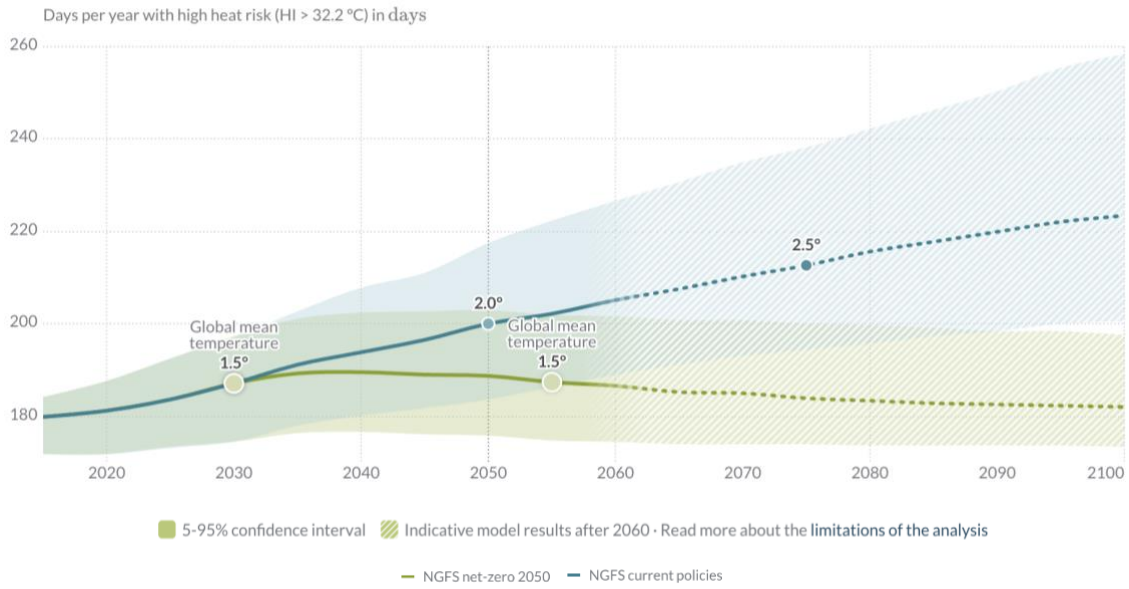


Figure 5: Days per year with high heat risk (HI > 32.2 °C) (expressed in days) will change over time in India at different global warming levels, based on the NGFS net-zero 2050 and NGFS current policies scenarios. Climate Impact Explorer, Source: ISIMIP

Brazil

Brazil, the seventh-largest emitter globally (sixth excluding the EU), is experiencing heat extremes, intense drought and ecosystem degradation across the country, where forest fires, prolonged dry seasons, and water scarcity are becoming increasingly severe (Lorenz et al., 2026). Deforestation and forest degradation in the Amazon, which is close to a tipping point, are driving increased aridity across Brazil. The recent historic record in reducing deforestation rates represents a significant advancement, as the biome has already lost almost 20% of its coverage (Franco et al., 2025). Both the frequency and intensity of forest fires have increased, with a longer fire season, in the Southeast, Centre-west and North (Flores et al., 2024).

This threatens the Amazon's "flying rivers", the moisture flowing from the Amazon that sustains rainfall in central and southern regions (Climate Policy Initiative, 2025). Many Brazilian urban centres and agribusiness depend on it. Brazilian agribusiness is extremely exposed to climate change, as it relies heavily on rainwater, with only 13% of agricultural areas irrigated. After the 2023 drought, for example, coffee prices rose by

55% in mid-2024: food price inflation associated with climate extremes not only impacts food security, but may also come to bear increasing political relevance (Kotz et al., 2025).

Heat extremes also pose huge challenges. Coffee workers were exposed to temperatures exceeding the safety limits established by the Occupational Health Standard (NHO-06), posing substantial risks to their health. In tropical America, and in particular the Amazon basin, the probability of hot extremes is projected to exceed 50% somewhere between 1.5°C and 2°C of warming, meaning that overshoot risks such extremes becoming the norm – effectively a continuous heatwave (Simolo & Corti, 2025).

Sea-level rise is also a huge risk. Major iconic Brazilian cities, such as Salvador and Rio de Janeiro, face substantially greater risks under 2°C warming compared to 1.5°C, including coastal flooding and saltwater intrusion threatening infrastructure, tourism assets, and densely populated urban areas (Climate Central, n.d.). For Brazil, the Climate Impact Explorer finds that a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the number of days with high heat risk by 2100 to 239, compared to 301 under current policies (62 fewer days)(Climate Analytics, 2026a).

Days with high heat risk in Brazil by 2100

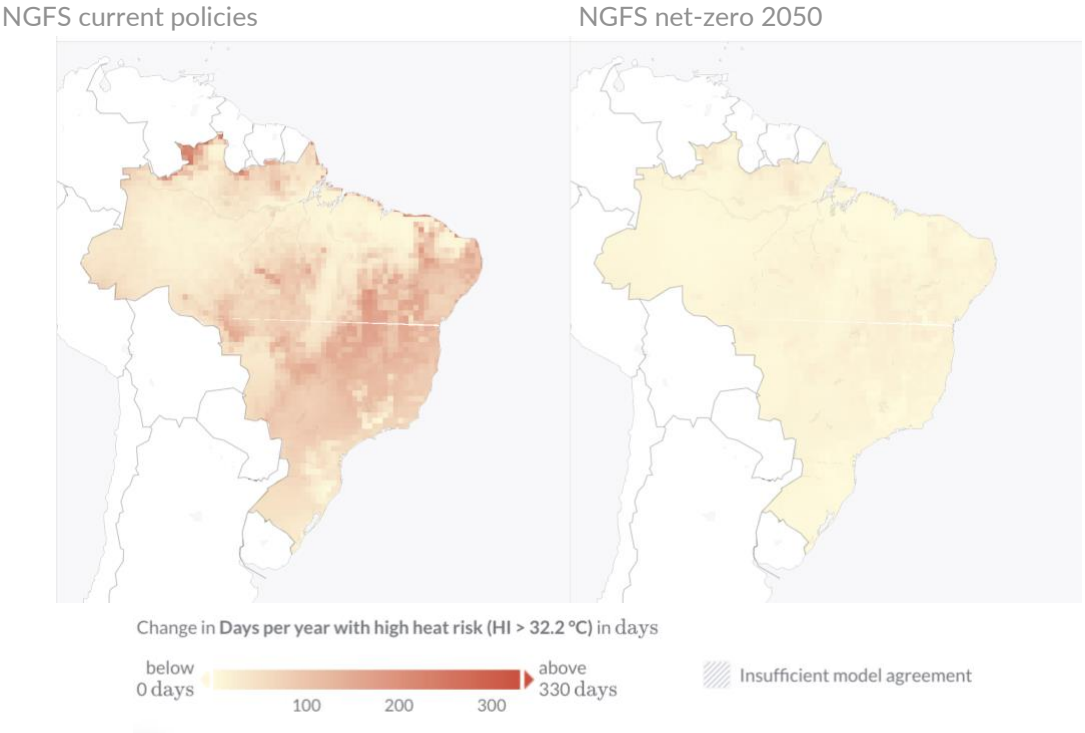


Figure 6: Days with high heat risk in Brazil by 2100, NGFS current policies vs Net-Zero 2050. Climate Impact Explorer

Middle East

The Middle East accounts for around 30% of global oil exports (Visual Capitalist, 2026). Although the production and export of fossil fuels are a large part of its economy, the region also suffers significantly from climate change.

The WMO warns that the region is heating at twice the global average rate, and experiencing intense heatwaves pushing society to the limits. Extreme events in 2024 affected nearly 3.8 million people and resulted in more than 300 deaths, mainly from heatwaves and floods. The true economic and human cost is certainly underestimated, the report stressed. The frequency and severity of extreme weather and climate events have increased significantly, with an 83% rise in recorded disasters between 1980–1999 and 2000–2019 (WMO, 2025).

Ongoing climate change also threatens key religious activities: the 2024 Hajj saw over 1300 people die as temperatures soared above 50°C (France24, 2025). A 2021 study on the potential risk of dangerous heat stress during the pilgrimage to Mecca, Saudi Arabia, finds that if the world limits global warming to 1.5°C, this would halve the number of heat-related deaths during the Hajj compared with 2°C of warming (Saeed et al., 2021).

The region's marine resources are also threatened. The Arabian Gulf/Persian Gulf has seen increases in sea surface temperature as high as 0.7°C per decade, leading to significant coral bleaching and exposing an area of high coastal development in low-lying areas to increasing risks of sea-level rise. Current warming trends could result in more frequent marine heatwaves with locally amplified peak temperatures of up to 8°C due to thermal pollution in the inner Arabian/Persian Gulf.

The Climate Impact Explorer finds that a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the number of days with high heat risk by 2100 in Saudi Arabia, as an example, to 182, compared to 217 under current policies (Climate Analytics, 2026a).

Days with high heat risk in Saudi Arabia by 2100

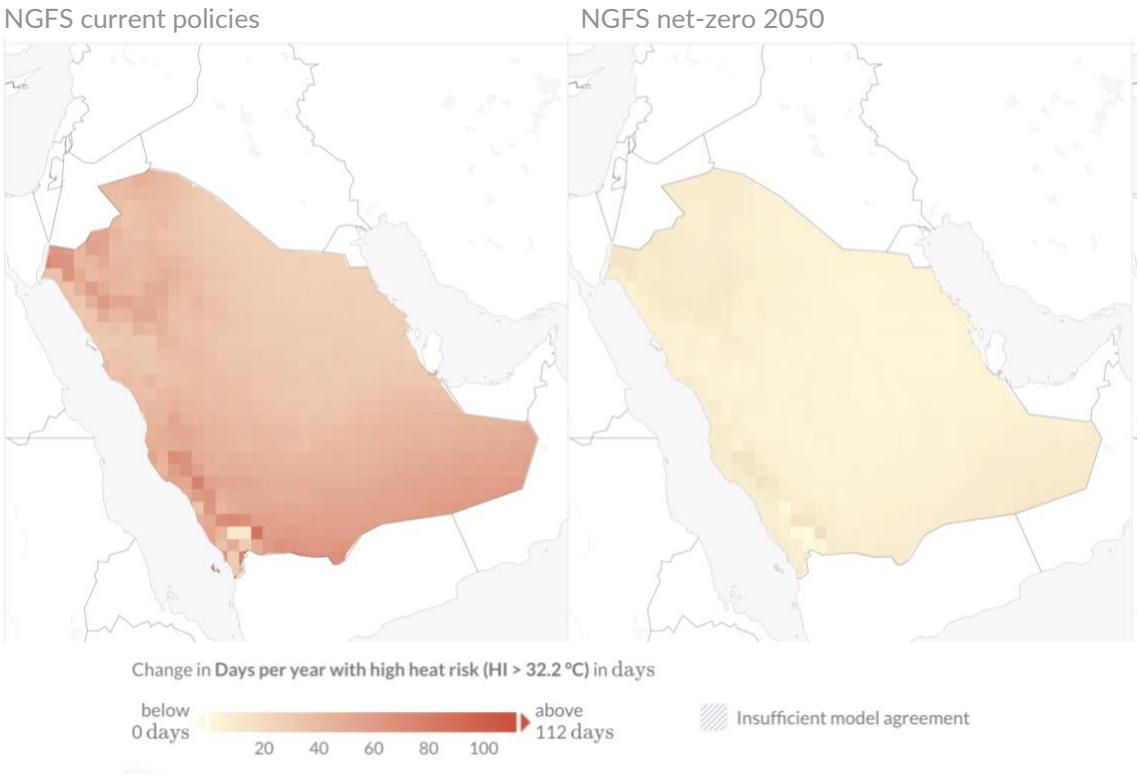


Figure 7: Days with high heat risk in Saudi Arabia by 2100, NGFS current policies vs Net-Zero 2050. Climate Impact Explorer

Australia

Australia consistently ranks among the world's top producers and exporters of coal and LNG. Despite an apparently small contribution to global warming, its carbon footprint far exceeds domestic emissions (Climate Analytics, 2024).

Heat stress is already taking a toll on the Great Barrier Reef. Mainly as a result of the 2024 mass bleaching event, compounded by cyclones and other pressures, hard coral cover fell by 30.6% in the southern region and by 24.8% in the northern region, in each case the largest annual decline recorded since monitoring began, and by 13.9% in the central region. Cover has since begun to recover in the north, but mass bleaching events are becoming more frequent while recovery periods are getting shorter (Australia Institute of Marine Science, 2025, 2026).

The country's own National Climate Risk Assessment (NCRA) shows climate hazards rising sharply with each increment of overshoot. Relative to current conditions (~1.2°C), with around four extreme heat days/year, this increases by around two days a year at 1.5°C, but by five at 2°C and fourteen at 3°C. Marine heatwaves lengthen from 18 days currently to 22 days at 1.5°C, 77 days at 2°C and 161 days at 3°C (Australia Climate Service, 2025).

The upper end of the projected increase in time spent in drought nearly doubles between 1.5°C and 2°C, from +36% to +69%. Extreme coastal water levels are projected to occur twice as often by 2050, rising to five times as often by 2090 at 2°C (Australia Climate Service, 2025).

Even a temporary overshoot could lock in the collapse of much of the Great Barrier Reef. That would also mean losing the reef tourism and fisheries it supports, including around AUD 6 billion a year in tourism revenue, and the natural coastal protection it gives Queensland communities. Sea-level rise is similarly persistent: it responds to warming over centuries, so the extra ocean heat and ice loss built up during an overshoot commits Australian coastlines to higher seas long after temperatures peak. This adds to the projected increase in coastal flooding and the growing pressure on insurability, with up to 185,000 Queensland homes already at very high risk (Australia Climate Service, 2025).

The Climate Impact Explorer finds that a pathway that limits overshoot and gets below 1.5°C by 2100 reduces the number of days with high heat risk by 2100 in Australia to 123, compared to 159 under current policies (36 fewer days)(Climate Analytics, 2026a).

Days with high heat risk in Australia by 2100

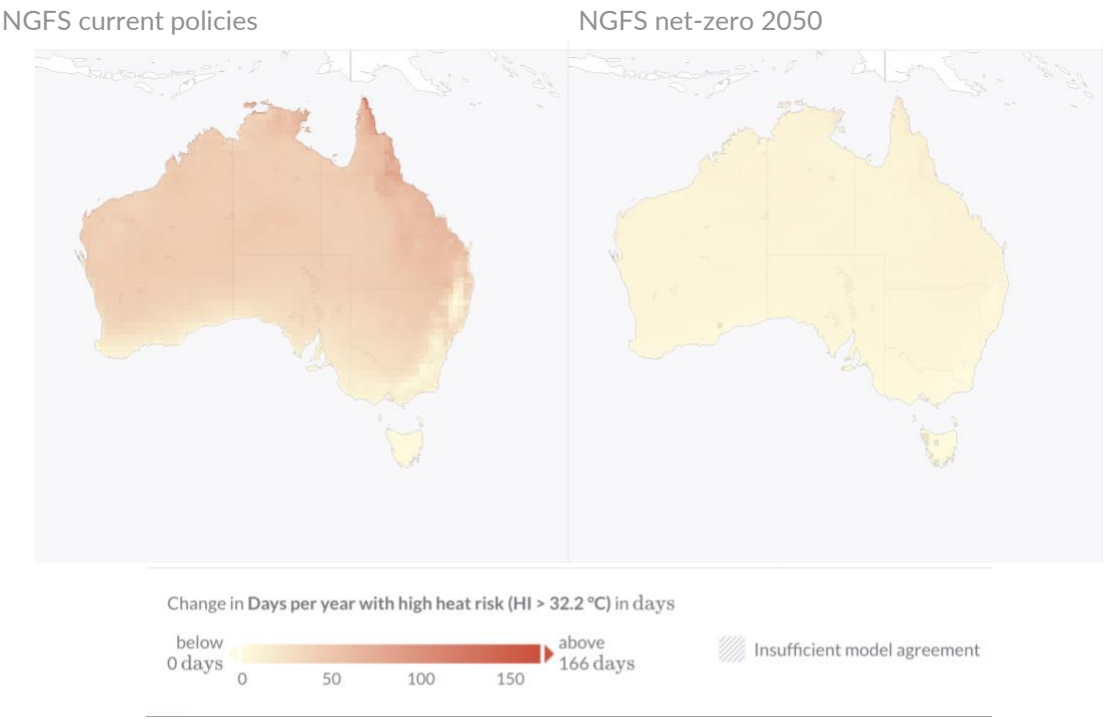


Figure 8: Days with high heat risk in Australia by 2100, NGFS current policies vs Net-Zero 2050. Climate Impact Explorer

2.4.2 SIDS and LDCs

For Small Island Developing States (SIDS), overshoot is an existential threat. Climate-related economic losses in SIDS are already large relative to the size of their economies, and growing. SIDS constitute two thirds of the countries suffering the highest relative losses from natural disasters and are acutely vulnerable to the impacts of climate change (between 1% and 9% of their GDP each year) (OECD, 2026), with disaster-related damage as a percentage of their GDP surging by nearly 90% from 2011 to 2022 (IIED, 2023). Over the same period, the population affected by disasters in SIDS increased by around 120% and deaths per million rose by about 60%(IIED, 2023). Between 1970 and 2020, SIDS recorded damages of USD 153 billion due to weather, climate and water-related hazards, while average GDP for SIDS is around USD 13.7 billion (WMO, 2020). Since 1995, 20 tropical cyclones have caused damages estimated at more than 10% of GDP in the Caribbean and Oceania; in eight of these cases, the estimated damages exceeded 50% (World Bank, 2024). Floods and storms are projected to result in additional loss and damage of USD 56 billion by 2050 under a 2°C warming scenario, representing an 11% increase in annual loss and damage over the next 23 years (2023–2045) compared with the past 23 years (2000–2022), and this excludes indirect economic impacts or the impacts of slow-onset events (ODI, 2023). Across Asia and the Pacific, current annual economic losses from coastal flooding amount to USD 26.8 billion and are projected to increase 4.4 and 6.4 times, reaching USD 143.7 to 197.8 billion annually, by 2050, severely affecting Southeast Asia, South Asia, and the Pacific Islands (Monioudi et al., 2025).

On many small islands, projected changes in aridity will increase freshwater stress, although Paris-aligned pathways could avoid a substantial fraction of it compared to 2°C(IPCC, 2018). Sea-level rise is projected to increase wave-induced run-up which might leave several atoll islands uninhabitable, leading to forced displacement and non-economic loss and damage, such as a loss of identity, culture and sense of place (Storlazzi et al., 2015). At 2°C warming, atolls could be almost fully covered (Vermeer & Rahmstorf, 2009). SIDS in the Pacific and Indian Oceans are located within persistent sea-level-rise hotspots where the ice-melt contribution to local sea-level rise systematically exceeds the global mean by up to ~24% (Powell et al., 2026).

Limiting overshoot reduces losses due to sea-level rise, but cannot eliminate them. Keeping global warming below 1.5°C would have avoided more than half of unmitigated damage (Vousdoukas et al., 2023), depending on the region, but several countries and especially SIDS would still suffer economic losses that correspond to considerable shares of their GDP, possibly leading to forced migration from low-lying coastal zones (Monioudi et al., 2025). Atoll nations, including Kiribati, the Maldives, the Marshall Islands and Tuvalu, would face the most severe losses relative to GDP (Monioudi et al., 2025).

Ocean warming also threatens the economic base of Pacific SIDS. Regardless of the emissions scenario, at least 37–54% of fish stocks are projected to shift between exclusive economic zones (EEZs) and the high seas by 2030–2050 (Palacios-Abrantes et

al., 2025). Critical fisheries species could decline locally by up to 17%, fundamentally altering food web structure and the economic dependencies built around them. As waters warm, tuna are moving away from EEZs of Pacific SIDS towards the high seas threatening the world's largest tuna fishery and SIDS economies (Bell et al., 2021).

In some Pacific SIDS, tuna fishery access fees make up the majority of government revenue, and research shows that the lower warming is kept, the smaller the impacts. At about 2.3°C warming, which current policies would reach by around 2060, catch of key tuna species in ten Pacific SIDS' waters may decline by a median of 20.2% compared to 2009–2018. At about 1.9°C warming, which current policies would reach in 2045, the median projected fall is of 3.4%, but can get as high as 11.9% for individual countries. Keeping warming as close as possible to 1.5°C and returning below it, in line with the Paris Agreement, would provide a pathway to sustainability for tuna-dependent Pacific Island economies.

Least developed countries (LDCs) also face disproportionate impacts despite contributing least to the problem. Over the last 50 years, 69% of worldwide deaths caused by climate-related disasters occurred in LDCs (UNCTAD, 2024), and disasters affect the economies of LDCs around 10 times worse than the economies of the richest countries, as a share of their GDP (UNDRR, 2022).

Heat is a growing threat. Countries with low Human Development Index (which largely overlaps with LDCs) are among those most affected by recent loss of labour productivity due to heat exposure at current levels of warming, losing 8% of GDP (Romanello et al., 2024). IPCC SR1.5 estimates that 14% and 37% of the world's population would be exposed to intense heatwaves under 1.5°C and 2°C warmer worlds, respectively (IPCC, 2018). This rise will disproportionately hit LDCs because most of them are geographically placed in already hot regions (Im et al., 2017), have scant cooling infrastructure, and have weaker public health systems.

Sea-level rise also threatens LDCs. In West Africa, 64% of coastal areas have a high to very high Coastal Vulnerability Index (CVI), and 17% a moderate CVI. High population growth and unsustainable human development at the coast add considerably to exposure and, ultimately, to the magnitude of impacts (Dada et al., 2024).

In addition, increasing deglaciation has critical effects on LDCs, as seen recently in Nepal. Warming can be a catalyst for a series of cascading events (Stanley et al., 2024). The permafrost that for millennia has helped to hold together high-altitude rock, ice, soil and glaciers is now weakening and becoming unstable (Cui et al., 2025). Glacier mass itself is projected to keep shrinking under every emissions pathway: modelling of the wider High Mountain Asia region projects a loss of roughly a third of glacier mass by 2100 even if warming could be held to the Paris Agreement's 1.5°C limit, rising to around two thirds under a high-emissions pathway. In the Central Himalaya, the loss at 1.5°C stands at around 60% of mass by 2100 (Kraaijenbrink et al., 2017). Every fraction of a degree of temperature rise avoided reduces the pace at which glaciers retreat, permafrost thaws, and slopes destabilise.

Food, water and health systems in LDCs are particularly exposed to climate change. Global warming has likely already caused 3–7% decreases in tropical crop yields (C. Zhao et al., 2017) and this is projected to rise to 10-15% or more at 2°C (IPCC, 2018), sharply increasing hunger and child malnutrition in LDCs with highly climate sensitive agriculture and food systems. Eastern Africa and Southern Asia are highly susceptible to drought and its damages to agricultural production (Freedman et al., 2025).

LDCs in Africa had the highest prevalence of severe food insecurity in 2021, of which Djibouti had 49% and Comoros had almost 80%. Based on FAO data, the prevalence of severe food insecurity in 2023 was at around 22% for LDCs, with an increasing cost of healthy diet for (FAO, 2026). The higher the peak, the more of these risks materialise. Water scarcity is projected to rise significantly between 1.5°C and 2°C, especially over dryland areas such as in the Sahel and Horn of Africa which host several LDCs, while in the Hindu Kush Himalaya, glacier volume is projected to decline by a further 30-50% by 2100 at 2°C compared with 1.5°C, affecting water supplies in South Asian LDCs (IPCC, 2022a). At 2°C, the expansion of vector-borne diseases such as malaria and dengue increases substantially compared to 1.5°C (Ryan et al., 2019). LDCs in tropical zones will experience higher year-round disease transmission, overwhelming public health systems and reversing hard-won gains in disease control. Climate-induced displacement rises sharply at 2°C, especially in vulnerable deltas, low-lying islands, and arid regions. LDCs – already facing fragile governance and urban stress – could see mass internal and cross-border migration that challenges stability (IPCC, 2022a).

Overshoot, even if temporary, intensifies climate impacts and raises the risk of irreversible economic and non-economic losses and damages. Physical changes may reverse as temperatures fall, but losses in communities with low adaptive capacity may not (Al Khourdajie et al., 2026) They extend beyond GDP to forced displacement and the loss of identity, culture and sense of place (Martyr-Koller et al., 2021), and they fall most heavily on the most vulnerable (Al Khourdajie et al., 2026).

2.5 Peaking warming, then bringing it down – why the shape of the overshoot matters, and why warming has to keep falling

The previous sections show that overshoot is not a single threshold crossed and then recrossed. How much damage it causes depends on its shape: how high warming peaks, how long it stays above 1.5°C, how fast it rises and falls, and where it ends. Different impacts respond to different features of this shape. Some follow the peak and ease as warming falls; others keep building up for every year spent above 1.5°C; and some cannot be reversed at all. Both the height of the peak and the length of the overshoot therefore need to be limited, and warming needs to keep falling afterwards.

Impacts that follow the peak. Heat extremes, record temperatures and many of their consequences for health, labour productivity and crops track the level of warming at any given time, and ease as temperatures decline. Under a pathway that limits warming

to around 1.5°C, the frequency of record-breaking hot days falls back below today's levels by the end of the century (Fischer et al., 2025). Peak warming, rather than the long-term outcome, determines adaptation needs and costs (Theokritoff et al., 2025). For many adaptation measures, particularly 'soft' options such as nature-based solutions, preparedness and early warning systems, adapting to the impacts expected at peak warming is more cost-efficient than planning for the lower levels expected after the overshoot. Most adaptation decisions are made over shorter planning horizons, so for these the peak is what counts. For long-lived infrastructure and for irreversible impacts such as sea-level rise, however, how far temperatures fall after the peak matters too (Theokritoff et al., 2025).

Impacts that build up over time. Other impacts respond to the time spent above 1.5°C rather than to the peak alone. Ice sheets and glaciers keep losing mass, and committed sea-level rise keeps growing, for every year that warming remains high. Around 2% of mountain glacier mass is lost, effectively permanently, for each 0.1°C of overshoot (Zekollari et al., 2025), and each additional 0.1°C of overshoot commits around 1.4 cm of additional sea-level rise by 2100, with much more over the longer term (Section 2.2). For ecosystems, the risks of collapse and extinction grow with both the magnitude and the duration of overshoot. In a 2°C overshoot scenario, species' exposure to potentially dangerous temperatures arrives suddenly but declines only gradually, lasting around 100 years in the oceans and 130 years on land, well beyond the roughly 60-year overshoot itself, with some ecological communities never returning to pre-overshoot conditions (Meyer et al., 2022).

Impacts that do not reverse. Some impacts will not reverse at all once warming comes down (IPCC, 2022c). Changes in the ocean, ice sheets and global sea level are irreversible for centuries to millennia (IPCC, 2021b); warm-water coral reefs may have already passed their estimated tipping point of around 1.2°C and face irreversible shifts above 1.5°C, even with only a temporary overshoot (Pearce-Kelly et al., 2025). Species losses are also irreversible (Meyer et al., 2022). Overshoot can also permanently narrow the options for adaptation. Hard limits have already been reached in some ecosystems, and above 1.5°C some ecosystem-based adaptation measures will lose their effectiveness, while limited freshwater may pose hard limits for small islands and glacier-dependent regions (IPCC, 2022c). These risks fall at a time when adaptive capacity in much of the world is still low (C.-F. Schleussner et al., 2024), and that capacity erodes further during overshoot, so that even impacts that later reverse physically can leave irreversible socioeconomic losses, concentrated among the most vulnerable (Al Khourdajie et al., 2026).

The rate of warming. How fast warming rises and falls also matters. Some tipping elements respond to the speed of change as well as to its magnitude: for the AMOC, a sufficiently rapid change in forcing, for example from increased freshwater input as the Greenland ice sheet melts, could trigger a collapse before the tipping point itself is reached (Dijkstra & van Westen, 2026). For societies, rapid warming leaves less time to adapt and is one of the ways in which climate impacts are converted into lasting losses; in an overshoot, the pace at which temperatures come back down adds a further

dimension of risk (Al Khourdajie et al., 2026). Slowing warming in the near term is therefore one of the most direct benefits of rapid emission reductions.

Implications. The shape of the overshoot is not predetermined, and different levers act on different parts of it. How high warming peaks depends mainly on how fast emissions, including methane, are cut in this decade and the next. How long the overshoot lasts, and where warming ends up, depend on reaching net zero greenhouse gas emissions which will bring temperatures back down. This matters: declining temperatures limit long-term risks compared with a mere stabilisation of warming (C.-F. Schleussner et al., 2024). But that decline cannot be taken for granted, given uncertainties in the climate response and in the scale of carbon dioxide removal that can be achieved; only rapid near-term emission reductions can reliably reduce climate risks (C.-F. Schleussner et al., 2024).

Warming has to keep falling. The evidence in this chapter points in one direction. From heat extremes and sea-level rise to ocean damage and tipping points, risks are lower the further and faster temperatures fall, and many of them keep growing for as long as warming stays near 1.5°C. Carbon cycle feedbacks, which amplify warming, also share a critical characteristic: they scale with temperature and are accelerated by sustained time at elevated temperatures. Stabilising at 1.5°C would lock in much of this damage; reaching well below 1.5°C by 2100 and continuing towards 1°C is what limits it. Chapter 3 sets out what this means for emission pathways.

3 Pathways: The latest evidence on how to get back below 1.5°C

Overshooting 1.5°C is now unavoidable (United Nations Environment Programme, 2026). How high warming peaks, how long it remains above 1.5°C and how far it subsequently declines are, however, not predetermined: they depend on decisions taken now and in the following years. This chapter draws on the latest emissions pathways to explore how low the magnitude and duration of overshoot can be limited if governments take climate action aligned with highest possible ambition from now onwards.

Based on the latest scenario literature, the evidence in this report shows that global warming can peak at around 1.7°C within the next 15 to 25 years and, after a period of overshoot, be brought back below 1.5°C (which we define as around 1.3°C) by 2100, with the potential to reach well below 1.5°C (which we define as ≤1.2°C) in those scenarios with lowest temperature outcomes.

How high warming peaks depends mainly on the pace of near-term emissions reductions and the date of net zero CO_2 emissions. How fast temperatures decline post-peak depends on scaling up CDR and how early net zero GHG emissions can be achieved in the second half of the century. This chapter explores what is needed to limit overshoot to as low as possible and keep the duration as short as possible, which defines how fast the solutions need to scale – a topic explored further in Chapter 4. It also explores how uncertainties in climate sensitivity could impact on the magnitude and duration of overshoot.

3.1 What can overshoot be limited to?

The 1.5°C pathways assessed in the IPCC Sixth Assessment Report (AR6) were able to limit warming to 1.5°C with no or low overshoot. This meant that peak temperatures would be kept to below ~1.6°C, and by 2100 warming would be brought back to around 1.2°C with net zero greenhouse gas emissions achieved by around 2070. However, these pathways assumed that globally coordinated mitigation would begin in 2020 (Riahi, K. et al., 2023). This did not happen. Global greenhouse gas (GHG) emissions in 2025 remained close to their 2019 level, roughly 25% above the level assumed in the AR6-assessed 1.5°C pathways (Climate Analytics, 2026c). This chapter looks at the latest scenario evidence to assess how low the peak and how short the overshoot can still be.

Two complementary lines of evidence address this question: the highest possible ambition scenario developed by Climate Analytics with the Potsdam Institute for Climate Impact Research (PIK), referred to in this report as HPA-2025 (Section 3.1.1), and a new generation of very low emissions pathways prepared for the IPCC Seventh Assessment Report (AR7) as part of the Coupled Model Intercomparison Project (CMIP7) (Van Vuuren et al., 2026). Both start from current emission levels, and both reach the same conclusion: peak warming can be limited to close to 1.7°C, followed by a return to below 1.5°C, and in the lowest scenarios, to well below 1.5°C, by 2100. Both sets also show the feasibility of reaching net zero GHG emissions in the second half of the century, by around the 2070s or earlier.

3.1.1 Highest possible ambition and the HPA-family

Article 4.3 of the Paris Agreement requires that each Party's successive nationally determined contribution (NDC) 'represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition (HPA), reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances' (Paris Agreement, 2015). Legal scholarship has read highest possible ambition, together with the principle of progression, as a normative standard that constrains how Parties set their NDCs, rather than leaving the level of ambition entirely to national discretion (Rajamani, 2016); (Voigt & Ferreira, 2016); (Mayer, 2024); (Schönfeld & Rogelj, 2025); (Schönfeld et al., 2026). The International Court of Justice's 2025 advisory opinion confirmed this reading: NDCs must reflect each Party's highest possible ambition, capable of making an adequate contribution to limiting warming to 1.5°C (para. 242), and, taken together, be capable of achieving the temperature goal of limiting global warming to 1.5°C (para. 245) (Section 1.2).

At the global level, highest possible ambition can be understood as a frontier: the fastest emission reductions that are technically and economically feasible from today, aligned with the temperature goal of the Paris Agreement. This frontier is not fixed. It moves as technologies mature, costs fall and evidence on mitigation options improves, while every year of insufficient action has implications for the lowest peak that can still be achieved. Global emissions pathways provide estimates of where the frontier lies at a given point in time. What countries commit to in their NDCs needs to be assessed against these estimates.

We use a set of pathways which quantify the frontier of highest possible ambition based on current emissions levels and technological progress. This consists currently of two key lines of evidence. These are:

1. **Climate Analytics' HPA scenario (HPA-2025).** Climate Analytics' and PIK's highest possible ambition scenario quantifies the frontier described above using the REMIND integrated assessment model (IAM). The scenario is referred to in this report as HPA-2025 (Climate Analytics, 2026c). It is the central modelled reference for this report.
2. **The Very Low (VL) pathways.** No single model or scenario can define the frontier on its own. We therefore combine the HPA-2025 scenario with a later set of pathways, developed as part of ScenarioMIP-CMIP7. Classified as "Very

Low" (VL), these pathways are designed to keep peak warming as low as can still be plausibly achieved and to return warming to 1.5°C or lower by the end of the century (Van Vuuren et al., 2026). These 11 pathways are drawn from across 7 different modelling frameworks: AIM (2 pathways), COFFEE (1), GCAM (1), IMAGE (2), MESSAGEix-GLOBIOM (2), REMIND-MAgPIE (2) and WITCH (1). Core design elements include rapid CO_2 reductions to net-zero as early as possible followed by sustained net-negative CO_2, deep near-term methane cuts, rapidly scaling electrification, and regionally differentiated carbon prices converging globally by 2050.

Together, these pathways form an envelope of what models currently find to be technically and economically feasible from today. We call these the "HPA-family" – although we note that the temperature outcomes across these 12 pathways vary noticeably, particularly at the end of the century. While they all can be used to help inform highest possible ambition, they should not be seen as equivalent across all dimensions.

An evolving family. Both elements will be updated as the evidence evolves. New pathways keep emerging, the costs of renewable energy and other zero-carbon technologies have fallen faster than anticipated, and our analytical framework is regularly updated. Climate Analytics will release new modelled versions of its own scenario, labelled by year, and will update the HPA family as new pathways become available. We will continue to assess, and push forward, the frontier of highest possible ambition wherever the evidence allows.

3.1.2 How low does the HPA family limit overshoot?

The HPA family demonstrates clearly that overshoot of 1.5°C is now unavoidable. In all pathways assessed, temperatures overshoot 1.5°C for around 40 years on average.

However, the current pathways and their temperature assessments suggest that the magnitude and duration of overshoot can still be limited, and by 2100 temperatures can be well below 1.5°C Figure 9. Across all pathways assessed, peak warming is limited to around 1.7°C or lower – this is consistent with limiting warming to "below 2°C" with a greater than 66% likelihood (see Box 2 on temperature thresholds). The HPA-2025 scenario reaches this around 2040, while the VL scenarios reach it around 2050. However, both lines of evidence show that warming can be halted in the next 15-25 years, with peak warming around 0.2°C above the 1.5°C limit. We note that the HPA-2025 scenario has its temperature assessed using the AR6 temperature assessment pipeline. In the assessment of the ScenarioMIP-CMIP7 VL scenarios, an updated pipeline was used, which can introduce some minor differences between the two studies (see Box 3 on uncertainties in temperature assessment).

Warming does not then plateau at 1.7°C but begins to decline. In the VL scenarios, all scenarios limit warming to 1.5°C or lower, and 6 scenarios achieve end of century temperatures around 1.3°C, which can be interpreted as "below" 1.5°C with a 66% likelihood (see Box 2). Meanwhile the HPA-2025 scenario brings end of century temperatures down to 1.2°C, showing one possible route to limiting warming to "well below" 1.5°C by 2100 (Box 2).

Together, the HPA family shows that, while overshoot is now unavoidable, peak warming can be limited to around 1.7°C, and end of century warming brought to below 1.5°C and ideally well below 1.5°C.

Reaching net zero CO_2 by around mid-century and net zero GHGs by around the 2070s or before is critical for bringing temperatures back down (Section 3.1.4). On average, temperatures remain above 1.5°C for around 40 years in these scenarios, with a range of 31-50 years in those pathways that get to below or well below 1.5°C by 2100, as defined by Box 2 (and a range of 31-65 years when including all VL scenarios).

Box 2: Interpreting "below" and "well below" temperature thresholds

The Paris Agreement and preceding agreements under the UNFCCC set temperature targets in relation to the language of limiting warming to "below" or "well below" a certain threshold. We here continue to use this logic in a consistent manner.

The "below 2°C" goal set in Cancun was widely interpreted as limiting warming to 2°C with a 66% probability (C. Schleussner et al., 2022). We use this same interpretation here and extend it to 1.5°C. Meanwhile, this demands that "well below" would have a higher probability of limiting warming. The next highest probability used by the IPCC is 83% (although this is not given a likelihood threshold, the next being >90% which is "very likely"). We therefore argue that to limit warming to "below" a threshold equals a >66% likelihood of limiting warming to this level, but less than 83%. Meanwhile limiting warming to well below a threshold requires a >83% likelihood of limiting warming to the same threshold. Using an approach developed by Lamboll and Rogelj (2026) we classify these thresholds as follows (Lamboll & Rogelj, 2026):

Temperature	Well below	Below but not well below
2°C (at peak)	1.6 or lower	1.7–1.8
1.5°C (end of century)	1.2 or lower	~1.3°C

The cost of the past five years of delay is evident from a comparison with the AR6 pathways: peak warming at least 0.1°C higher, an overshoot around a decade longer, and roughly three times greater cumulative exposure to warming above 1.5°C (Climate Analytics, 2026c). Yet the delay has not closed off a return below 1.5°C. It means that deeper emission reductions must now be achieved in less time.

Peak warming can be limited to around 1.7°C and end-of-century warming brought down to around 1.3°C

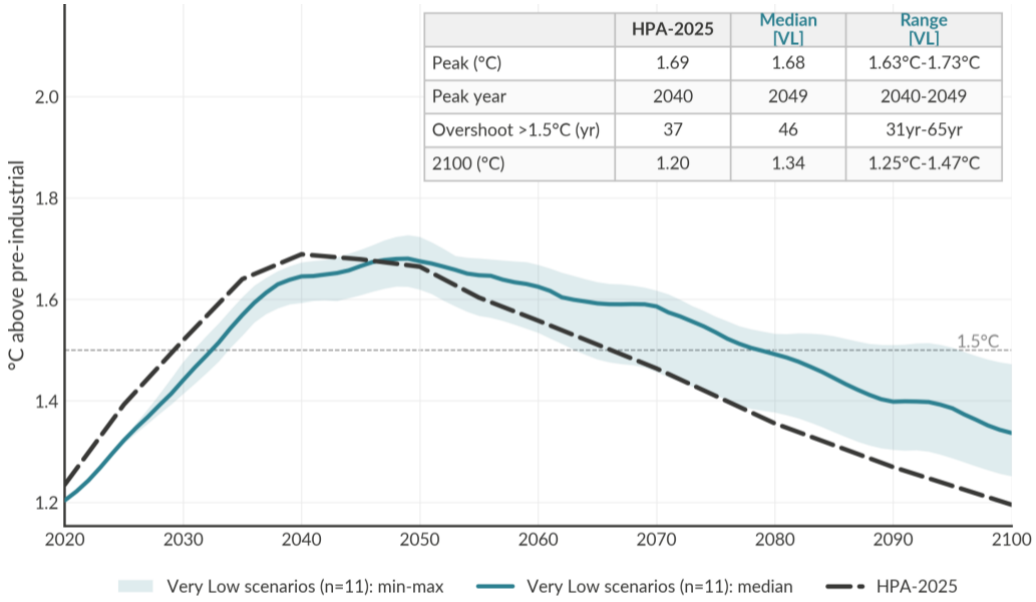


Figure 9: Temperature outcomes of the HPA family. This figure shows GMST as reported by MAGICC 7.5.3 (HPA-2025) and MAGICC 7.6.0a3 (Very Low scenarios).

These latest pathways no longer limit warming to 1.5°C with no or low overshoot of 1.5°C. As such, they are no longer fully compatible with Paris Agreement's long term temperature goal (C. Schleussner et al., 2022). However, many of them still align with the spirit of the Paris Agreement and its architecture – limiting peak warming, achieving net zero GHGs in the second half of the century and thereby bringing temperatures back below 1.5°C before 2100. As such we term these pathways "Paris-aligned". We define Paris-aligned pathways as those which limit peak warming to below 2°C, bring end of century warming to below 1.5°C, and reach net zero greenhouse gas emissions before 2100 (on average around 2070). This compares with fully Paris-compatible pathways, which limit peak warming at well below 2°C and bring end of century warming to below 1.5°C, while still reaching net zero GHGs pre-2100, and on average around 2070–2075.

In this framing, the HPA-2025 qualifies as Paris-aligned but not Paris-compatible – as it does not limit warming to well below 2°C but to around 1.7°C, which is only "below" 2°C. However, it does bring warming in 2100 to "well below" 1.5°C.

In the case of the 11 VL pathways, all 11 limit peak warming to at least "below 2°C". In 2100, 6 VL pathways limit warming to "below 1.5°C", and none of them limit warming in 2100 to "well below" 1.5°C. The other 5 are "around 1.5°C" (i.e. under 1.5°C but not

strongly). Meanwhile 8 of the VL pathways reach NZ GHGs before 2100, with 3 not reaching it by 2100.

In combination, only 4 of the VL pathways are consistent with our definition of Paris-aligned pathways, across peak and end-of-century temperatures and net zero dates. However, many of the remaining pathways are very close to the definition. Three more VL pathways would be consistent with Paris-aligned if their end of century temperatures were only 0.01–0.02°C lower, and two more would be Paris-aligned if their GHG emissions in 2100 were reduced by under 500 $MtCO_2e$ /yr. As a result, we keep all 11 VL scenarios in our analysis here, while noting that not all strictly align with our definition – but all are useful for assessing how to minimise the magnitude and duration of overshoot.

We now turn to explore the shape of the emissions pathway which achieves these "Paris-aligned" temperature outcomes.

Box 3: Uncertainties in temperature assessment

Scientists use reduced-complexity emulators to estimate the temperature implications of a given emissions pathway. A wide range of emulators exist that can be used here, including MAGICC, FAiR, CICERO-SCM and more , (Leach et al., 2021), (Meinshausen et al., 2011).

In pre-processing the emissions data to conduct a temperature assessment, it is necessary to harmonise the emissions to an agreed historical reference and infill any missing gases for a scenario, to ensure scenarios are compared consistently (Kikstra et al., 2022).

The methods used in temperature assessments are continually evolving. For the IPCC AR6 report, a published workflow exists (Kikstra et al., 2022), which is what is used for our internal temperature assessments of the HPA-2025. However, an updated approach is being developed as part of the scenario development forCMIP7, which is used for these scenarios. This includes:

- more recent historical data that extends to 2023 (CMIP7) compared to 2015 (AR6)
- an updated harmonisation routine
- an update to the MAGICC emulator and its calibration from v7.5.3 to v7.6.0

This is part of the reason for the differences in temperature profile between the HPA-2025 and the broader HPA family. In particular, the updated temperature assessment pipeline appears to lead to lower near-term temperatures but also delays in the timing of peak warming.

As harmonisation workflows are still under development, we have not updated the HPA-2025 temperature assessment to the latest workflow yet. However, a preliminary investigation of the differences between the workflows suggests that the impact is relatively minor, with peak temperatures falling by 0.02°C on average under the new routine, the date of peak warming delayed by around a decade and end of century temperatures down by 0.01°C.

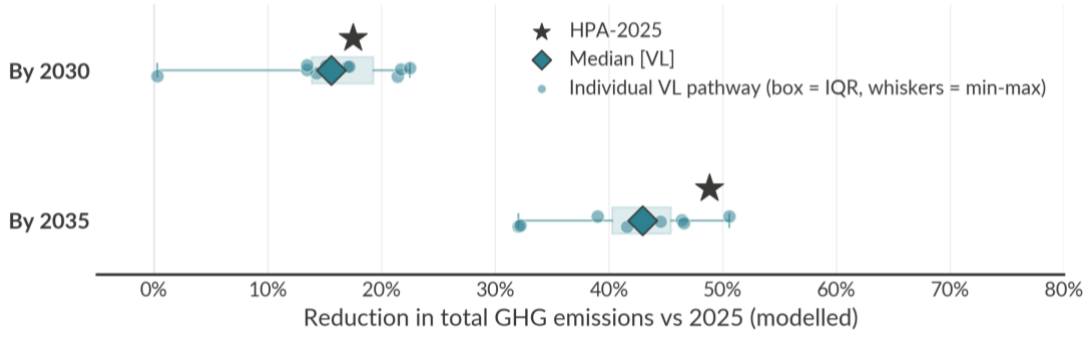
3.1.3 Near-term emissions cuts

The HPA family all attempt (in different ways) to start from today's emissions levels and explore the fastest pace of emissions reductions that is feasible from this point onwards.

Under highest possible ambition, global emissions peak as soon as possible and have fallen significantly by 2030 – by a little under 20%, relative to 2025 levels Figure 10. This means global emissions fall by around 10 $GtCO_2e$ over the next 4 years.

This lays the foundations for even deeper cuts in the 2030s. Emissions fall by 49% over 2025-2035 in the HPA-2025 scenario. The median VL scenario is not far behind, with emissions falling 43% over 2025-2035.

The HPA family sees emissions fall rapidly by 2035



	HPA-2025	Median [VL]	Range [VL]
By 2030	18%	16%	0% to 22%
By 2035	49%	43%	32% to 51%

Figure 10: Near-term emissions reductions under the HPA family. The variable used is the harmonised and infilled total Kyoto basket in each scenario, measured in AR6 GWP100.

Near-term emissions cuts are critical to minimising overshoot. In the near-term they can make a significant difference to the rate of warming, which is critical for many adaptation thresholds and impacts (Section 2.5). And only by rapidly cutting emissions can we reach net zero CO_2 and GHG emissions as soon as possible, which is the only way to halt and ultimately reverse global warming.

3.1.4 Net-Zero timing

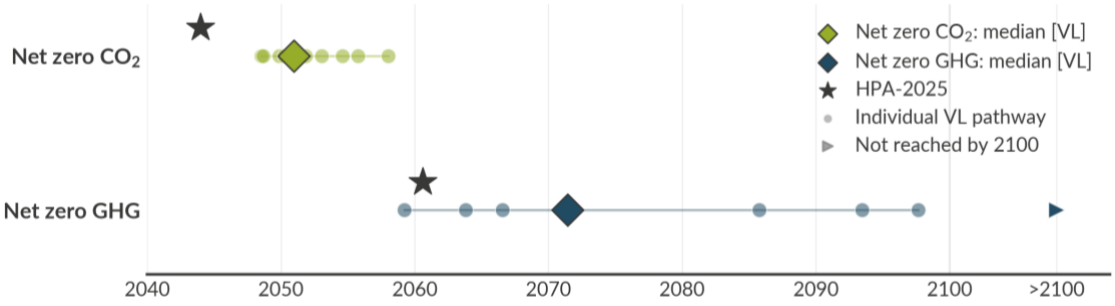
Reaching net zero CO_2 emissions will stop global warming (MacDougall et al., 2020)[1] Reaching net zero GHG emissions is what brings temperatures back down and limits long-term tipping risks (Tarshish et al., 2026), (Möller et al., 2024).

Both the HPA-2025 and the new set of scenarios from ScenarioMIP demonstrate the critical importance of achieving net zero CO_2 and GHG emissions as soon as possible (Figure 11).

In the VL set, net zero CO_2 is reached on average by 2051 (range 2049–2058) across the pathway set; net zero GHGs are reached in the 2070s (range 2059–98) among 8 of 11 pathways that reach it by 2100. Overall, 5 VL scenarios reach net zero GHGs by the 2070s or earlier. In HPA-2025, both milestones occur earlier: net zero CO_2 in 2044 and net zero GHG around 2060.

Achieving net zero CO_2 around 2050 determines how high warming peaks. Reaching net zero GHG around the 2070s or before determines how quickly warming returns below 1.5°C and where it stands in 2100. Both milestones are critical to minimising the magnitude and duration of overshoot.

Reaching net zero CO_2 and GHG emissions is crucial for limiting the magnitude and duration of overshoot



	HPA-2025	Median [VL] (reached only)	Range [VL] (reached only)
Net zero CO_2	2044	2051	2049-2058
Net zero GHG	2061	2071	2059-2098

Figure 11: Dates of net zero in the HPA family

3.1.5 CDR as a key lever in bringing temperatures back down

CDR is essential to limiting overshoot, but *only* if it is paired with immediate and ambitious cuts to emissions. In a world overshooting 1.5°C, CDR is a necessity not a

[1] The latest climate science suggests CO_2-induced warming will stop when CO_2 emissions reach net zero, with an average zero emissions commitment of -0.11°C temperature change after reaching net zero CO_2 (R. G. Williams et al., 2025). Total warming is a function of other Kyoto gases such as CH_4, N_2O and F-gases, as well as non-Kyoto species such as BC, OC and other short-lived climate forces. However, if emissions from these other warming species are flat or declining (as is the case in these scenarios), then reaching net zero CO_2 would be sufficient to stop warming.

choice in minimising the magnitude and duration of overshoot. The latest minimum overshoot scenarios all rely on removals to help bring temperatures back below 1.5°C. However, in a world that is not also cutting emissions in line with highest possible ambition, then CDR is futile – as it cannot be scaled sufficiently to bring temperatures down on its own. CDR must be paired with deep emissions reductions to limit the magnitude and duration of overshoot.

Figure 12 shows the total CDR deployment in the HPA-2025 and in the VL scenarios, across the methods which are deployed in these scenarios. IAMs are increasingly incorporating a broader set of CDR routes, with most scenarios representing bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS) and Afforestation/Reforestation (A/R). Many models also include deployment of enhanced weathering (EW), soil carbon sequestration (SCS) and biochar as well.

Cumulative CDR over 2020-1200 by route in the HPA family

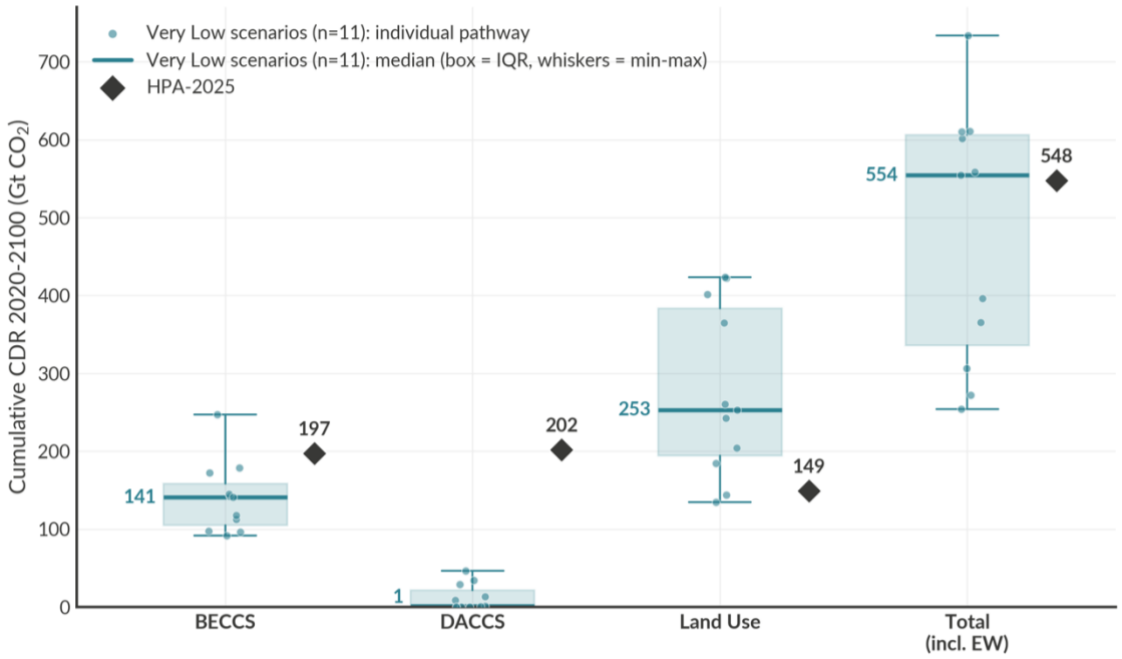


Figure 12: Cumulative CDR deployment in the HPA family

In general, these pathways which align with highest possible ambition require cumulative removals of over 500 $GtCO_2$ over the century. The HPA-2025 relies more heavily on novel removals from BECCS and DACCS, and less on removals from the land-use system, which come largely from A/R. Meanwhile the VL scenarios rely more heavily on land-use removals, which they derive from a mix of conventional removals from A/R and SCS, as well as some removals from new land-based novel CDR routes

such as biochar. They generally have lower BECCS/DACCS deployment (particularly DACCS).[2]

While there are variations in the portfolio of CDR options used across models, there is agreement that overall CDR deployment needs to rapidly scale up. In the VL set of scenarios, removals reach around 6 $GtCO_2/y$ by 2050 and rise to around 11 $GtCO_2/y$ in 2100 (Figure 13). The HPA-2025 has a faster near-term scale-up but a lower long-term saturation level, with both leading to the same levels of cumulative removals.

Rapidly scaling up removals is essential to bring temperatures back below 1.5°C

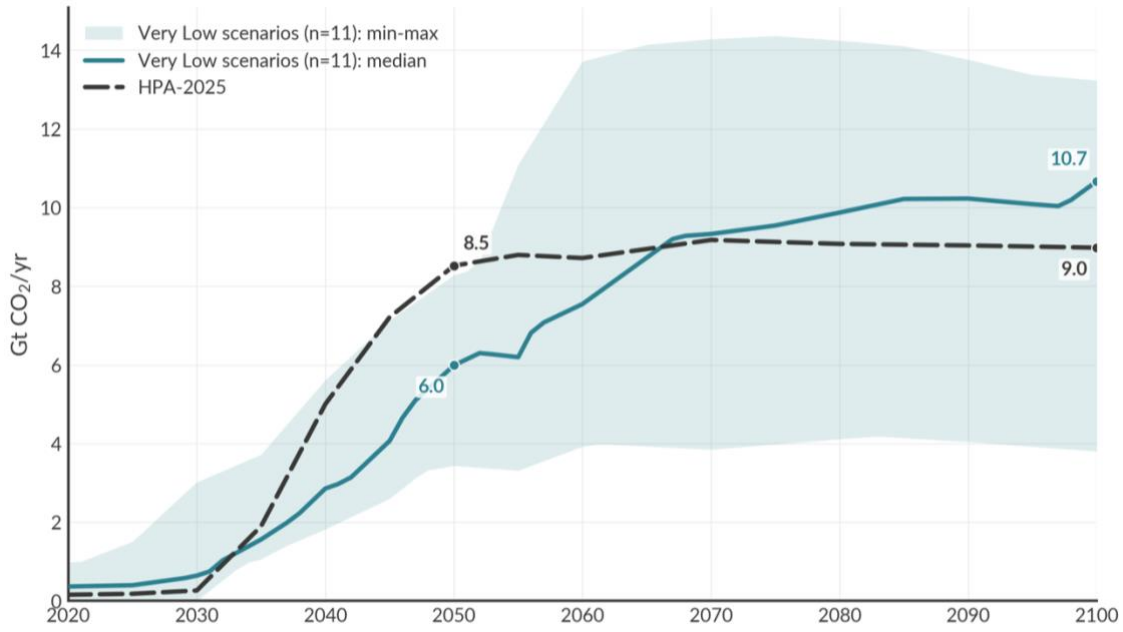


Figure 13: CDR deployment trajectories in the HPA family

3.1.6 Summary: What do the latest pathways tell us?

The shape of the overshoot – its height, its duration and the extent of subsequent cooling – is determined by different factors at different stages. The pace of near-term emissions cuts and the date by which we reach net zero CO_2 emissions are key to controlling the magnitude of overshoot, and how high we peak. Meanwhile, the date of net zero GHG emissions and the scale of CDR rollout are critical to controlling the duration of overshoot and how quickly we get back below 1.5°C. Both elements are critical in a world of overshoot.

Both the HPA-2025 and the broader HPA family show that peak temperatures can be limited to near 1.7°C, and by 2100 temperatures can be limited to below, or well below, 1.5°C. Key metrics from each set of pathways are shown in Table 1.

[2] Note that the sum of the median deployment of BECCS + DACCS + Land use does not equal the total deployment. This is a common phenomenon when looking at medians of sub-categories, which are not necessarily additive.

Table 1: Key metrics from the scenarios

	HPA-2025	VL scenarios
Peak warming (°C)	1.69	1.68 [1.63-1.73]
Year of peak warming	2040	2049 [2040-2049]
Limits peak warming to below 2°C?	Yes	All 11 do so
Limits peak warming to well below 2°C?	No	4 of 11 still do so
Years above 1.5°C	37	46 [31-65][3]
Warming in 2100 (°C)	1.2	1.34 [1.25-1.47]
Limits warming in 2100 to below 1.5°C?	Yes	6 of 11 do so (with 3 further very close)
Limits warming in 2100 to well below 1.5°C?	Yes	None do so
Year of peak emissions	2025	2025
Net zero CO_2	2044	2051 [2049-2058]
Net zero GHG	2061	2071 [2059–2098] for the 8 reaching net zero GHGs before 2100
Cumulative CDR (2020-2100) ($GtCO_2$)	548	554
Number of pathways	1	11

[3] And an overshoot duration window of 31-50 years for those which return 2100 warming to below 1.5°°C with a 66% probability

4 Solutions exist, the pace does not yet

In this chapter, we look at the range of levers essential to minimising the magnitude and duration of overshoot and returning global warming below 1.5°C by the end of the century. We show a path to this end with technologies that can deliver the lion's share of the effort.

As fossil fuels cause the majority of global greenhouse gas emissions, phasing out fossil fuels is essential. This depends critically on rapid, large-scale deployment of both renewable electricity and end-use electrification to replace coal, oil and gas. Making the energy system more efficient will constrain the scale of deployment needed across clean energy infrastructure. Other levers will also be required, including a rapid reduction in methane emissions and a major scale-up in carbon dioxide removal to bring temperatures down after peak overshoot is reached.

We look at real-world progress against targets and against benchmarks set primarily by the HPA-2025 and AR6 where these offer a better alternative. Finally, we look at the economics of the transition, focussing on price trends, investment needs and international support. The solutions assessed in this chapter all act on greenhouse gases, the root cause of climate change. Annex B sets out why solar radiation modification, which leaves those gases in the atmosphere, is a dangerous distraction from them.

4.1 A fossil fuel phase-out is essential

Fossil fuels are at the heart of the climate crisis, and the means to replace them already exist. Fossil fuels account for around 70% of global greenhouse gas emissions (Schumer et al., 2025), so transitioning away from them needs to be at the heart of the solution to climate change.

In the HPA-2025 scenario, coal is effectively phased out in the 2040s, gas in the 2050s and oil in the 2060s (Table 2 and Figure 14). Different sectors decarbonise at different paces, with the power sector leading the phase-out, followed by buildings, transport and industry (Climate Analytics, 2026). Reductions need to start now, with most of coal demand and half of gas demand dropping to zero before 2035.

The global transition away from fossil fuels in the HPA-2025

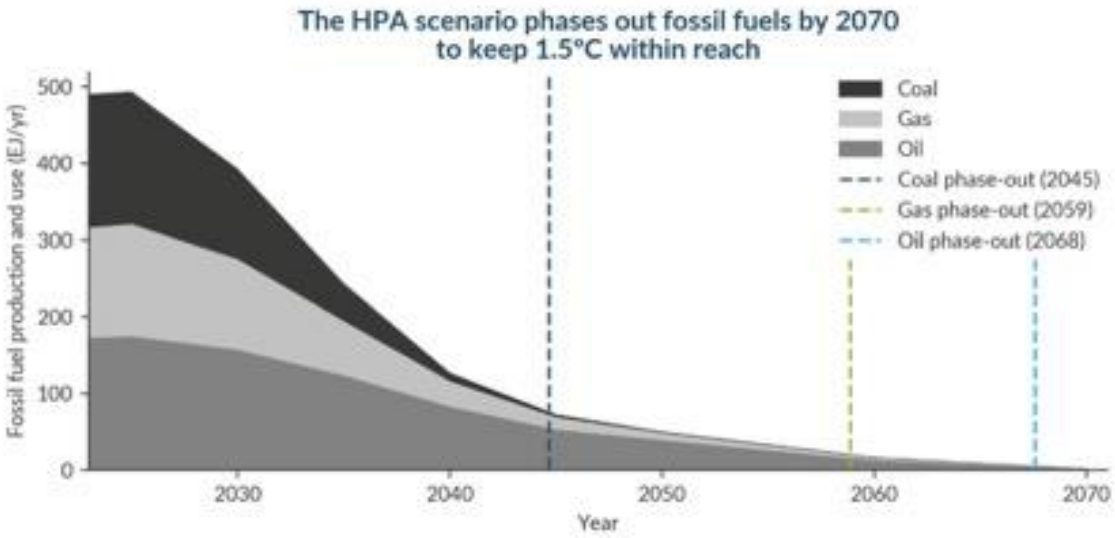


Figure 14: The global transition away from fossil fuels in the HPA-2025. Under the scenario, all coal, gas and oil exit the global economy by 2070, facilitating a complete phase-out of fossil fuel use across sectors. We define a phase-out as when production falls by over 97.5% relative to 2023 levels.

Table 2: Global reductions in fossil fuel production and use in the HPA-2025, relative to 2023

	2030	2035	2050	2070
Coal	-32%	-72%	-99%	-100%
Gas	-18%	-51%	-94%	-100%
Oil	-9%	-28%	-77%	-99%
Total	-20%	-50%	-90%	-100%

The power, road transport and building sectors account for about two-thirds of global fossil fuel demand; and for most applications within those sectors, alternatives are readily available. Table 3 shows the centrality of renewable generation and electrification to system-wide decarbonisation, with these two measures representing the dominant alternatives to fossil fuels in virtually every application.

Table 3: The breakdown of global fossil fuel demand and the primary options that exist to displace fossil fuels

Sector	Share of global fossil fuel demand in 2023	Primary fossil-free options
Power sector	37%	Wind / solar / batteries / zero-carbon firm generation / demand-side response
Surface transport	20%	Electrification / active transport / public transport
Buildings	10%	Electrification / district heating / energy efficiency
Steel	4%	Electrification (both primary and secondary) / H_2 - DRI
Chemicals (excl. feedstocks)	3%	Electrification / H_2 / Sustainable biomass
Rest of manufacturing	5%	Electrification / Sustainable biomass / H_2
Cement	3%	Sustainable biomass / electrification (+ CCS for process emissions) / Alternative chemistries
Feedstocks	10%	Increased circularity / Product substitution / Sustainable biomass / Synthetic feedstocks
Aviation and shipping	5%	Major demand shifts / Sustainable biofuels / Synthetic feedstocks / Partial electrification
Remainder	<3%	Largely electrification

Renewables, particularly solar and wind, are the dominant route to decarbonising the power sector as they are cheap and fast to deploy, whereas nuclear and CCS have made little progress. The near-stasis in CCS also increases the importance of electrification and other technologies, such as green hydrogen, in industry. Section 4.2 sets out the goals, the 1.5°C-aligned benchmarks and the progress so far for each of these levers.

4.2 Goals, benchmarks and progress in the key levers

4.2.1 Electrification

Goal: there is no formally agreed goal on electrification to date. A target of raising the global electrification rate from the current level of 23% to 35% by 2035 has been proposed by the Turkish COP31 presidency and may be endorsed by some governments at COP31.

1.5°C alignment: in the HPA-2025, the global electrification rate increases to 39% in 2035 and 65% by 2050[4], which exceeds the goal mentioned above and implies that this goal should be taken as a floor for setting the ambition required to limit overshoot.

Progress: achieving the 35% target by 2035 would require a significant acceleration. The global electrification rate has increased by only 4.3 percentage points since 2010, an average of 0.3 percentage points per year (Enerdata, 2026). Delivering the mooted 2035 target would therefore imply quadrupling the current rate of progress.

As indicated, electrification is fundamental to a clean energy transition. It enables us to replace fossil fuels with clean, renewable electricity in key end-use sectors, including buildings, transport, and industry. Furthermore, electrotechnologies offer major energy efficiency gains, converting final energy into useful services 2 to 4 times more efficiently than fossil fuel equivalents.

Table 4: Global sectoral electrification rates under the HPA-2025 per time horizon

	2023	2030	2035	2050
Buildings	36%	44%	**57%**	83%
Transport (excluding aviation and shipping)	2%	9%	**22%**	74%
Industry	22%	28%	**37%**	50%
Industry (excl. feedstocks)	25%	32%	**42%**	57%
Total	21%	28%	**39%**	65%

[4] The electrification rate can vary a few % points depending on whether non-energy and bunkers are added

Achieving an energy transition in line with the Paris Agreement requires rapid, renewables-driven electrification matched with robust grid infrastructure and system flexibility.

The growth trajectories, underlying drivers, and structural dynamics differ significantly across sectors:

- **Transport** is currently the least electrified end-use demand sector and remains heavily reliant on oil. However, under the HPA-2025, it experiences the steepest rate of growth of any sector, undergoing a massive transformation driven by a rapid expansion in battery electric vehicle (BEV) sales across light-duty vehicles, buses, and short-haul road freight. As battery technologies improve and production costs fall, direct electrification will also address heavy-duty trucking. For harder-to-abate segments with high energy-density requirements, such as long-distance aviation and maritime shipping, direct electrification is complemented by indirect electrification via sustainable biofuels, green hydrogen/ammonia, and synthetic fuels.
- **Industry** represents the largest global consumer of final energy and is currently one of the most challenging sectors to decarbonise due to diverse heat requirements and reliance on fossil fuels for feedstocks. Industrial electrification undergoes substantial acceleration, primarily driven by the deployment of commercially mature electro-technologies such as industrial heat pumps, electric boilers, and electro-thermal energy storage for low- and medium-temperature process heat and steam. High-temperature applications rely on direct electrification through electric arc furnaces (EAF) for secondary steelmaking, alongside emerging innovations like electric kilns and steam crackers. For primary chemical feedstocks and high-temperature processes that cannot be directly electrified, indirect electrification using electrolytic green hydrogen plays a critical role.
- **Buildings** is currently the most electrified end-use sector globally, benefiting from widespread electricity use in lighting, appliances, and cooling. The sector maintains a steady and continuous rate of increase, driven by replacing fossil fuel space and water heating with highly efficient electric heat pumps, transitioning to electric cooking, and integrating on-site solar and thermal storage. Growth is further shaped by expanding global cooling demand under rising temperatures, rapidly increasing electricity consumption from data centres, and parallel investments in building envelope energy efficiency.

As noted above, the increase in the electrification rate needs to accelerate markedly to reach the 35% mark by 2035 – still more to reach the 1.5°C-aligned 39% level.

While technologies like electric passenger vehicles and residential heat pumps are expanding under existing policies, systemic infrastructure bottlenecks, underdeveloped grids, high financing costs, and insufficient policy frameworks continue to hold back the scale and speed of adoption required across major economies.

To ramp up deployment, national policies must anchor electrification targets in measurable, quantifiable bottom-up indicators. Headline goals like '35 by 35' provide helpful political orientation, but must be underpinned by granular, technology-specific indicators such as annual heat pump sales, electric vehicle stock shares, and clean industrial heat deployment, while explicitly linking to clean power capacity so that rapid electrification does not inadvertently prolong reliance on fossil generation.

Trajectories under the HPA-2025 illustrate sharp regional divergence based on industrial structure and infrastructure readiness, where advanced economies and frontrunners such as Germany (47%), Japan (47%), and China (46%) achieve high 2035 electrification rates, while emerging economies such as India (33%) progress more slowly due to structural hurdles requiring low-cost capital and technology transfer.

Crucially, policy implementation faces growing operational bottlenecks from unexpected load pressures driven by data centres and industrial expansion, and surging cooling demand from rising global temperatures. This is accompanied by varying regional factors, for example, in Brazil, where sustainable biofuels may offer a more immediate fit, or in South Africa, where entrenched coal generation could see electrification reinforcing fossil dominance. Finally, national policy frameworks must place basic electricity access at the very heart of the electrification agenda, ensuring that the benefits of energy security, reliability and affordability through electrification are experienced by all segments of society.

At COP28 in Dubai, as part of the outcomes of the first Global Stocktake (GST1), Parties to the Paris Agreement agreed to two headline targets by 2030: tripling global installed renewable energy capacity and doubling the annual global rate of energy efficiency improvements ((UNFCCC, 2023); hereinafter referred to as the GST1 targets).[5]

4.2.2 Renewables

Goal: in the first Global Stocktake under the Paris Agreement (GST1, 2023) governments endorsed the goal of tripling global renewable capacity from 3.4 TW (2022 level) to 11 TW by 2030.

1.5°C alignment: in the HPA-2025, global renewable capacity reaches 11.9 TW by 2030 (a 3.5-fold increase from 2022), with wind and solar accounting for 10.2 TW, and 25 TW by 2035.

Progress: with solar energy continuing its remarkable exponential expansion – capacity doubling every three years for more than a decade (Ember, 2025a) – renewables overall are virtually on course to reach the above-stated goal. In 2025, capacity rose by 15.5%

[5] 11 days before the end of COP 28, the COP Presidency launched the Global Renewables and Efficiency pledge. Unlike the GST outcome, which was agreed by all Parties under the Paris Agreement, the pledge brings together around 130 signatories which do not include some large countries such as China, India, Russia and Saudi Arabia. The pledge commits signatories to work together to triple the world's installed renewable energy generation capacity to at least 11,000 GW by 2030 from 2022 levels, taking into consideration different starting points and national circumstances; and to collectively double the global average annual rate of energy efficiency improvements from around 2% to over 4% by 2030.

(or 0.7 TW) and if this rate of increase continues to the end of the decade, renewable capacity will stand at 10.6 TW in 2030, within touching distance of the GST1 target (International Renewable Energy Agency, COP31 Presidency, Global Renewables Alliance, 2026).

Renewables continue to break records and have already become – and remain – the most cost-competitive source of new electricity generation, with more than 90% of utility-scale projects commissioned in 2025 being cheaper than the cheapest fossil fuel alternative (International Renewable Energy Agency (IRENA), 2026). Since 2010, solar PV costs have fallen by 89% and onshore wind by 71% (International Renewable Energy Agency (IRENA), 2026).

In 2025, global capacity reached 5.2 TW, led by China (44% of the global fleet), the EU (18%), the US (9%) and India (5%) (IRENA, 2026b). Renewables provided 34% of global electricity (IEA, 2026a). In 2025, renewables avoided an estimated USD 480 billion in fossil fuel costs and about 8.4 gigatonnes of CO_2 emissions. In the same year, solar PV was the fastest-growing energy source and, for the first time on record, a modern renewable supplied the largest share (over 25%) of global energy demand growth (IEA, 2026a).

Global renewable capacity gap against GST1 target is already 1 TW by 2025

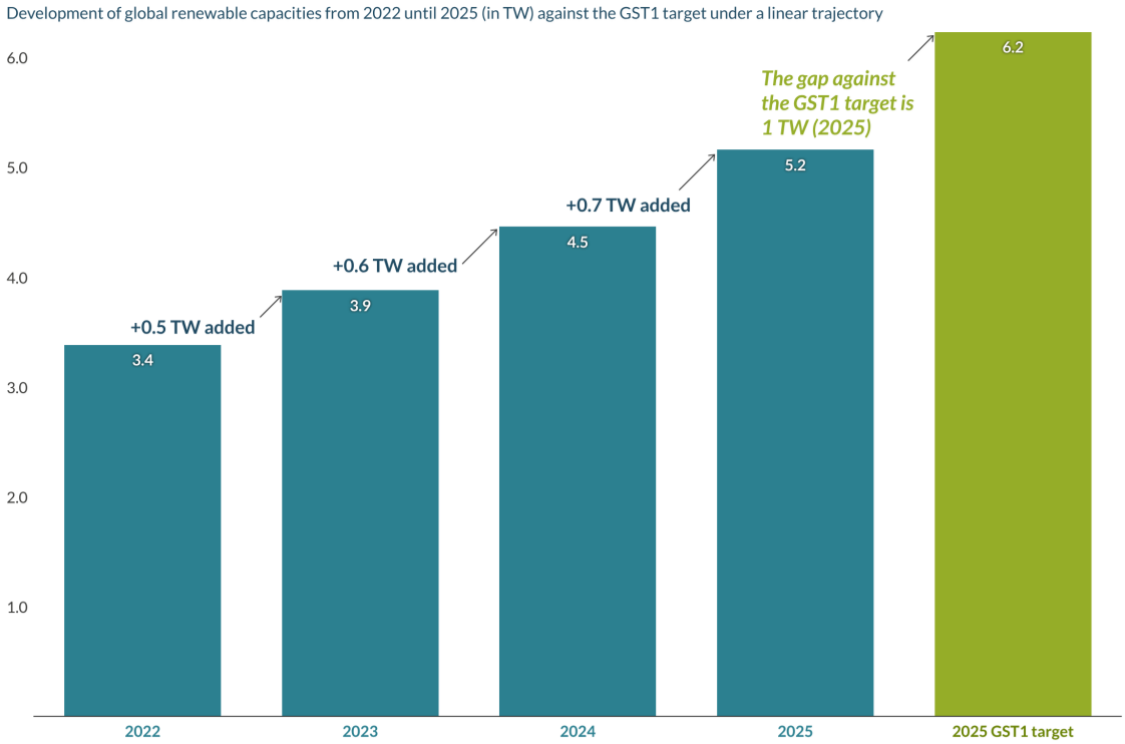


Figure 15: Global renewable capacity (2022 - 2025) indicates a theoretical gap of 1 TW by 2025 compared to the expected global renewable capacity, based on the GST1 target. Chart: Climate Analytics, Source: Renewable Energy Statistics 2026 – IRENA

Despite annual additions increasing by roughly 0.1 TW each year, even the sustained deployment of 0.95 TW annually from 2026 would bring capacity to 10 TW by 2030. Meeting the global tripling goal instead, using 2025 as the starting point, requires average additions of 1.2 TW annually – twice the recent average – while achieving the HPA-2025 level of 11.9 TW to limit overshoot requires an average of 1.35 TW annually. That translates into an existing double gap, that of implementation as well as one of ambition, to get on a trajectory commensurate with minimising overshoot.

As regards future trends (Figure 16 below), the IEA (IEA, 2024) estimates that all existing goals, plans and targets of 150 countries would add up to about 8 TW of total global renewable capacity by 2030 (IEA 2024 (Plans & Targets)), whereas IEA's 2025 (Main case) which assumes recent cost trends, current policies and market developments (IEA, 2025b) reaches 9.5 TW in 2030. Both scenarios fall short of the levels required to limit overshoot (HPA-2025) by roughly 2.5 to 4 TW by 2030, highlighting an important gap.

Global renewable capacity projections

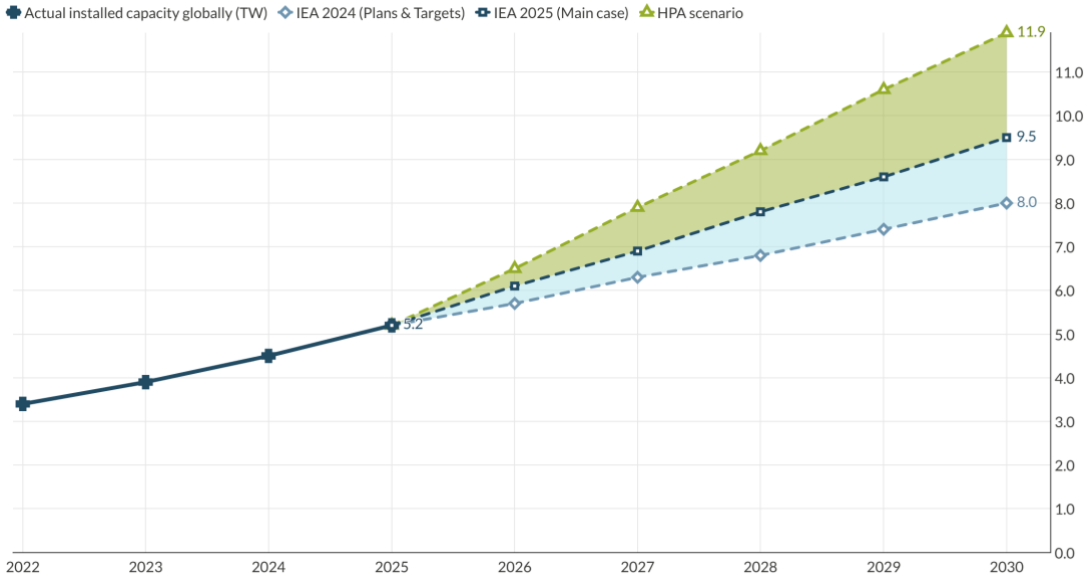


Figure 16: Global renewable capacity projections, considering 2 IEA scenarios and HPA-2025. Actual installed capacity globally taken from IRENA Energy Statistics 2025; IEA (Plans & Targets) refer to all existing goals, targets and plans of 150 countries - ''IEA, Renewables 2024 - Analysis and forecast to 2030''; IEA (Main Case) refers to IEA's main case, recent cost trends, current policies and market developments taken from the updated 2025 projections from IEA, Renewables 2025 - Analysis and forecasts to 2030. Chart: Climate Analytics • Source: 1. IRENA Energy Statistics 2026; 2. IEA, Renewables 2024 - Analysis and forecast to 2030; 3. IEA, Renewables 2025, Analysis and forecast to 2030;

Renewables can expand energy access in developing and emerging economies, improving livelihoods and economic competitiveness. Yet higher investment risks often make identical projects more expensive than in developed markets. The cost of capital is a major barrier: financing utility-scale solar PV costs 7.1% in India versus 2.2% in Germany, while an increase in the cost of capital from 2% to 10% raises electricity costs

by 80% (IRENA, 2023a). International cooperation, targeted de-risking and concessional or blended finance can help bridge this gap.

Ancillary investments alongside renewable energy technologies will also be required. The growth in curtailments highlights the need for firm renewable power around the clock. For example, in Brazil, curtailment has increased sharply with the recent growth of solar (21%) and wind (14%) in the first half of 2025, up from near zero in 2022 (IRENA, 2026a). In prime solar and wind regions, hybrid solutions combined with storage deliver round-the-clock power at lower costs than fossil fuels. According to IRENA, solar plus battery costs can range from USD 54-82 per megawatt-hour (MWh) in high-quality resource regions, compared with USD 70–85 per MWh for new coal in China and more than USD 100 per MWh for new gas globally (IRENA, 2026a) .

Storage – which together with grids will define the ability to accelerate and deepen the energy transition – saw a record increase of 48% and 112 GW globally (or 307 GWh) installed (with China accounting for more than 50%), with an impressive year-on-year cost reduction of 30% (2024-2025), reaching 140 USD/kWh. Battery storage costs have declined more than 95% since 2010 (International Renewable Energy Agency, COP31 Presidency, Global Renewables Alliance, 2026). After a period of stagnation, investment in grids globally has accelerated in recent years, with an increase in total spending of USD 45 billion in 2025 to reach roughly USD 450 billion, marking the largest increase across the power system. A further 17% growth is expected in 2026, noting though that this increase partly reflects pressures from higher inflation on grid equipment, like transformers, cables, and overhead lines, not just higher volumes of the infrastructure that was delivered (IEA, 2026c). Taken together, under the assumption of cost reduction in the future, renewables, storage and grids will be the key enablers for a successful decarbonisation and electrification of the global economies, displacing fossil fuels.

Alongside investment in grids, storage, system flexibility, electrification and efficiency, stable regulation, competitive auctions and long-term power purchase agreements can accelerate deployment. Together, these measures can turn efforts to limit climate overshoot into an opportunity for cheaper, more secure and more accessible clean electricity.

4.2.3 Energy efficiency

Goal: also during the first Global Stocktake in 2023, governments committed to doubling the annual rate of energy efficiency improvements by 2030, from 2% to 4%.

1.5°C alignment: the HPA-2025 features a 3.6% compound efficiency improvement rate by 2030 and 3.9% by 2035, compared to 2022 (Climate Analytics, 2026).

Progress: global energy efficiency improvement has averaged around 1.3-1.8% annually since 2019 (IEA, 2025a), indicating a gap of 1.8 to 2.3 percentage points against the required levels (HPA-2025), with annual improvements in the last three years standing at 1.1%, 1.1% and 1.7%.

Three years on from COP28, energy efficiency improvement remains a largely neglected, although critical, element of the transition. The serial shortfall against the GST1 target means that to deliver that target, efficiency now needs to increase by 5.6% per year to 2030 (International Renewable Energy Agency, COP31 Presidency, Global Renewables Alliance, 2026). A substantial acceleration is also needed to align with the HPA-2025 and minimise overshoot.

There are significant regional differences. Energy intensity progress in 2025 is estimated to be over 3% in China and over 4% in India, well above their averages in the years since 2019. In the United States and the European Union (EU), on the other hand, progress in 2025 is set to fall to under 1% after several years of stronger performance following the energy crisis (IEA, 2025a).

On the sectoral front, industry is lagging and slowing global progress. Industry accounts for nearly 40% of global final energy use, yet energy intensity improvements have fallen to under 0.5% per year since 2019, compared to almost 2% in the previous decade, undermining overall progress due to weak efficiency progress (IEA, 2025a). Renewables and electrification can contribute to the overall energy efficiency target, but those are only part of the solution. According to the IEA Net Zero Emissions by 2050 Scenario (NZE Scenario), to double the efficiency improvement rate, three equally important actions exist globally: switching to more efficient fuels (EVs, heat pumps, clean cooking) could bring 0.7% of the needed improvement. The rest of the increase would come from improving the technical efficiency (renovations, insulation, better appliances, improved industrial processes) with another 0.7 percentage points and another 0.8 percentage points could come from using energy and materials more efficiently (using more public transport, other behavioural changes, increased circularity for materials and others)(IEA, 2023).

Highly efficient appliances, such as air conditioners for cooling or heat pumps and deep renovations should be prioritised in the buildings sector.

Electricity demand is growing two to three times faster than energy demand, partly due to end-use electrification. This needs to be met with renewable energy generation, and also indicates a need for increased grid buildout. Although electrification will itself bring some efficiency benefits, further investment in efficiency improvements will restrain the amount of investment needed in generation and transmission.

By implementing adequate efficiency measures, across end-use sectors such as industry and buildings, energy efficiency can become a key driver of the transition. The HPA-2025 is effectively suggesting an immediate doubling by 2030 against the current levels.

4.2.4 Methane

Goal: the 2021 Global Methane Pledge aims to reduce methane emissions by at least 30% during the decade to 2030, while the first Global Stocktake in 2023 also called for substantial cuts by 2030.

1.5°C alignment: across Paris-aligned pathways methane emissions must decline by 17-33% from 2020 levels by 2030, equivalent to a reduction of 19-35% from current emissions levels (IEA, 2023).

Progress: global methane emissions rose by 3.5% from 2020 to 2023 (1.1% pa) – a marked acceleration from the rate of rise in the previous three decades (0.6% pa) (Hou et al., 2026). Emissions rose in all three key sectors – waste, agriculture and energy.

Methane is responsible for approximately one-third of global warming to date (IPCC, 2021a). Due to its short atmospheric lifetime, reducing methane can slow warming in the near-term, making it a critical lever for limiting overshoot and supporting long-term temperature decline (Climate Analytics, 2025a).

Agriculture is the largest source of anthropogenic methane emissions (50%), followed by energy (30%) and waste (20%) (Gütschow et al., 2025). Immediate reductions across all sectors are critical this decade, but emissions must fall fastest and furthest in the energy sector (48%–62%) driven by rapid phase out of fossil fuels and targeted abatement. Reductions in agriculture and waste – up to 15% and 39%, respectively – are relatively lower but nevertheless critical.

As noted earlier, however, methane emissions have risen by 24% between 1990 and 2023, and by 3.5% since 2020 (Hou et al., 2026). The increase is seen across all three emitting sectors since 1990: 55% in waste, 20% in agriculture, and 18% in energy.

Current policies are not sufficient to align global methane emissions with the Paris limit. In the median current policy pathway from IAMs, methane emissions remain flat between 2020 and 2030, leaving an annual implementation gap of 49–97 Mt CH_4 relative to Paris-aligned pathways and around 88 Mt CH_4 relative to the Global Methane Pledge in 2030 (Figure 17). At the sector level, current policies are projected to reduce energy-related methane emissions by 11%, while agriculture and waste are expected to see increases of 6% and 9% respectively. This leaves annual implementation gaps of 33–46 Mt CH_4 in energy, 9–30 Mt CH_4 in agriculture, and 4–28 Mt CH_4 in waste by 2030) (Hou et al., 2026).

Global methane gap analysis

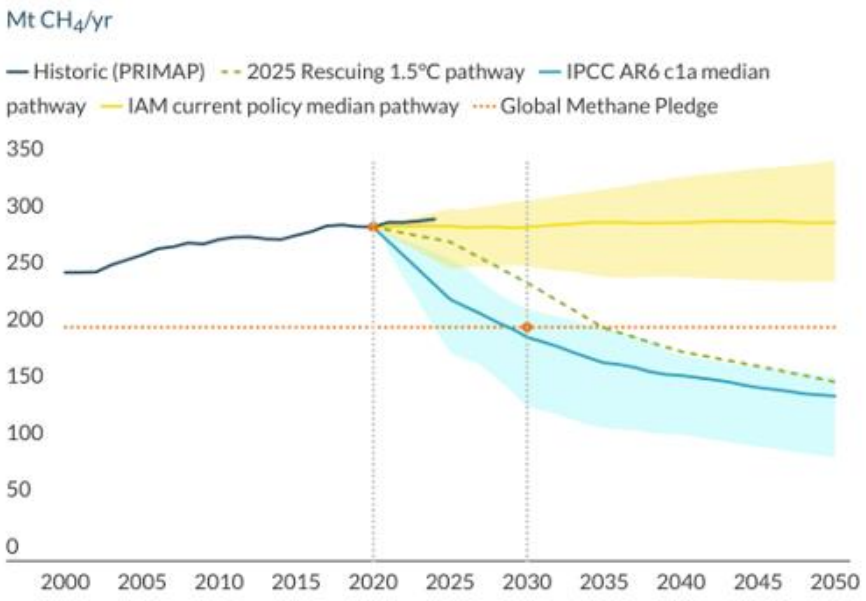


Figure 17: Historic emissions are taken from PRIMAP-hist v2.7 (2025 release). The yellow shaded area represents the IAM current policy range (percentile 10-percentile 90). The blue fill area shows the range of IPCC AR6 C1a pathways (10th–90th percentile).

Adoption of national methane reduction targets and policies has accelerated in the past decade, but significant policy and implementation gaps remain. Eighty-one percent of countries covering more than 90% of global methane emissions include methane in their NDCs, but only 16% have methane-specific reduction targets. The review identified 260 methane-related policies, predominantly focused on the energy sector, with considerably fewer addressing agriculture and waste. Some policies remain stalled or have been rolled back, while several major emitters lack comprehensive regulations to reduce methane from key emitting sources (Climate Analytics, 2025a).

Closing the methane gap is achievable through the rapid scaling of existing, proven, and cost-effective measures across all sectors.

- The greatest near-term opportunities lie in the **energy** sector. Phasing out fossil fuels is the fastest way to tackle these emissions, though targeted actions to reduce methane emissions from remaining infrastructure will also be critical, especially in the near-term. The IEA (2026) estimates that around 30% of methane emissions from fossil fuel operations could be avoided at no net cost, while existing technologies could reduce emissions by almost 70%. Mandatory leak detection and repair, restrictions on venting and flaring, and methane performance standards can deliver substantial reductions (IEA, 2026b).
- In **agriculture**, improved livestock feeding and manure management, low-emission rice cultivation and dietary shifts offer practical mitigation opportunities, supported by financial incentives and technical assistance.

- In **waste**, cost-effective measures such as organic waste diversion, composting, landfill gas capture, and improved wastewater treatment can deliver substantial reductions.

Stronger regulation, targeted financing, and capacity-building can accelerate the deployment of these solutions and bring methane emissions into alignment with Paris-aligned pathways.

4.2.5 Carbon dioxide removal

Goal: there is no global goal for scaling up carbon dioxide removal.

1.5°C alignment: pathways that strictly limit overshoot and return global warming to or below 1.5°C this century see total removals reaching around 6-9 $GtCO_2$/yr in 2050, and by 2100 remove 500 $GtCO_2$ from the atmosphere. The split into conventional removals from land-use vs novel CDR varies from model to model.

Progress: as of 2025, engineered removals stood at 0.002 $GtCO_2$/yr, while conventional removals from land-use stood at around 2 $GtCO_2$/year (Smith et al., 2026).

Carbon dioxide removal (CDR) has long been proposed as part of the toolkit for addressing climate change (Obersteiner et al., 2001). For many years, concerns have been raised about overreliance on CDR (Anderson & Peters, 2016) – that the hope of future removals will enable mitigation deterrence and erode willingness for rapid emissions cuts in the present (Markusson et al., 2018), (N. Grant et al., 2021), (Carton et al., 2020), that large-scale CDR is not feasible and risks delivery failure (N. Grant et al., 2021), or that, if CDR is successfully upscaled, it will have widespread negative side-effects on biodiversity, food prices, water use and more (Heck et al., 2018), (Deprez et al., 2024).

In 1.5°C-aligned scenarios such as the HPA-2025, CDR is a necessity, not a choice. As seen in Chapter 3, the latest scenarios which bring temperatures back below 1.5°C before 2100 rely on average on around 500 $GtCO_2$ of cumulative CDR by 2100. Its purpose is not to compensate for emissions from ongoing fossil fuel use, but to remove CO_2 from the atmosphere to bring global warming down from its peak back below 1.5°C and out of the danger zone. The question has to become not “do we scale CDR”, but “how do we scale CDR in a manner which aligns with highest possible ambition, but also does not dilute the essential need to phase out fossil fuels and does not transgress sustainability and feasibility limits?”

A wide range of options for carbon removal have been proposed – some of which are already being deployed, others of which are still in a conceptual or demonstration phase. These different routes all face different biophysical, geological, technological, institutional and infrastructural barriers which could limit the rate at which they can be

scaled up, and their maximum potential. Table 5 highlights potential estimates for six major CDR routes, drawing from the State of CDR report and other key sources.[6]

Table 5: Six major CDR routes – current scale, sustainable potential, cost and key constraints

Method	Type	Current scale	Constrained / sustainable potential	Cost range (US$/$tCO_2$)	Key constraints
Afforestation/ Reforestation (A/R)	Conventional	~2.2 $GtCO_2$/yr	~2.2–4.4 $GtCO_2$/yr	$5–$53	Land availability, climate feedbacks, permanence
Soil carbon sequestration (SCS)	Conventional	Not quantified	0.5–3.4 $GtCO_2$/yr	–$45 to $105	Saturation, reversibility, MRV
Biochar	Novel	1.46 $MtCO_2$/yr	Up to 2.7 $GtCO_2$/yr	$70–$360	Feedstock quality and availability
BECCS	Novel	0.51 $MtCO_2$/yr	0.5–5 $GtCO_2$/yr by 2050	$15–$400	Sustainable biomass supply, land, storage availability
DACCS	Novel	0.0015 $MtCO_2$/yr	0.5–5 $GtCO_2$/yr by 2050	$400–$2,500	Cost, energy demand, storage and injection rates
Enhanced weathering	Novel	0.0038 $MtCO_2$/yr	~0.7 $GtCO_2$/yr	$50–>$300	MRV, biogeochemical cycling losses

All CDR types face challenges around permanence, sustainability and scalability, which differ across conventional vs novel routes. This means that minimising reliance on CDR by pursuing rapid emissions reductions remains key to robust climate action.

- Conventional CDR such as A/R and SCS faces challenges regarding permanence. In a warming world where wildfires and disturbances of natural carbon sinks are only growing, there is a real risk that these methods will only store their carbon temporarily, which could negate their climate benefits entirely. Changes in land-use policy and enforcement could also lead to reversals in carbon storage in the biosphere. They also face challenges around scalability – governments' current climate pledges collectively require around one billion hectares of land for conventional CDR, exceeding what is realistically feasible and creating conflict

[6] **Potentials:** Technical potential reflects biogeophysical limits. Constrained/sustainable potential applies stricter deployment or sustainability assumptions, or reflects higher agreement across studies. Potentials are not additive across methods because of competing demands for land, biomass, energy and geological storage. Sources produce varying estimates due to differences in assumptions and methods.

Costs: Not directly comparable across methods due to differences in scope, technological maturity and timescales

Sources: Smith et al. 2026, Fuss et al. 2026, SoCDR Chs 7 & 10

with food provision, biodiversity conservation and critical land uses (Dooley et al., 2022).

- Meanwhile engineered, novel and other technological CDR approaches are constrained by financial costs, biomass availability limits, scalability and access to adequate geological storage. Novel early-stage CDR approaches face environmental hazards, unresolved side effects, financial/technological immaturity and legal uncertainty. Demand for bioenergy under BECCS can bring some of the same land-use conflicts that A/R and SCS risk.

It is likely that a broad portfolio of different options will be necessary, if we are to scale cumulative removals to over 500 $GtCO_2$ by 2100, and the even larger levels which would be needed to hedge against uncertainties in climate sensitivity (see Annex A). As short-term action is needed to reach gigatonne scale by mid-century, policies and measures to incubate and upscale these approaches today are sorely needed (Zurbriggen et al., 2026). While some action is being taken to support and incubate CDR methods, such as the UK demonstration programme (UK Government, 2026), much more action will be needed to accelerate CDR development and deployment, if we are to align with highest possible ambition.

Further work will be needed to assess the HPA family against the sustainability/feasibility potentials for individual CDR methods, and determine what the route to upscaling CDR within these limits is.

4.3 Finance needs, economic gains

4.3.1 Climate finance needs a major boost

The implementation of specific policies and actions depends heavily on climate finance. Scaled-up investment in both mitigation and adaptation is critical to embarking on a Paris-aligned trajectory, whereas delays will make climate impacts more severe and responses (including returning to a 1.5°C-aligned pathway) significantly more costly.

The Independent High-Level Expert Group (IHLEG) on Climate Finance estimates that emerging markets and developing economies (EMDEs) excluding China will require climate and related development investments of $3.2 trillion per year by 2035 (IHLEG, 2025). Of this amount, $1.9 trillion per year will be sourced domestically, while $1.3 trillion per year will require international sourcing, both public and private.

Developing economies, particularly those most vulnerable to climate change, are recognised as facing higher investment risk, which is reflected in a higher cost of capital – making finance less affordable and stable (Calcaterra et al., 2024). While Article 9.1 of the Paris Agreement indicates that "*developed country Parties shall provide financial resources to assist developing country Parties*," both targeted and observed flows fall short with respect to these needs of developing countries.

- The New Collective Quantified Goal, agreed at COP29, settled for only $300 billion per year to flow from developed to developing countries by 2035 and

only vaguely references $1.3 trillion without further specifying its sources and quality aspects such as concessionality.

- For 2025, preliminary estimates point to approximately $2 trillion in global climate finance including domestic and international markets (Climate Policy Initiative, 2026). However, over 85% of this comes from domestic markets, with the vast majority going towards mitigation. Because the large majority of the money is directed towards advanced economies and China,[7] the climate finance needs of developing countries seem to be neglected.

This results in a clear gap between needs and provision for countries with less developed domestic financial markets, reduced capacity and higher cost of capital, as well as enhanced vulnerability (both on physical and economic terms). SIDS and LDCs are particularly affected. Ensuring these states have access to concessional and accessible climate finance will be essential for Paris-alignment to materialise and for fossil fuels to be phased down.

An important piece of the financing puzzle is fossil fuel subsidies which distort prices, create the wrong incentives and consume resources which otherwise could support the energy transition. Global expenditure is vast, amounting to $0.73 trillion (explicit subsidies) and $6.7 trillion (implicit subsidies), representing 0.6% and 5.8% of global GDP respectively in 2024 (International Monetary Fund, n.d.). These subsidies would need to be phased out in a just and equitable way, and the sums released could contribute substantially to closing the financing gap. In developing countries, these resources could be used domestically, while some of the resources in developed countries could be shifted to international finance.

4.3.2 Fossil fuel phase-out comes with economic gains, which can be invested

Aligning economies with pathways that limit overshoot does not need to come at a net cost. Limiting overshoot requires upfront capital for energy technologies and ancillary infrastructure, reducing GDP in the near term, but these losses are more than compensated by higher GDP growth in the second half of the century (Riahi et al., 2021). A rapid transition away from a fossil fuel-based system can bring energy system costs down resulting in net savings of many trillions of dollars globally without accounting for avoided impacts and co-benefits (Way et al., 2022).

The health benefits of phasing out fossil fuels are among the largest and best quantified co-benefits. Air pollution from fossil fuels is estimated to be responsible for more than 5 million excess deaths per year globally (Lelieveld et al., 2023). The benefits of the transition on air pollution are already materialising in many areas of the world. The switch from fossil fuel to renewable generation alone has brought significant economic benefits to many countries from avoided air pollution damages, including Australia (US$2 bn), Brazil ($4 bn), Germany ($6 bn) and the United States ($21.5 bn) in 2024 alone. While current actions have saved China $261 billion in 2024 (IRENA, 2025), the

[7] Together, they received around 80% of global flows since 2019

benefits of reduced air pollution outweigh the mitigation cost of meeting the Paris Agreement in all future scenarios in the country (Markandya et al., 2018).

The transition can also be a net source of employment growth. In a 1.5°C-aligned scenario, the energy sector would employ 50 million more people by 2050 than under currently planned policies, including 18 million additional jobs in renewable energy. As with all co-benefits, the gains are unevenly distributed; while Asia seems to hold the majority of global renewable energy jobs by 2050, Sub-Saharan Africa would hold under 10% while employment in fossil-related energy services decreases (IRENA, 2023b). Realising the full benefits therefore depends on enacting a set of policies that puts a just and inclusive transition on the agenda by investing in skills, retraining and support for workers and regions that currently depend on fossil fuel industries.

While the list of co-benefits is longer than this, it already shows that policymakers serious about the wellbeing and economic prosperity of their citizens should aim to pursue a 1.5°C-aligned pathway with severely limited overshoot.

While countries dependent on fossil fuel income face a major drop in revenue, this can be managed by coordination between countries so that richer and less dependent countries exit production first, with poorer and more dependent ones gaining a few additional years of production compared to a purely market-driven exit (Climate Analytics, 2026b).

About three-quarters of the world's population lives in countries that are net fossil fuel importers (Ember, 2025b), and these countries will see significant benefits from phasing out fossil fuels additional to the economic gains. Geopolitical instability around major production centres and transit chokepoints, most recently the Strait of Hormuz, leaves fuel-importing nations heavily exposed to sudden price spikes in spot markets for oil, oil products and LNG, instantly inflating trade deficits and forcing governments to divert scarce foreign exchange reserves toward emergency fuel imports.

This price volatility is further compounded by legacy contractual frameworks: to secure thermal generation, utilities often lock themselves into long-term, rigid fuel-supply or thermal Power Purchase Agreements (PPAs) that feature strict take-or-pay or capacity-charge obligations (RMI, 2023). Price spikes caused by both the Russian invasion of Ukraine and the Strait of Hormuz crisis have left some poorer Asian countries unable to secure gas or other fuels, resulting in power cuts, rationing and heavily inflated prices (Henderson, 2024); (WEF, 2026).

Ultimately, the central reason for limiting the magnitude and duration of overshoot and returning below 1.5°C as soon as possible is to limit the negative consequences described in Chapter 2. Updated quantifications of the macroeconomic impacts of climate change have found the costs to be six times larger than previously documented, with even a 1°C rise in temperature accounting for a 20% decrease in the world's GDP (Bilal & Känzig, 2026).

The scale and duration of overshoot are important parameters that affect the macroeconomic impact. Comparing a pathway stabilising at 1.5°C with no overshoot (*REF*), a pathway that overshoots to 1.7°C (*NEG*), and a pathway peaking at 2.3°C (*SSP5-3.4-OS*), the latter results in much larger and persistent economic damages. Each additional 0.1°C of warming by 2030 locks in losses of 1.7 to 12 percentage points of end-of-century global GDP. Even the temporary overshoot pathway compared to no overshoot induces GDP losses of roughly 15% to 30% after peak (Schoengart et al., 2025).

5 Conclusion

Overshooting 1.5°C is now unavoidable. What is still in our hands is how high warming peaks, how long it stays above 1.5°C and how far it falls by the end of the century. This report shows that these three features of the overshoot are not technical details. They decide how much damage the world suffers, how much of it can still be reversed, and who bears it.

The risks are rising, and the most vulnerable are hit first and hardest. Every tenth of a degree matters. Heat extremes, record temperatures and many of their consequences follow the peak, and ease as warming falls. Other impacts build up for every year spent above 1.5°C: ice sheets and glaciers keep losing mass, and committed sea-level rise keeps growing. Some, such as the loss of warm-water coral reefs and of species, may not reverse at all. The lower the peak and the faster warming falls, the better the chance of avoiding tipping points in the Amazon, the West Antarctic ice sheet and the Atlantic overturning circulation. Small Island Developing States and Least Developed Countries, which did least to cause the crisis, face the greatest losses and the hardest limits to adaptation.

Limiting the height and duration of the overshoot, and getting back below 1.5°C by 2100, has to be the goal

The Paris Agreement, the advisory opinion of the International Court of Justice and the Parties' own decisions, most recently the COP30 Global Mutirão, all establish 1.5°C as the limit against which climate action is judged. Exceeding it does not weaken the obligation to act; it intensifies it. Countries must act with their highest possible ambition, limit both the magnitude and the duration of overshoot, and bring warming back below 1.5°C as soon as possible.

Warming can still return below 1.5°C by 2100

In our Highest Possible Ambition pathway (HPA-2025), warming peaks at around 1.7°C around 2040 and falls to about 1.2°C by 2100, after 37 years above 1.5°C. The broader family of Very Low emissions pathways reaches a median of about 1.3°C by 2100. Stabilising at 1.5°C would not be enough, as it is far too dangerous: the evidence in this report shows that warming has to keep falling, towards around 1°C in the long term, to limit the risks from sea-level rise and ice sheet loss.

The next decade sets the course for the century. How fast emissions fall this decade and next largely decides the peak. Keeping it low requires cutting global greenhouse gas emissions by around 20% by 2030 and 49% by 2035 from 2025 levels, and reaching net zero CO_2 around the mid-2040s. How long the overshoot lasts, and where warming ends, depend on reaching net zero greenhouse gas emissions around the 2070s or before.

The solutions exist

A rapid phase-out of fossil fuels is essential: in the HPA-2025 pathway, coal is effectively phased out in the 2040s, gas in the 2050s and oil in the 2060s. Renewable energy is growing at a pace that could take the world close to the COP28 tripling goal, and electrification, efficiency and methane abatement can bring the peak down further. Carbon dioxide removal is a necessity to bring warming down, but not a substitute for cutting emissions. It needs to be scaled up responsibly from today, within sustainability limits, and must not delay the phase-out of fossil fuels. The transition also pays off: in jobs, energy security, cleaner air and avoided damages that far outweigh its costs.

What needs to happen

- **Close the 2035 gap**. Current NDCs fall far short of what the highest possible ambition requires. Countries should use the Global Implementation Accelerator and the Belém Mission to 1.5 to strengthen implementation now and bring forward targets, with emissions reductions in line with 49% below 2025 levels by 2035.
- **Commit to a fossil fuel phase-out**. Countries should translate the COP28 commitment to transition away from fossil fuels into national plans with timelines, end new fossil fuel development, and phase out fossil fuel subsidies in a just and equitable way.
- **Deliver the key levers**. These are tripling renewables, doubling the rate of energy efficiency improvements, accelerating electrification, rapidly reducing methane emissions, and ending deforestation.
- **Plan for carbon dioxide removal now**. Develop both conventional and novel removals within sustainability limits, as a complement to rapid emissions reductions, never a replacement.
- **Scale up finance for the most vulnerable**. Close the gap between the New Collective Quantified Goal and the needs of developing countries, especially SIDS and LDCs, for mitigation, adaptation and loss and damage.

What happens next

The choices made at COP31 and in the coming years will decide whether overshoot is short and limited, or long, damaging and even permanent.

Current policies put the world on course for a permanent overshoot, with global warming of at least 2.6°C by 2100. Even full implementation of the most ambitious pledges, including net zero targets around mid-century, would lock the world into a permanent overshoot close to 2°C. A permanent overshoot can only be avoided with a step change in action and political commitments.

Climate Analytics will update this analysis each year, tracking the peak, the duration of overshoot and progress on each lever. Rescuing 1.5°C is no longer about avoiding overshoot. It is about keeping it as low and as short as possible, and bringing warming back down.

6 References

Abernethy, S., Monteverde, D., Schädel, C., Buma, B., Duffy, P. B., Jackson, R. B., Natali, S. M., Ocko, I., Rogers, B. M., & Poulter, B. (2026). Projected amplification of global warming by warming-induced greenhouse gas emissions. *Environmental Research Letters*, *21*(17), 174022. https://doi.org/10.1088/1748-9326/ae9e24

Al Khourdajie, A., Andrijevic, M., Byers, E., Pathak, M., Pirani, A., Schleussner, C.-F., & Stuart-Smith, R. (2026). Overshoot pathways: Reversible biophysical change, irreversible socioeconomic impacts. *Environmental Research Letters*, *21*(16), 164002. https://doi.org/10.1088/1748-9326/ae96c9

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183. https://doi.org/10.1126/science.aah4567

Armour, K. C., Proistosescu, C., Dong, Y., Hahn, L. C., Blanchard-Wrigglesworth, E., Pauling, A. G., Jnglin Wills, R. C., Andrews, T., Stuecker, M. F., Po-Chedley, S., Mitevski, I., Forster, P. M., & Gregory, J. M. (2024). Sea-surface temperature pattern effects have slowed global warming and biased warming-based constraints on climate sensitivity. *Proceedings of the National Academy of Sciences*, *121*(12), e2312093121. https://doi.org/10.1073/pnas.2312093121

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Australia Climate Service. (2025). *National Climate Risk Assessment*. https://www.acs.gov.au/pages/national-climate-risk-assessment

Australia Institute of Marine Science. (2025). *Annual Summary Report of Coral Reef Condition 2024/25*. https://www.aims.gov.au/monitoring-great-barrier-reef/gbr-condition-summary-2024-25

Australia Institute of Marine Science. (2026). *Annual Summary Report of Coral Reef Condition 2025/26*. https://www.aims.gov.au/monitoring-great-barrier-reef/gbr-condition-summary-2025-26

Barnes, C., Konstantinoudis, G., Masselot, P., Mistry, M., Gasparrini, A., Vicedo-Cabrera, A. M., Theokritoff, E., Clarke, B., & Otto, F. (2025). *Summer heat deaths in 854 European cities more than tripled due to climate change*. https://doi.org/10.25560/123873

Baur, S., Nauels, A., Nicholls, Z., Sanderson, B. M., & Schleussner, C.-F. (2023). The deployment length of solar radiation modification: An interplay of mitigation, net-negative emissions and climate uncertainty. *Earth System Dynamics*, *14*(2), 367–381. https://doi.org/10.5194/esd-14-367-2023

Bell, J. D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert, M., Gehlen, M., Gorgues, T., Hampton, J., Hanich, Q., Harden-Davies, H., Hare, S. R., Holmes,

G., Lehodey, P., Lengaigne, M., Mansfield, W., Menkes, C., Nicol, S., … Williams, P. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, *4*(10), 900–910. https://doi.org/10.1038/s41893-021-00745-z

Ben-Yami, M., Good, P., Jackson, L. C., Crucifix, M., Hu, A., Saenko, O., Swingedouw, D., & Boers, N. (2024). Impacts of AMOC Collapse on Monsoon Rainfall: A Multi-Model Comparison. *Earth's Future*, *12*(9), e2023EF003959. https://doi.org/10.1029/2023EF003959

Bilal, A., & Känzig, D. R. (2026). The Macroeconomic Impact of Climate Change: Global Versus Local Temperature. *The Quarterly Journal of Economics*, *141*(2), 889–944. https://doi.org/10.1093/qje/qjag011

Boardman, P. J. L., Clarke, J., Cox, P. M., Huntingford, C., Jones, C. D., & Williamson, M. S. (2026). Emergent constraints on climate sensitivity and recent record-breaking warm years. *Earth System Dynamics*, *17*(3), 829–841. https://doi.org/10.5194/esd-17-829-2026

Bossert, I., Séférian, R., Santana-Falcón, Y., & Guinaldo, T. (2026). *Ocean and marine heatwaves responses to multiple net-zero worlds*. Climate change/Ocean/atmosphere interactions/Earth system and climate modeling. https://doi.org/10.5194/egusphere-2026-993

Bowden, C., Foster, T., & Parkes, B. (2025). Risk of rice production failure in India under climate change. *Environmental Research Letters*, *20*(9), 094038. https://doi.org/10.1088/1748-9326/adf459

Bozec, Y.-M., Adam, A. A. S., Arellano-Nava, B., Cresswell, A. K., Haller-Bull, V., Iwanaga, T., Lachs, L., Matthews, S. A., McWhorter, J. K., Anthony, K. R. N., Condie, S. A., Halloran, P. R., Ortiz, J.-C., Riginos, C., & Mumby, P. J. (2025). A rapidly closing window for coral persistence under global warming. *Nature Communications*, *16*(1), 9704. https://doi.org/10.1038/s41467-025-65015-4

Bronkalla, & Ruddigkeit. (2025). *Solar Radiation Modification (SRM) Concepts, Risks and Governance of intervention in the global climate system through solar geoengineering*. UBA.

Burger, F. A., Terhaar, J., & Frölicher, T. L. (2022). Compound marine heatwaves and ocean acidity extremes. *Nature Communications*, *13*(1), 4722. https://doi.org/10.1038/s41467-022-32120-7

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2021). Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nature Geoscience*, *14*(3), 118–120. https://doi.org/10.1038/s41561-021-00699-z

Caesar, L., Sakschewski, B., Andersen, L. S., Bai, Y., Bala, G., Bednarsek, N., Beringer, T., Beusen, A., Billing, M., Bodirsky, B. L., Botsyun, S., Braun, J., Breitburg, D., Dahlmann, H., DeClerck, F., Dennis, D. P., Diamond, M. L., Donges, J. F., Dou, X., … Rockström, J. (2026). Planetary Health Check 2026: A Scientific Assessment of the State of the Planet. In N. H. Kitzmann, B. Sakschewski, L. Caesar, & J.

Rockström (Eds.), *Planetary Boundaries Science (PBScience)* (p. 120 pages, 27 MB) [Application/pdf]. Potsdam Institute for Climate Impact Research. https://doi.org/10.48485/PIK.2026.25

Calcaterra, M., Aleluia Reis, L., Fragkos, P., Briera, T., de Boer, H. S., Egli, F., Emmerling, J., Iyer, G., Mittal, S., Polzin, F. H. J., Sanders, M. W. J. L., Schmidt, T. S., Serebriakova, A., Steffen, B., van de Ven, D. J., van Vuuren, D. P., Waidelich, P., & Tavoni, M. (2024). Reducing the cost of capital to finance the energy transition in developing countries. *Nature Energy*, *9*(10), 1241–1251. https://doi.org/10.1038/s41560-024-01606-7

Canadell, J. G., Monteiro, P. M. S., Costa, M. H., & L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld. (2021). Global Carbon and other Biogeochemical Cycles and Feedbacks. In Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Ed.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 673–816). Cambridge University Press.

Carlot, J., Vousdoukas, M., Rovere, A., Karambas, T., Lenihan, H. S., Kayal, M., Adjeroud, M., Pérez-Rosales, G., Hedouin, L., & Parravicini, V. (2023). Coral reef structural complexity loss exposes coastlines to waves. *Scientific Reports*, *13*(1), 1683. https://doi.org/10.1038/s41598-023-28945-x

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., & Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Climate Change*, *11*(6). https://wires.onlinelibrary.wiley.com/doi/10.1002/wcc.671

Ceppi, P., Wilson Kemsley, S., Andersen, H., Andrews, T., Kramer, R. J., Nowack, P., Wall, C. J., & Zelinka, M. D. (2026). Emerging low-cloud feedback and adjustment in global satellite observations. *Atmospheric Chemistry and Physics*, *26*(6), 4153–4171. https://doi.org/10.5194/acp-26-4153-2026

Chen, S., Lim, J., Koh, J., Beard, J., Rowe, J. W., Rowe, J., Antonucci, T., Berkman, L., Börsch-Supan, A., Carstensen, L., Goldman, D., Fried, L., Furstenberg, F., Jackson, J., Kohli, M., Olshansky, J., Rehkopf, D., Rother, J., Zissimopoulos, J., & for the Research Network on an Aging Society. (2025). Long-term impacts of heatwaves on accelerated ageing. *Nature Aging*, *5*(1), 113–121. https://doi.org/10.1038/s43587-024-00772-3

Chu, B.-W., Luo, J.-F., Wang, K.-X., Xing, Z.-C., & Wang, H.-K. (2024). Substantial increase of heat-induced labor and economic loss in China under rapid economic and environmental temperature growth. *Advances in Climate Change Research*, *15*(4), 708–716. https://doi.org/10.1016/j.accre.2024.06.006

Climate Action Tracker. (2025). *Mid-year check on 2035 climate plans*. Climate Analytics, NewClimate Institute. https://climateactiontracker.org/publications/mid-year-check-on-2035-climate-plans/

Climate Analytics. (2024). *Australia's global fossil fuel carbon footprint*. https://climateanalytics.org/publications/australias-global-fossil-fuel-carbon-footprint

Climate Analytics. (2025a). *Clearing the Air on Methane: A Global Review of Emissions, Ambition and the Policy Landscape*. Climate Analytics. https://climateanalytics.org/publications/clearing-the-air-on-methane-a-global-review-of-emissions-ambition-and-the-policy-landscape

Climate Analytics. (2025b). *Latest science on the 1.5°C limit of the Paris Agreement*.

Climate Analytics (with Grant, N., Geiges, A., Forner, C., & Hare, B.). (2025c). *Why stronger 2030 targets along with 1.5°C-aligned 2035 targets are essential* (Briefing). Climate Analytics.

Climate Analytics. (2026a). *Climate Impact Explorer*. https://climate-impact-explorer.climateanalytics.org/

Climate Analytics. (2026b). *Highest possible ambition: Science-aligned fossil fuel phase-out pathways*.

Climate Analytics, P. (2026c). *Rescuing 1.5°C: new evidence on the highest possible ambition to deliver the Paris Agreement*. Climate Analytics. Climate Analytics and PIK (2025). Rescuing 1.5°C: New Evidence on Highest Possible Ambition to Deliver the Paris Agreement. https://climateanalytics.org/publications/rescuing-1-5c

Climate Central. (n.d.). *Picturing Salvador's Future*. Retrieved https://picturing.climatecentral.org/location/-12.974928,-38.513633

Climate Central. (2026). *2025 in Review: U.S. Billion-Dollar Disasters*. https://www.climatecentral.org/climate-matters/2025-in-review

Climate Policy Initiative. (2025). *Quando a Fonte Seca: As Ameaças do Desmatamento da Amazônia para a Economia Brasileira*. https://www.climatepolicyinitiative.org/wp-content/uploads/2025/10/REL-Sintese-Rios-Voadores.pdf

Climate Policy Initiative. (2026). *Global Landscape of Climate Finance*. Climate Policy Initiative. https://glcf.climatepolicyinitiative.org/#contentSection

CONSTRAIN. (2022). *The Critical Decade Insights from the Latest IPCC Reports on the Paris Agreement, 1.5°C, and Climate Impacts*. https://www.constrain-eu.org/wp-content/uploads/2022/11/CONSTRAIN_ZeroIn_Report_2022_V6_for_dissemination.pdf

Copernicus. (2026, September 10). *Copernicus: August was the world's joint hottest month on record, pushing global temperatures back above 1.5°C above pre-industrial levels*. https://climate.copernicus.eu/copernicus-august-was-worlds-joint-hottest-month-record-pushing-global-temperatures-back-above

Cui, M., Ji, D., & Chen, Y. (2025). Permafrost response and feedback under temperature stabilization and overshoot scenarios with different global warming levels. *EGUsphere*, *2025*, 1–21. https://doi.org/10.5194/egusphere-2024-4100

Dada, O. A., Almar, R., & Morand, P. (2024). Coastal vulnerability assessment of the West African coast to flooding and erosion. *Scientific Reports*, *14*(1), 890. https://doi.org/10.1038/s41598-023-48612-5

Dangendorf, S., Sun, Q., Wahl, T., Thompson, P., Mitrovica, J. X., & Hamlington, B. (2024). Probabilistic reconstruction of sea-level changes and their causes since 1900. *Earth System Science Data*, *16*(7), 3471–3494. https://doi.org/10.5194/essd-16-3471-2024

Deprez, A., Leadley, P., Dooley, K., Williamson, P., Cramer, W., Gattuso, J.-P., Rankovic, A., Carlson, E. L., & Creutzig, F. (2024). Sustainability limits needed for CO2 removal. *Science*, *383*(6682), 484–486. https://doi.org/10.1126/science.adj6171

Dijkstra, H. A., & van Westen, R. M. (2026). The Probability of an AMOC Collapse Onset in the Twenty-First Century. *Annual Review of Marine Science*, *18*, 23–46. https://doi.org/10.1146/annurev-marine-040324-024822

Dixon, A. M., Forster, P. M., Heron, S. F., Stoner, A. M. K., & Beger, M. (2022). Future loss of local-scale thermal refugia in coral reef ecosystems. *PLOS Climate*, *1*(2), e0000004. https://doi.org/10.1371/journal.pclm.0000004

Dooley, K., Nicholls, Z., & Meinshausen, M. (2022). Carbon removals from nature restoration are no substitute for steep emission reductions. *One Earth*, *5*, 812–824.

Duffey, A., Irvine, P., Tsamados, M., & Stroeve, J. (2023). Solar Geoengineering in the Polar Regions: A Review. *Earth's Future*, *11*(6), e2023EF003679. https://doi.org/10.1029/2023EF003679

Ember. (2025a). *Ember Electricity Data Explorer, version 1.2.2*. https://ember-energy.org/data/electricity-data-explorer/

Ember. (2025b). *Energy Security in an Insecure World*. https://ember-energy.org/latest-insights/energy-security-in-an-insecure-world/

Enerdata. (2026). *World Energy & Climate Statistics – Yearbook 2026*. https://yearbook.enerdata.net/electricity/share-electricity-final-consumption.html

EPRS. (2026). *Options for the responsible governance of research on solar radiation modification*. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2026)789310

ESA. (2026). *Sentinel-1 captures major ice loss from Greenland glacier*. https://www.esa.int/articles/about-us/directorates/earth-observation-programmes/copernicus/sentinel-1/sentinel-1-captures-major-ice-loss-from-greenland-glacier

FAO. (2026). *FAOSTAT*. https://www.fao.org/faostat/en/#home

Fischer, E. M., Bador, M., Huser, R., Kendon, E. J., Robinson, A., & Sippel, S. (2025). Record-breaking extremes in a warming climate. *Nature Reviews Earth & Environment*, *6*(7), 456–470. https://doi.org/10.1038/s43017-025-00681-y

Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., Levis, C., Lapola, D. M., Esquível-Muelbert, A., Jakovac, C., Nobre, C. A., Oliveira, R. S., Borma, L. S., Nian, D., Boers, N., Hecht, S. B., Ter Steege, H., Arieira, J., Lucas, I. L., … Hirota, M. (2024). Critical transitions in the Amazon forest system. *Nature*, *626*(7999), 555–564. https://doi.org/10.1038/s41586-023-06970-0

Forster, P. M., Walsh, T., Smith, C., Lamb, W. F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.-Y., Palmer, M. D., Von Schuckmann, K., Slangen, A. B. A., Szopa, S., Trewin, B., Yun, J., Gillett, N. P., Jenkins, S., Matthews, H. D., Raghavan, K., … Zhai, P. (2026). Indicators of Global Climate Change 2025: Annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*, *18*(6), 3889–3933. https://doi.org/10.5194/essd-18-3889-2026

Foster, G., & Rahmstorf, S. (2026). Global Warming Has Accelerated Significantly. *Geophysical Research Letters*, *53*(5), e2025GL118804. https://doi.org/10.1029/2025GL118804

France24. (2025). *Hajj pilgrims gather in Mecca under scorching desert sun*. https://www.france24.com/en/live-news/20250602-pilgrims-come-together-in-mecca-under-scorching-desert-heat

Franco, M. A., Rizzo, L. V., Teixeira, M. J., Artaxo, P., Azevedo, T., Lelieveld, J., Nobre, C. A., Pöhlker, C., Pöschl, U., Shimbo, J., Xu, X., & Machado, L. A. T. (2025). How climate change and deforestation interact in the transformation of the Amazon rainforest. *Nature Communications*, *16*(1), 7944. https://doi.org/10.1038/s41467-025-63156-0

Freedman, H., AghaKouchak, A., Rigden, A. J., Hoek, A. van der, & Tomlinson, B. (2025). Disparities in the impact of drought on agriculture across countries. *Scientific Reports*, *15*(1), 13465. https://doi.org/10.1038/s41598-025-94166-z

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*(7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

Goessling, H. F., Rackow, T., & Jung, T. (2025). Recent global temperature surge intensified by record-low planetary albedo. *Science*, *387*(6729), 68–73. https://doi.org/10.1126/science.adq7280

Gordon-Strachan, G. M., Parker, S. Y., Harewood, H. C., Méndez-Lázaro, P. A., Saketa, S. T., Parchment, K. F., Walawender, M., Abdulkadri, A. O., Beggs, P. J., Buss, D. F., Chodak, R. J., Dasgupta, S., De Santis, O., Guthrie-Dixon, N. G., Hassan, S., Kennard, H., Maharaj, S. B., Marshall, K. G., McFarlane, S. R., … Romanello, M. (2025). The 2024 small island developing states report of the Lancet Countdown on health and climate change. *The Lancet Global Health*, *13*(1), e146–e166. https://doi.org/10.1016/S2214-109X(24)00421-2

Grant, L., Vanderkelen, I., Gudmundsson, L., Fischer, E., Seneviratne, S. I., & Thiery, W. (2025). Global emergence of unprecedented lifetime exposure to climate extremes. *Nature*, *641*(8062), 374–379. https://doi.org/10.1038/s41586-025-08907-1

Grant, N., Hawkes, A., Mittal, S., & Gambhir, A. (2021). The policy implications of an uncertain carbon dioxide removal potential. *Joule*, *5*, 2593–2605. https://doi.org/10.1016/j.joule.2021.09.004

Gu, L., Schumacher, D. L., Fischer, E. M., Slater, L. J., Yin, J., Sippel, S., Chen, J., Liu, P., & Knutti, R. (2025). Flash drought impacts on global ecosystems amplified by extreme heat. *Nature Geoscience*, *18*(8), 709–715. https://doi.org/10.1038/s41561-025-01719-y

Gutiérrez-González, L., Robinson, A., Alvarez-Solas, J., Tabone, I., Swierczek-Jereczek, J., Moreno-Parada, D., & Montoya, M. (2026). Hysteresis of the Greenland ice sheet from the Last Glacial Maximum to the future. *The Cryosphere*, *20*(2), 1139–1162. https://doi.org/10.5194/tc-20-1139-2026

Gütschow, J., Busch, D., & Pflüger, M. (2025). *The PRIMAP-hist national historical emissions time series (1750-2024) v2.7* (Version 2.7) [Data set]. https://doi.org/10.5281/zenodo.17090760

Hamlington, B. D., Bellas-Manley, A., Willis, J. K., Fournier, S., Vinogradova, N., Nerem, R. S., Piecuch, C. G., Thompson, P. R., & Kopp, R. (2024). The rate of global sea level rise doubled during the past three decades. *Communications Earth & Environment*, *5*(1), 601. https://doi.org/10.1038/s43247-024-01761-5

Hare, B., Klönne, U., Kellou, D., & Cangussu, G. (2025). *Latest science on the 1.5°C limit of the Paris Agreement* (Briefing). Climate Analytics. https://climateanalytics.org/publications/latest-science-on-the-1-5-c-limit-of-the-paris-agreement

Haywood, J. M., Boucher, O., Lennard, C., Storelvmo, T., Tilmes, S., & Visioni, D. (2025). World Climate Research Programme lighthouse activity: An assessment of major research gaps in solar radiation modification research. *Frontiers in Climate*, *7*, 1507479. https://doi.org/10.3389/fclim.2025.1507479

He, M., Chen, T., Pan, Y., Zhou, L., Lv, Y., & Zhao, L. (2025). Seasonal and Interannual Variations in Hydrological Dynamics of the Amazon Basin: Insights from Geodetic Observations. *Remote Sensing*, *17*(15), 2739. https://doi.org/10.3390/rs17152739

Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, *8*(February). https://doi.org/10.1038/s41558-017-0064-y

Henderson, J. (2024). The Impact of the Russia-Ukraine War on Global Gas Markets. *Current Sustainable/Renewable Energy Reports*, *11*(1), 1–9. https://doi.org/10.1007/s40518-024-00232-x

Hermans, T. H. J., Malagón-Santos, V., Katsman, C. A., Jane, R. A., Rasmussen, D. J., Haasnoot, M., Garner, G. G., Kopp, R. E., Oppenheimer, M., & Slangen, A. B. A. (2023). The timing of decreasing coastal flood protection due to sea-level rise. *Nature Climate Change*, *13*(4), 359–366. https://doi.org/10.1038/s41558-023-01616-5

Heyen, D., & Tavoni, A. (2024). Strategic dimensions of solar geoengineering: Economic theory and experiments. *Journal of Behavioral and Experimental Economics*, *112*, 102271. https://doi.org/10.1016/j.socec.2024.102271

Hou, A., Grant, N., Kanduth, A., & Khan, Z. (2026). *The role of short-lived climate forcers in limiting overshoot and returning warming well below 1.5°C*. Climate Analytics.

Hwong, Y. L., Shmuel, A., Nauels, A., & Schleussner, C.-F. (2026). *Not All 1.5°C Worlds Are Equal: Mitigation versus Solar Radiation Modification*. https://doi.org/https://doi.org/10.22541/essoar.15011295/v1

IEA. (2023). *Energy Efficiency 2023*. https://www.iea.org/reports/energy-efficiency-2023

IEA. (2024). *Renewables 2023 – Analysis*. IEA. https://www.iea.org/reports/renewables-2023

IEA. (2025a). *Energy Efficiency 2025*. https://www.iea.org/reports/energy-efficiency-2025

IEA. (2025b). *Renewables 2025*. https://www.iea.org/reports/renewables-2025

IEA. (2026a). *Global Energy Review 2026*. https://www.iea.org/reports/global-energy-review-2026

IEA. (2026b). *Global Methane Tracker 2026—Key Findings*. International Energy Agency. https://www.iea.org/reports/global-methane-tracker-2026/key-findings

IEA. (2026c). *World Energy Investment 2026*. https://www.iea.org/reports/world-energy-investment-2026

IHLEG. (2025). *Delivering an integrated climate finance agenda in support of the Baku to Belém Roadmap to 1.3T*. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2025/11/IHLEG-on-Climate-Finance-4th-Report-Delivering-an-integrated-climate-finance-agenda.pdf

IIED. (2023). *Sinking islands, rising debts*. https://www.iied.org/sites/default/files/pdfs/2023-09/21606IIED.pdf

Im, E.-S., Pal, J. S., & Eltahir, E. A. B. (2017). Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*, *3*(8), e1603322. https://doi.org/10.1126/sciadv.1603322

International Court of Justice. (2025). *Obligations of States in respect of Climate Change (Advisory Opinion)*. https://icj-cij.org

International Monetary Fund. (n.d.). *Energy Subsidies*. Retrieved https://www.imf.org/en/topics/climate-change/energy-subsidies

International Renewable Energy Agency, COP31 Presidency, Global Renewables Alliance. (2026). *Delivering on the UAE Consensus: Tracking progress toward tripling renewable energy capacity and doubling energy efficiency by 2030,*. https://www.irena.org/Publications/2026/Sep/UAE-Consensus-2030-tripling-renewables-doubling-efficiency

International Renewable Energy Agency (IRENA). (2026). *Renewable Power Generation Costs in 2025*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2026/Jul/IRENA_TEC_RPGC_in_2025_2026.pdf

IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield, Eds.). Cambridge University Press. https://www.ipcc.ch/sr15/

IPCC. (2021a). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

IPCC. (2021b). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3–32). Cambridge University Press. https://doi.org/10.1017/9781009157896.001

IPCC. (2022a). Climate Change 2022: Impacts, Adaptation and Vulnerability—Summary for Policymakers. In *Intergovernmental Panel on Climate Change (IPCC)*. https://doi.org/10.4324/9781315071961-11

IPCC. (2022b). *IPCC - WG3*. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/

IPCC. (2022c). Summary for Policymakers. In P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley (Eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IRENA. (2023a). *The cost of financing for renewable power*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/May/IRENA_The_cost_of_financing_renewable_power_2023.pdf

IRENA. (2023b). World Energy Transitions Outlook 2023: 1.5°C Pathway. *International Renewable Energy Agency, Abu Dhabi.*, *Volume 1*.

IRENA. (2025, July 22). *Renewable Power Generation Costs in 2024*. https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024

IRENA. (2026a). *24/7 renewables: The economics of firm solar and wind*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2026/May/IRENA_TEC_24-7_renewables_2026.pdf

IRENA. (2026b). *Renewable Statistics 2026*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2026/Jul/IRENA_DAT_RE_Statistics_2026.pdf

Irvine, P. J., Ridgwell, A., & Lunt, D. J. (2010). Assessing the regional disparities in geoengineering impacts. *Geophysical Research Letters*, *37*(18), 2010GL044447. https://doi.org/10.1029/2010GL044447

IUCN. (2026). *IUCN Red List of Ecosystems*. https://iucn.org/story/202610/red-list-coral-reef-ecosystems

Kikstra, J. S., Nicholls, Z. R. J., Smith, C. J., Lewis, J., Lamboll, R. D., Byers, E., Sandstad, M., Meinshausen, M., Gidden, M. J., Rogelj, J., Kriegler, E., Peters, G. P., Fuglestvedt, J. S., Skeie, R. B., Samset, B. H., Wienpahl, L., van Vuuren, D. P., van der Wijst, K.-I., Al Khourdajie, A., … Riahi, K. (2022). The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: From emissions to global temperatures. *Geoscientific Model Development*, *15*(24), 9075–9109. https://doi.org/10.5194/gmd-15-9075-2022

Kotz, M., Donat, M. G., Lancaster, T., Parker, M., Smith, P., Taylor, A., & Vetter, S. H. (2025). Climate extremes, food price spikes, and their wider societal risks. *Environmental Research Letters*, *20*(8), 081001. https://doi.org/10.1088/1748-9326/ade45f

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, *549*(7671), 257–260. https://doi.org/10.1038/nature23878

Kumari, G., Sajjad, H., & Sharma, A. (2025). Assessing household level climate change induced livelihood vulnerability of rural workers using IPCC approach: Evidence from Dimapur district, India. *Mitigation and Adaptation Strategies for Global Change*, *30*(7), 54. https://doi.org/10.1007/s11027-025-10243-8

Kumler, A., Kravitz, B., Draxl, C., Vimmerstedt, L., Benton, B., Lundquist, J. K., Martin, M., Buck, H. J., Wang, H., Lennard, C., & Tao, L. (2025). Potential effects of climate change and solar radiation modification on renewable energy resources. *Renewable and Sustainable Energy Reviews*, *207*, 114934. https://doi.org/10.1016/j.rser.2024.114934

Lamboll, R. D., & Rogelj, J. (2026). Future-proofing interpretations of the Paris Agreement's limit of well below 2 °C. *Nature Climate Change*, *16*(8), 907–910. https://doi.org/10.1038/s41558-026-02685-y

Leach, N. J., Jenkins, S., Nicholls, Z., Smith, C. J., Lynch, J., Cain, M., Walsh, T., Wu, B., Tsutsui, J., & Allen, M. R. (2021). FaIRv2.0.0: A generalized impulse response model for climate uncertainty and future scenario exploration. *Geoscientific Model Development*, *14*(5), 3007–3036. https://doi.org/10.5194/gmd-14-3007-2021

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., & Zhou, T. (2023). Chapter 4: Future Global Climate: Scenario-based Projections and Near-term Information. In *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157896

Lelieveld, J., Haines, A., Burnett, R., Tonne, C., Klingmüller, K., Münzel, T., & Pozzer, A. (2023). Air pollution deaths attributable to fossil fuels: Observational and modelling study. *BMJ*, *383*. https://doi.org/10.1136/bmj-2023-077784

Lemoine, D. (2025). Climate change has already made the United States poorer. *Proceedings of the National Academy of Sciences*, *122*(51), e2504376122. https://doi.org/10.1073/pnas.2504376122

Lenton, T., Milkoreit, M., Willcock, S., Abrams, J. F., & Armstrong McKay, D. I. (2025). *Global Tipping Points Report 2025*. Global Tipping Points. https://global-tipping-points.org/

Lin, Y., Zhang, X., Golledge, N. R., Kopp, R. E., Church, J. A., Jin, Y., Zhao, C., & Stokes, C. R. (2026). Committed Antarctic Ice Sheet mass loss by the end of the twenty-first century. *Nature Geoscience*. https://doi.org/10.1038/s41561-026-02102-1

Liu, J., Wang, A., Zhang, T., Pan, P., & Ren, Y. (2024). Projected Increase in Heatwaves under 1.5 and 2.0 °C Warming Levels Will Increase the Socio-Economic Exposure across China by the Late 21st Century. *Atmosphere*, *15*(8), 900. https://doi.org/10.3390/atmos15080900

Liu, W., Duarte Cavalcante Pinto, D., Fedorov, A., & Zhu, J. (2023). The Impacts of a Weakened Atlantic Meridional Overturning Circulation on ENSO in a Warmer Climate. *Geophysical Research Letters*, *50*(8), e2023GL103025. https://doi.org/10.1029/2023GL103025

Lorenz, C., Cavendish, T. A., Azevedo, T. S. de, Bell, M., Nardocci, A., Andrade, M. de F., & Nogueira, T. (2026). Brazil is already experiencing the brutal impacts of climate change. *Revista de Saúde Pública*, *60*, e6. https://doi.org/10.11606/s1518-8787.2026060007009

Lüthi, S., Fairless, C., Fischer, E. M., Scovronick, N., Ben Armstrong, Coelho, M. D. S. Z. S., Guo, Y. L., Guo, Y., Honda, Y., Huber, V., Kyselý, J., Lavigne, E., Royé, D., Ryti, N., Silva, S., Urban, A., Gasparrini, A., Bresch, D. N., & Vicedo-Cabrera, A. M.

(2023). Rapid increase in the risk of heat-related mortality. *Nature Communications*, *14*(1), 4894. https://doi.org/10.1038/s41467-023-40599-x

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., … Ziehn, T. (2020). Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences*, *17*(11), 2987–3016. https://doi.org/10.5194/bg-17-2987-2020

Markandya, A., Sampedro, J., Smith, S. J., Dingenen, R. V., Pizarro-Irizar, C., Arto, I., & González-Eguino, M. (2018). Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, *2*(3), e126–e133. https://doi.org/10.1016/S2542-5196(18)30029-9

Markusson, N., McLaren, D., & Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustainability*, *1*. https://doi.org/10.1017/sus.2018.10

Martyr-Koller, R., Thomas, A., Schleussner, C.-F., Nauels, A., & Lissner, T. (2021). Loss and damage implications of sea-level rise on Small Island Developing States. *Slow Onset Events Related to Climate Change*, *50*, 245–259. https://doi.org/10.1016/j.cosust.2021.05.001

Mathesius, S., Hofmann, M., Caldeira, K., & Schellnhuber, H. J. (2015). Long-term response of oceans to CO2 removal from the atmosphere. *Nature Climate Change*, *5*(12), 1107–1113. https://doi.org/10.1038/nclimate2729

Mayer, B. (2024). THE 'HIGHEST POSSIBLE AMBITION' ON CLIMATE CHANGE MITIGATION AS A LEGAL STANDARD. *International and Comparative Law Quarterly*, *73*(2), 285–317. https://doi.org/10.1017/S0020589324000010

Meinshausen, M., Raper, S. C. B., & Wigley, T. M. L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*, *11*(4), 1417–1456. https://doi.org/10.5194/acp-11-1417-2011

Mercer, J. H. (1978). West Antarctic ice sheet and CO2 greenhouse effect: A threat of disaster. *Nature*, *271*(5643), 321–325. https://doi.org/10.1038/271321a0

Meyer, A. L. S., Bentley, J., Odoulami, R. C., Pigot, A. L., & Trisos, C. H. (2022). Risks to biodiversity from temperature overshoot pathways. *Philosophical Transactions of the Royal Society B*, *377*(1857), 20210394. https://doi.org/10.1098/rstb.2021.0394

Möller, T., Högner, A. E., Schleussner, C.-F., Bien, S., Kitzmann, N. H., Lamboll, R. D., Rogelj, J., Donges, J. F., Rockström, J., & Wunderling, N. (2024). Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nature Communications*, *15*(1), 6192. https://doi.org/10.1038/s41467-024-49863-0

Monioudi, I. N., Vousdoukas, M. I., Giardino, A., Stocchino, A., Mentaschi, L., & Feyen, L. (2025). Impacts of sea level rise and adaptation across Asia and the Pacific. *Scientific Reports*, *15*(1), 35742. https://doi.org/10.1038/s41598-025-11517-6

Morée, A. L., Lacroix, F., Cheung, W. W. L., & Frölicher, T. L. (2025). Long-term impacts of global temperature stabilization and overshoot on exploited marine species. *Biogeosciences*, *22*(4), 1115–1133. https://doi.org/10.5194/bg-22-1115-2025

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., Goel, V., Greenbaum, J. S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat, W., … Young, D. A. (2020). Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience*, *13*(2), 132–137. https://doi.org/10.1038/s41561-019-0510-8

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., … Zinglersen, K. B. (2017). BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. *Geophysical Research Letters*, *44*(21), 11,051-11,061. https://doi.org/10.1002/2017GL074954

Nauels, A., Nicholls, Z., Möller, T., Hermans, T. H. J., Mengel, M., Kloenne, U., Smith, C., Slangen, A. B. A., & Palmer, M. D. (2025). Multi-century global and regional sea-level rise commitments from cumulative greenhouse gas emissions in the coming decades. *Nature Climate Change*, *15*(11), 1198–1204. https://doi.org/10.1038/s41558-025-02452-5

Naughten, K. A., Holland, P. R., & De Rydt, J. (2023). Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. *Nature Climate Change*, *13*(11), 1222–1228. https://doi.org/10.1038/s41558-023-01818-x

Nian, D., Willeit, M., Wunderling, N., Ganopolski, A., & Rockström, J. (2026). Collapse of the Atlantic meridional overturning circulation would lead to substantial oceanic carbon release and additional global warming. *Communications Earth & Environment*, *7*(1), 295. https://doi.org/10.1038/s43247-026-03427-w

NOAA. (2020). *2020 U.S. billion-dollar weather and climate disasters in historical context*. https://www.climate.gov/disasters2020

Obersteiner, M., Azar, Ch., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., Read, P., Riahi, K., Schlamadinger, B., Yamagata, Y., Yan, J., & Van Ypersele, J.-P. (2001). Managing Climate Risk. *Science*, *294*(5543), 786–787. https://doi.org/10.1126/science.294.5543.786b

ODI. (2023). *The Costs of Inaction: Calculating climate change-related loss and damage from extreme weather in Small Island Developing States*. https://odi.org/en/publications/calculating-loss-and-damage-from-extreme-weather-in-sids/

OECD. (2026). *Small Island Developing States*. https://www.oecd.org/en/topics/sub-issues/small-islands-developing-states.html

Oliver, E. C. J., Burrows, M. T., Donat, M. G., Sen Gupta, A., Alexander, L. V., Perkins-Kirkpatrick, S. E., Benthuysen, J. A., Hobday, A. J., Holbrook, N. J., Moore, P. J., Thomsen, M. S., Wernberg, T., & Smale, D. A. (2019). Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science*, *6*, 734. https://doi.org/10.3389/fmars.2019.00734

O'Neill, B., Aalst, M. van, Zaiton Ibrahim, Z., Ford, L. B., Bhadwal, S., Buhaug, H., Diaz, D., Frieler, K., Garschagen, M., Magnan, A., Midgley, G., Mirzabaev, A., Thomas, A., & Warren, R. (2022). Key Risks Across Sectors and Regions. In Poertner, H-O., D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 2411–2538). Cambridge Univ Press. https://doi.org/10.1017/9781009325844.025.

Oschlies, A. (2021). A committed fourfold increase in ocean oxygen loss. *Nature Communications*, *12*(1), 2307. https://doi.org/10.1038/s41467-021-22584-4

Palacios-Abrantes, J., Santos, B. S., Frölicher, T. L., Reygondeau, G., Sumaila, U., Wabnitz, C. C. C., & Cheung, W. W. L. (2025). Climate change drives shifts in straddling fish stocks in the world's ocean. *Science Advances*, *11*(31), eadq5976. https://doi.org/10.1126/sciadv.adq5976

Paris Agreement. (2015). *15 December 2015*. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27

Pearce-Kelly, P., Altieri, A. H., Bruno, J. F., Cornwall, C. E., McField, M., Muñiz-Castillo, A. I., Rocha, J., Setter, R. O., Sheppard, C., Roman-Cuesta, R. M., & Yesson, C. (2025). Considerations for determining warm-water coral reef tipping points. *Earth System Dynamics*, *16*(1), 275–292. https://doi.org/10.5194/esd-16-275-2025

Pichevin, L. E., Bollasina, M., Nederbragt, A. J., & Ganeshram, R. S. (2024). North Atlantic temperature control on deoxygenation in the northern tropical Pacific. *Nature Communications*, *15*(1), 7919. https://doi.org/10.1038/s41467-024-52197-6

Portmann, V., Swingedouw, D., Khattab, O., & Chavent, M. (n.d.). Observational constraints project a ~50% AMOC weakening by the end of this century. *Science Advances*, *12*(16), eadx4298. https://doi.org/10.1126/sciadv.adx4298

Powell, R. S., Cederberg, G., Dangendorf, S., Lucas, E., Bao, X., Creveling, J. R., Oelsmann, J., Tsuji, S. R. J., Tsuji, L., & Mitrovica, J. X. (2026). Global ice loss drives source-independent amplification of sea-level rise at Pacific and Indian Ocean Small Island Developing States. *Communications Earth & Environment*. https://doi.org/10.1038/s43247-026-04132-4

Proelss, A., & Steenkamp, R. C. (2023). Geoengineering: Methods, Associated Risks and International Liability. In P. Gailhofer, D. Krebs, A. Proelss, K. Schmalenbach, & R. Verheyen (Eds.), *Corporate Liability for Transboundary Environmental Harm* (pp. 419–503). Springer International Publishing. https://doi.org/10.1007/978-3-031-13264-3_9

Quaglia, I., & Visioni, D. (2024). Modeling 2020 regulatory changes in international shipping emissions helps explain anomalous 2023 warming. *Earth System Dynamics*, *15*(6), 1527–1541. https://doi.org/10.5194/esd-15-1527-2024

Rajamani, L. (2016). Ambition and differentiation in the 2015 Paris Agreement: Interpretative possibilities and underlying politics. *International & Comparative Law Quarterly*, *65*(2), 493–514.

Rezaei, A., Moore, J., Tilmes, S., & Karami, K. (2025). Regional and Seasonal Hydrological Changes With and Without Stratospheric Aerosol Intervention Under High Greenhouse Gas Climates. *Journal of Geophysical Research: Atmospheres*, *130*(12), e2025JD044163. https://doi.org/10.1029/2025JD044163

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., Fujimori, S., Harmsen, M., Hasegawa, T., Krey, V., Luderer, G., Paroussos, L., Schaeffer, R., Weitzel, M., van der Zwaan, B., … Zakeri, B. (2021). Cost and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change*, *11*(12), 1063–1069. https://doi.org/10.1038/s41558-021-01215-2

Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, & D.P. van Vuuren. (2023). Mitigation Pathways Compatible with Long-term Goals. In Intergovernmental Panel On Climate Change (Ipcc) (Ed.), *Climate Change 2022—Mitigation of Climate Change* (1st ed., pp. 295–408). Cambridge University Press. https://doi.org/10.1017/9781009157926.005

Ritchie, P. D. L., Huntingford, C., & Cox, P. M. (2025). ESD Ideas: Climate tipping is not instantaneous – the duration of an overshoot matters. *Earth System Dynamics*, *16*(5), 1523–1526. https://doi.org/10.5194/esd-16-1523-2025

Ritchie, P. D. L., Smith, G. S., Davis, K. J., Fezzi, C., Halleck-Vega, S., Harper, A. B., Boulton, C. A., Binner, A. R., Day, B. H., Gallego-Sala, A. V., Mecking, J. V., Sitch, S. A., Lenton, T. M., & Bateman, I. J. (2020). Shifts in national land use and food production in Great Britain after a climate tipping point. *Nature Food*, *1*(1), 76–83. https://doi.org/10.1038/s43016-019-0011-3

Ritchie, P. D. L., Steinert, N. J., Abrams, J. F., Alkhayuon, H., Arnscheidt, C. W., Bochow, N., Chapman, R. R., Clarke, J., Dennis, D. P., Donges, J. F., Flores, B. M., Garbe, J., Högner, A., Huntingford, C., Lenton, T. M., Lohmann, J., Lux-Gottschalk, K., Milkoreit, M., Möller, T., … Wunderling, N. (2026). The implications of overshooting 1.5 °C on Earth system tipping elements—A review. *Environmental Research Letters*, *21*(4), 043001. https://doi.org/10.1088/1748-9326/ae3cad

RMI. (2023). *Coal Power Purchase Agreements (PPAs): Breaking Down the Basics*. https://rmi.org/app/uploads/dlm_uploads/2023/06/rmi_unlocking_coal_contracts_explainer_brief.pdf

Rogelj, J., & Rajamani, L. (2025). *The pursuit of 1.5°C endures as a legal and ethical imperative in a changing world*.

Romanello, M., Walawender, M., Hsu, S.-C., Moskeland, A., Palmeiro-Silva, Y., Scamman, D., Ali, Z., Ameli, N., Angelova, D., Ayeb-Karlsson, S., Basart, S., Beagley, J., Beggs, P. J., Blanco-Villafuerte, L., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J. D., Chicmana-Zapata, V., … Costello, A. (2024). The 2024 report of the Lancet Countdown on health and climate change: Facing record-breaking threats from delayed action. *The Lancet*, *404*(10465), 1847–1896. https://doi.org/10.1016/S0140-6736(24)01822-1

Rosser, J. P., Winkelmann, R., & Wunderling, N. (2024). Polar ice sheets are decisive contributors to uncertainty in climate tipping projections. *Communications Earth & Environment*, *5*(1), 702. https://doi.org/10.1038/s43247-024-01799-5

Ryan, S. J., Carlson, C. J., Mordecai, E. A., & Johnson, L. R. (2019). Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PLOS Neglected Tropical Diseases*, *13*(3), e0007213. https://doi.org/10.1371/journal.pntd.0007213

Saeed, F., Schleussner, C.-F., & Almazroui, M. (2021). From Paris to Makkah: Heat stress risks for Muslim pilgrims at 1.5 °C and 2 °C. *Environmental Research Letters*, *16*(2), 024037. https://doi.org/10.1088/1748-9326/abd067

Sanderson, B. M., Baur, S., Schleussner, C.-F., Peters, G. P., Mittal, S., Sandstad, M., Kallbekken, S., Smith, C., Fuss, S., Van Ruijven, B., Fisher, R. A., Rogelj, J., Séférian, R., Samset, B., Steinert, N. J., Terray, L., & Fuglestvedt, J. (2026). *Robust assessment of Solar Radiation Modification risks and uncertainties must include shocks and societal feedbacks*. Earth system/Human/Earth system interactions/Earth system and climate modeling. https://doi.org/10.5194/egusphere-2026-28

SAPEA (with Cantoni, R., Chiodo, G., Corry, O., Fountoulakis, I., Geden, O., Grasso, M., gupta, aarti, Heyward, C., Korhonen, H., Lohmann, U., Michaelowa, A., Oschlies, A., Quaas, J., Rabitz, F., Russchenberg, H., Sovacool, B., Sulyok, K., tavoni, massimo, & Tilmes, S.). (2024). *Solar radiation modification: Evidence review report* (Version 1.0). SAPEA. https://doi.org/10.5281/ZENODO.14283096

Schädel, C., Gasser, T., Rogers, B. M., Treharne, R., Turetsky, M. R., Smith, T., MacDonald, E., & Natali, S. M. (2026). Permafrost and wildfire carbon emissions indicate need for additional action to keep Paris Agreement temperature goals within reach. *Communications Earth & Environment*, *7*(1), 306. https://doi.org/10.1038/s43247-026-03189-5

Schleussner, C., Ganti, G., Rogelj, J., & Gidden, M. J. (2022). An emission pathway classification reflecting the Paris Agreement climate objectives. *Communications Earth & Environment*, *3*(1), 1–11. https://doi.org/10.1038/s43247-022-00467-w

Schleussner, C.-F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., Ciais, P., Frölicher, T. L., Fuss, S., Gasser, T., Gidden, M. J., Kropf, C. M., Lacroix, F., Lamboll, R., Martyr, R., Maussion, F., McCaughey, J. W., Meinshausen, M., Mengel, M., … Rogelj, J. (2024). Overconfidence in climate overshoot. *Nature*, *634*(8033), 366–373. https://doi.org/10.1038/s41586-024-08020-9

Schoengart, S., Schwarz, M., Schwaab, J., & Pretis, F. (2025). *Temporary Warming, Lasting Losses: Economic damages from climate overshoot may be irreversible within this century*. https://www.researchsquare.com/article/rs-7241437/v1

Schönfeld, J. K., Pelz, S., Beath, H., & Rogelj, J. (2026). Assessing processes and evidence for highest possible ambition in Nationally Determined Contributions under the Paris Agreement. *Environmental Research Letters*, *21*(20), 204021. https://doi.org/10.1088/1748-9326/aeb55f

Schönfeld, J. K., & Rogelj, J. (2025). A framework to assess highest possible ambition in nationally determined contributions under Article 4 of the Paris Agreement. *Environmental Research Letters*, *20*(11), 114081. https://doi.org/10.1088/1748-9326/ae15aa

Schumer, C., Boehm, S., Jaeger, J., Levin, K., Santo, R., Lebling, K., Riedl, D., Lee, A., Singh, N., Sims, M., Chin, N., Majid, A., Cassius, S., Lamb, W., Gangotra, A., Grant, N., Zhang-Billert, Y., & Petroni, M. (2025). *State of Climate Action 2025*. https://doi.org/10.46830/wrirpt.25.00006

Schuster, L., Maussion, F., Rounce, D. R., Ultee, L., Schmitt, P., Lacroix, F., Frölicher, T. L., & Schleussner, C.-F. (2025). Irreversible glacier change and trough water for centuries after overshooting 1.5 °C. *Nature Climate Change*, 1–8. https://doi.org/10.1038/s41558-025-02318-w

Shue, K., & Hartzmark, S. M. (2026). *The Geoengineering Put: Ecological Debt, Termination Risk, and Asset Prices*. SSRN. https://doi.org/10.2139/ssrn.6799198

Sidhu, B. S. (2023). Likely impacts of the 2022 heatwave on India's wheat production. *Environmental Research Letters*, *18*(10), 105001. https://doi.org/10.1088/1748-9326/acf871

Siegert, M., Sevestre, H., Bentley, M. J., Brigham-Grette, J., Burgess, H., Buzzard, S., Cavitte, M., Chown, S. L., Colleoni, F., DeConto, R. M., Fricker, H. A., Gasson, E., Grant, S. M., Gulisano, A. M., Hancock, S., Hendry, K. R., Henley, S. F., Hock, R., Hughes, K. A., … Truffer, M. (2025). Safeguarding the polar regions from dangerous geoengineering: A critical assessment of proposed concepts and future prospects. *Frontiers in Science*, *3*, 1527393. https://doi.org/10.3389/fsci.2025.1527393

Simolo, C., & Corti, S. (2025). Enhanced risk of hot extremes revealed by observation-constrained model projections. *Communications Earth & Environment*, *6*(1), 165. https://doi.org/10.1038/s43247-025-02133-3

Smith, C., Ramme, L., Wells, C. D., Gjermundsen, A., Li, H., Ilyina, T., Muralidhar, A., Bourgeois, T., Schwinger, J., Romero-Prieto, A., Li, C., & Mauritzen, C. (2026). Overshoot and (ir)reversibility to 2300 in two CO_2 -emissions driven Earth

System models. *Earth System Dynamics*, *17*(3), 893–911. https://doi.org/10.5194/esd-17-893-2026

Stanley, T. A., Soobitsky, R. B., Amatya, P. M., & Kirschbaum, D. B. (2024). Landslide Hazard Is Projected to Increase Across High Mountain Asia. *Earth's Future*, *12*(10), e2023EF004325. https://doi.org/10.1029/2023EF004325

Stokes, C. R., Abram, N. J., Bentley, M. J., Edwards, T. L., England, M. H., Foppert, A., Jamieson, S. S. R., Jones, R. S., King, M. A., Lenaerts, J. T. M., Medley, B., Miles, B. W. J., Paxman, G. J. G., Ritz, C., van de Flierdt, T., & Whitehouse, P. L. (2022). Response of the East Antarctic Ice Sheet to past and future climate change. *Nature*, *608*(7922), 275–286. https://doi.org/10.1038/s41586-022-04946-0

Stokes, C. R., Bamber, J. L., Dutton, A., & DeConto, R. M. (2025a). Warming of +1.5 °C is too high for polar ice sheets. *Communications Earth & Environment*, *6*(1), 351. https://doi.org/10.1038/s43247-025-02299-w

Stokes, C. R., Bamber, J. L., Dutton, A., & DeConto, R. M. (2025b). Warming of +1.5 °C is too high for polar ice sheets. *Communications Earth & Environment*, *6*(1), 1–12. https://doi.org/10.1038/s43247-025-02299-w

STOMMEL, H. (1961). Thermohaline Convection with Two Stable Regimes of Flow. *Tellus*, *13*(2), 224–230. https://doi.org/10.1111/j.2153-3490.1961.tb00079.x

Storlazzi, C. D., Elias, E. P. L., & Berkowitz, P. (2015). Many Atolls May be Uninhabitable Within Decades Due to Climate Change. *Scientific Reports*, *5*(1), 14546. https://doi.org/10.1038/srep14546

Tanaka, S., & Matsubayashi, T. (2026). Clouding the mind? Assessing the suicide impacts of solar radiation management in the United States. *The Japanese Economic Review*. https://doi.org/10.1007/s42973-026-00273-5

Tarshish, N., Jeevanjee, N., & Fung, I. (2026). Multi-century cooling after net-zero greenhouse gas emissions. *Nature Climate Change*, *16*(8), 941–946. https://doi.org/10.1038/s41558-026-02700-2

Terhaar, J., Frölicher, T. L., & Joos, F. (2023). Ocean acidification in emission-driven temperature stabilization scenarios: The role of TCRE and non-CO_2 greenhouse gases. *Environmental Research Letters*, *18*(2), 024033. https://doi.org/10.1088/1748-9326/acaf91

The Royal Society. (2025). *Solar radiation modification: Policy briefing*.

Theokritoff, E., Lejeune, Q., Costa, H. P., Irfan, K., Khan, M. S., Kropf, C. M., Lindberg, H. G., Marques, I. G., Menke, I., Schleussner, C.-F., Thomas, A., & Lourenço, T. C. (2025). Climate overshoot implications for local adaptation planning. *Climate Policy*, *26*(2), 344–351. https://doi.org/10.1080/14693062.2025.2502111

Theokritoff, E., Lejeune, Q., Costa, H. P., Irfan, K., Khan, M. S., Kropf, C. M., Lindberg, H. G., Marques, I. G., Menke, I., Schleussner, C.-F., Thomas, A., & Lourenço, T. C. (2026). Climate overshoot implications for local adaptation planning. *Climate Policy*, *26*(2), 344–351. https://doi.org/10.1080/14693062.2025.2502111

Trisos, C. H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L., & Zambri, B. (2018). Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nature Ecology & Evolution*. https://doi.org/10.1038/s41559-017-0431-0

UK Government. (2026). *Direct Air Capture and Greenhouse Gas Removal Innovation Programme: Phase 2 projects*. GOV.UK. https://www.gov.uk/government/publications/direct-air-capture-and-greenhouse-gas-removal-innovation-programme-selected-projects/direct-air-capture-and-greenhouse-gas-removal-innovation-programme-phase-2-projects

UNCTAD. (2024). *The Least Developed Countries Report 2024 (Overview)*. https://unctad.org/system/files/official-document/ldc2024overview_en.pdf

UNDRR. (2022). *Our World at Risk Transforming Governance for a Resilient Future*. https://www.undrr.org/gar/gar2022-our-world-risk-gar

UNFCCC. (2015). *Report on the structured expert dialogue on the 2013–2015 review. Note by the co-facilitators of the structured expert dialogue*. https://unfccc.int/documents/8707

UNFCCC. (2021). *Decision 1/CMA.3: Glasgow Climate Pact* (FCCC/PA/CMA/2021/10/Add.1). UNFCCC. https://unfccc.int/documents/460952

UNFCCC. (2023). *Outcome of the first global stocktake*. https://unfccc.int/documents/637073

UNFCCC. (2025). *Global Mutirão: Uniting humanity in a global mobilization against climate change* [Decision adopted by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA.7)]. UNFCCC. https://unfccc.int/sites/default/files/resource/Mutir%C3%A3o_cop30.pdf

United Nations Environment Programme. (2026). *Limiting Overshoot: Navigating exceedance of 1.5°C and pathways towards return* (Nos. 978-92-807-4301–2). United Nations Environment Programme. https://doi.org/10.59117/20.500.11822/49857

Usman, S., González-Torres Fernández, G., & Parker, M. (2025). Going NUTS: The regional impact of extreme climate events over the medium term. *European Economic Review*, *178*, 105081. https://doi.org/10.1016/j.euroecorev.2025.105081

van Leeuwen, C., Sgubin, G., Bois, B., Ollat, N., Swingedouw, D., Zito, S., & Gambetta, G. A. (2024). Climate change impacts and adaptations of wine production. *Nature Reviews Earth & Environment*, *5*(4), 258–275. https://doi.org/10.1038/s43017-024-00521-5

Van Tricht, L., Zekollari, H., Huss, M., Rounce, D. R., Schuster, L., Aguayo, R., Schmitt, P., Maussion, F., Tober, B., & Farinotti, D. (2026). Peak glacier extinction in the mid-twenty-first century. *Nature Climate Change*, *16*(2), 143–147. https://doi.org/10.1038/s41558-025-02513-9

Van Vuuren, D. P., O'Neill, B. C., Tebaldi, C., Sanderson, B. M., Chini, L. P., Friedlingstein, P., Hasegawa, T., Riahi, K., Govindasamy, B., Bauer, N., Eyring, V., Fall, C. M. N., Frieler, K., Gidden, M. J., Gohar, L. K., Högner, A., Jones, A. D., Kikstra, J., King, A., … Ziehn, T. (2026). The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7). *Geoscientific Model Development*, *19*(7), 2627–2656. https://doi.org/10.5194/gmd-19-2627-2026

Van Westen, R. M., & Baatsen, M. L. J. (2025). European Temperature Extremes Under Different AMOC Scenarios in the Community Earth System Model. *Geophysical Research Letters*, *52*(12), e2025GL114611. https://doi.org/10.1029/2025GL114611

van Westen, R. M., Börner, R., & Dijkstra, H. A. (2026). Failure to track a stable AMOC state under rapid climate change. *Nature Climate Change*. https://doi.org/10.1038/s41558-026-02730-w

van Westen, R. M., Vanderborght, E., Kliphuis, M., & Dijkstra, H. A. (2025). Physics-Based Indicators for the Onset of an AMOC Collapse Under Climate Change. *Journal of Geophysical Research: Oceans*, *130*(8), e2025JC022651. https://doi.org/10.1029/2025JC022651

van Westen, R. M., Vanderborght, E. Y. P., Kliphuis, M., & Dijkstra, H. A. (2024). *Substantial Risk of 21st Century AMOC Tipping even under Moderate Climate Change* (Version 1). arXiv. https://doi.org/10.48550/ARXIV.2407.19909

Vermeer, M., & Rahmstorf, S. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, *106*(51), 21527–21532. https://doi.org/10.1073/pnas.0907765106

Visioni, D., MacMartin, D. G., Kravitz, B., Boucher, O., Jones, A., Lurton, T., Martine, M., Mills, M. J., Nabat, P., Niemeier, U., Séférian, R., & Tilmes, S. (2021). Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations. *Atmospheric Chemistry and Physics*, *21*(13), 10039–10063. https://doi.org/10.5194/acp-21-10039-2021

Visual Capitalist. (2026). *Ranked: The World's Largest Oil Exporters in 2025*. https://www.visualcapitalist.com/ranked-worlds-largest-oil-exporters-2025/

Vogt-Vincent, N. S., McManus, L. C., & Toonen, R. J. (2026). Global coral reef collapse is not inevitable. *Trends in Ecology & Evolution*, *41*(7), 571–573. https://doi.org/10.1016/j.tree.2026.04.018

Voigt, C., & Ferreira, F. (2016). 'Dynamic Differentiation': The Principles of CBDR-RC, Progression and Highest Possible Ambition in the Paris Agreement. *Transnational Environmental Law*, *5*(2), 285–303. https://doi.org/10.1017/S2047102516000212

Volkov, D. L., Zhang, K., Johns, W. E., Willis, J. K., Hobbs, W., Goes, M., Zhang, H., & Menemenlis, D. (2023). Atlantic meridional overturning circulation increases flood risk along the United States southeast coast. *Nature Communications*, *14*(1), 5095. https://doi.org/10.1038/s41467-023-40848-z

Vousdoukas, M. I., Athanasiou, P., Giardino, A., Mentaschi, L., Stocchino, A., Kopp, R. E., Menéndez, P., Beck, M. W., Ranasinghe, R., & Feyen, L. (2023). Small Island Developing States under threat by rising seas even in a 1.5 °C warming world. *Nature Sustainability*, *6*(12), 1552–1564. https://doi.org/10.1038/s41893-023-01230-5

Wang, H., Deng, H.-M., Liu, L.-J., Jiang, H.-D., Purohit, P., & Liang, Q.-M. (2025). Air pollution and climate change drive health inequities across China's provinces (2000–2023). *iScience*, *28*(10). https://doi.org/10.1016/j.isci.2025.113582

Wang, T., An, J., Chen, B., Webster, C. J., Gong, P., & Lin, C. (2025). In utero exposure to extreme heat increases neonatal mortality. *PNAS Nexus*, *4*(8), pgaf240. https://doi.org/10.1093/pnasnexus/pgaf240

Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. *Joule*, *6*(9), 2057–2082. https://doi.org/10.1016/J.JOULE.2022.08.009

WEF. (2026). *The global energy crisis is foremost an Asian energy crisis. It needs an Asian response*. https://www.weforum.org/stories/energy-transition/asian-energy-crisis-security-hormuz

Wells, I., & Guinto, J. (2026, October 17). *Brazil sees record fall in Amazon deforestation as key election looms*.

Williams, M. St. M., Clarke, L. A., Koon Koon, R., Taylor, M. A., Campbell, J. D., & Stephenson, T. S. (2025). The effects of solar radiation modification on solar and wind resource and power generation in the Caribbean. *PLOS One*, *20*(6), e0325226. https://doi.org/10.1371/journal.pone.0325226

Williams, R. G., Goodwin, P., Ceppi, P., Jones, C. D., & MacDougall, A. H. (2025). A normalised framework for the Zero Emissions Commitment. *Biogeosciences*, *22*(22), 7167–7186. https://doi.org/10.5194/bg-22-7167-2025

WMO. (2020). *State of Climate Services 2020 Report: Move from Early Warnings to Early Action*.

WMO. (2022). *Scientific Assessment of Ozone Depletion* (GAW Report No. 278, p. 509 pp.). World Meteorological Organization (WMO).

WMO. (2025). *Temperature increase is accelerating in Arab Region, with escalating impacts*. Temperature increase is accelerating in Arab Region, with escalating impacts

WMO. (2026a). *State of the Climate in Asia 2025*. https://library.wmo.int/viewer/69873/download?file=WMO-1397-2026_en.pdf&type=pdf&navigator=1

WMO. (2026b). *State of the Global Climate 2025* (2025th ed.). World Meteorological Organization. https://doi.org/10.59327/WMO/S/CRI/SOC/1

World Bank. (2024). *Four things you should know: Climate change & Small Island Developing States—By the numbers*. https://blogs.worldbank.org/en/climatechange/four-things-you-should-know--climate-change---small-island-devel

World Weather Attribution. (2022). *Climate change made devastating early heat in India and Pakistan 30 times more likely*. World Weather Attribution. https://www.worldweatherattribution.org/climate-change-made-devastating-early-heat-in-india-and-pakistan-30-times-more-likely/

Wunderling, N., Donges, J. F., Kurths, J., & Winkelmann, R. (2021). Interacting tipping elements increase risk of climate domino effects under global warming. *Earth System Dynamics*, *12*(2), 601–619. https://doi.org/10.5194/esd-12-601-2021

Xu, W., Yuan, W., Wu, D., Zhang, Y., Shen, R., Xia, X., Ciais, P., & Liu, J. (2024). Impacts of record-breaking compound heatwave and drought events in 2022 China on vegetation growth. *Agricultural and Forest Meteorology*, *344*, 109799. https://doi.org/10.1016/j.agrformet.2023.109799

Young, D. N. (2023). Considering stratospheric aerosol injections beyond an environmental frame: The intelligible 'emergency' techno-fix and preemptive security. *European Journal of International Security*, *8*(2), 262–280. https://doi.org/10.1017/eis.2023.4

Young, Yao, Considine, & Golja. (2026). *Comprehensive Report Negotiating solar radiation modification governance: Evidence from non-ideal simulations*. https://cfg.eu/negotiating-solar-radiation-modification-governance/

Zekollari, H., Schuster, L., Maussion, F., Hock, R., Marzeion, B., Rounce, D. R., Compagno, L., Fujita, K., Huss, M., James, M., Kraaijenbrink, P. D. A., Lipscomb, W. H., Minallah, S., Oberrauch, M., Van Tricht, L., Champollion, N., Edwards, T., Farinotti, D., Immerzeel, W., … Sakai, A. (2025). Glacier preservation doubled by limiting warming to 1.5°C versus 2.7°C. *Science*, *388*(6750), 979–983. https://doi.org/10.1126/science.adu4675

Zelinka, M. D., Myers, T. A., Qin, Y., Chao, L.-W., Klein, S. A., Po-Chedley, S., Ma, P.-L., Wall, C. J., Ceppi, P., & Gettelman, A. (2026). Recent cloud trends and extremes reaffirm established bounds on cloud feedback and aerosol-cloud interactions. *Communications Earth & Environment*, *7*(1), 615. https://doi.org/10.1038/s43247-026-03461-8

Zemp, M., Jakob, L., Dussaillant, I., Nussbaumer, S. U., Gourmelen, N., Dubber, S., A, G., Abdullahi, S., Andreassen, L. M., Berthier, E., Bhattacharya, A., Blazquez, A., Boehm Vock, L. F., Bolch, T., Box, J., Braun, M. H., Brun, F., Cicero, E., Colgan, W., … The GlaMBIE Team. (2025). Community estimate of global glacier mass changes from 2000 to 2023. *Nature*, *639*(8054), 382–388. https://doi.org/10.1038/s41586-024-08545-z

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., … Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, *114*(35), 9326–9331. https://doi.org/10.1073/pnas.1701762114

Zhao, M., Zhu, M., Chen, Y., Zhang, C., & Cai, W. (2024). The uneven impacts of climate change on China's labor productivity and economy. *Journal of Environmental Management*, *351*, 119707. https://doi.org/10.1016/j.jenvman.2023.119707

Zheng, H., Cheng, L., Dangendorf, S., Meyssignac, B., Barnoud, A., Trenberth, K. E., Fasullo, J. T., & Abraham, J. (2026). Improved closure of the global mean sea level budget from observational advances since 1960. *Science Advances*, *12*(21), eaea0652. https://doi.org/10.1126/sciadv.aea0652

Zurbriggen, T., Brazzola, N., Odenweller, A., Ueckerdt, F., & Rogelj, J. (2026). Short-term action is key for gigaton-scale Direct Air Capture by 2050. *Nature Communications*. https://doi.org/10.1038/s41467-026-72691-3

Annex A: Rescuing 1.5°C if the climate runs hot

The temperature outcomes of HPA-2025 and its variants are based on the climate response assessed in IPCC AR6, as represented in the MAGICC model. Observed warming has accelerated markedly over the past decade, and the evidence on what is driving it, and on whether the climate is more sensitive than assessed, is still evolving (see below). Some recent work points towards the upper part of the assessed sensitivity range: analyses of cloud feedback point that way and paleoclimate evidence has been read as implying substantially higher sensitivity.

Other recent work does not agree: accounting for paleoclimate pattern effects constrains sensitivity to 2.1–4.0°C, with a best estimate of 2.8°C.

The question is unresolved and will be reassessed comprehensively in AR7. Meanwhile, carbon-cycle feedbacks such as permafrost thaw and Arctic wildfire add further warming for any given emissions pathway and are not represented in the MAGICC model as used here (Schädel et al., 2026).

A.1 Observed physical climate feedbacks: current science

The rate of observed warming has itself accelerated markedly, leading to concerns that this could be a positive feedback emerging.

Foster and Rahmstorf (2026) find that, after removing the influence of El Niño, volcanic eruptions and solar variability, the warming rate since around 2015 is approximately 0.35°C per decade – around 75% faster than the average rate of just under 0.2°C per decade recorded from 1970 to 2015, and the fastest observed rate in any decade since instrumental records began (Foster & Rahmstorf, 2026).

The anomalous warming of 2023–2025 has now been substantially attributed to a combination of physical feedbacks and forcing changes that are distinct from carbon cycle responses.

Satellite data from CERES confirm that a record decline in planetary albedo, driven by reduced low-level cloud cover over northern mid-latitude and tropical oceans, contributed approximately 0.22°C to the 2023 temperature anomaly (Goessling et al., 2025); and a 2026 analysis extending over the full 2003–2024 CERES record finds that this low-cloud decline accounts for roughly half the observed increase in Earth's energy imbalance over that period (Ceppi et al., 2026).

The aerosol reduction behind much of the cloud-cover change – principally the ~80% cut in shipping SO_2 from IMO 2020 regulations (Quaglia & Visioni, 2024), compounded by Chinese industrial emission reductions – now has a well-established role. Though full attribution remains contested (Zelinka et al., 2026), the effect of the shipping

component alone is estimated as modest at 0.08 ± 0.03°C – with other work suggesting less (Quaglia & Visioni, 2024).

In the case of the cloud feedback component, these changes represent a positive physical feedback loop: warming reduces low cloud cover, which reduces reflected sunlight, which drives further warming.

Importantly, updated observational constraints on climate sensitivity – Boardman et al. (2026), using CMIP6 models and observational data through 2024 – give a transient climate response (TCR) of 1.81 K (very likely range 1.28–2.33 K), essentially unchanged from the AR6 central estimate of 1.8 K (Boardman et al., 2026). They explicitly conclude that the record-breaking warming of 2023–2024 does not justify a higher value. However, Armour et al. (2024) show these models fail to reproduce the observed pattern of sea-surface temperature change, and that this pattern effect has both slowed warming to date and biased warming-based sensitivity estimates low (Armour et al., 2024). Observationally constrained TCR near the AR6 value is therefore consistent with, rather than evidence against, an equilibrium climate sensitivity (ECS) in the upper part of the assessed range.

The observed acceleration may be explained by the reduction in aerosol cooling and the associated low-cloud-cover changes rather than by an increase in climate sensitivity above the AR6 likely range, though that possibility cannot yet be fully excluded.

It is, however, well established that carbon-cycle feedbacks can amplify warming. Abernethy et al. (2026) find that together they could add 0.2–0.4°C of additional warming by 2100 across scenarios, amplifying post-2020 anthropogenic warming by 20–30%(Abernethy et al., 2026). For low-emission scenarios this amplification is 0.2 ± 0.2°C, but – with median warming much lower than in other scenarios – this represents a relatively large fraction of up to 30%. Note that around 2050 the effect is only ~0.06 ± 0.06°C and amplification is 10 ± 10% across all scenarios, meaning that for low-emission scenarios such as HPA-2025, this amplification is a bigger concern for returning to below 1.5°C than for peak warming.

There is as yet no basis for a new best estimate of climate sensitivity and its uncertainty range. But it is fair to say that the median estimates of peak warming of around 1.7°C and an end-of-century warming of around 1.2°C by 2100 can potentially be at the lower end of the range, and if uncertainties in the climate system go against us, peak temperatures could be higher even with emissions cut in line with highest possible ambition.

A.2. What if the climate runs hot? HPA-2025 under a higher climate response

What if the peak warming of around 1.7°C in our current best case, HPA-2025, turned out to be higher because the climate is more sensitive than assumed? And if so, what could still limit the overshoot? To explore this, HPA-2025 is run with an existing set of

MAGICC parameters representing a high transient climate response.[8] The parameter set is used as an illustration of a hotter climate, not as a new central estimate.

Figure 18 shows the implication of the high transient climate response on warming levels on the Climate Action Tracker's "Policies & action" and "Pledges & targets" scenarios (Climate Action Tracker, 2025) and the HPA-2025.

Increases in warming if the climate runs hot

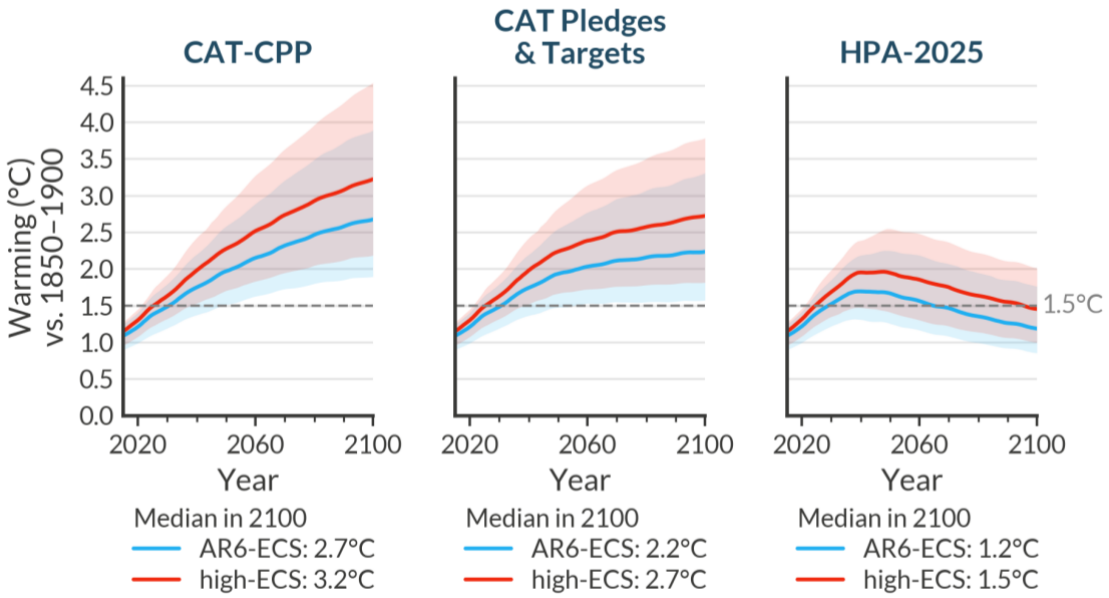


Figure 18: Increases in warming if the climate runs hot: shown for the Climate Action Tracker's "Policies & action" scenario and "Pledges & targets" scenario as well as for HPA-2025.

Under the high-sensitivity configuration:

- In the Climate Action Tracker scenarios, the end-of-century warming increases for "Policies & action" from 2.7°C to 3.2°C and for "Pledges & targets" from 2.2°C to 2.7°C.
- In the HPA-2025, global surface temperature keeps increasing longer, delaying the warming peak by 8 years. Peak warming rises from 1.7°C to 2°C and end-of-century warming increases to 1.5°C from 1.2°C.

A.3. Limiting the overshoot in a hotter climate

Two additional mitigation options are explored to address the high transient climate response and bring temperatures further down again: deeper methane reductions and

[8] Warming pathways for a given emissions scenario are calculated with the reduced-complexity climate model MAGICC (Meinshausen et al., 2020), using the 600-member parameter set calibrated to the IPCC Sixth Assessment Report (Forster et al., 2021; Kikstra et al., 2022). For the high-sensitivity case, we reweight the ensemble so that median sensitivity rises from 3.0°C to 4.0°C, the top of the range IPCC AR6 assessed as *likely*.

additional carbon dioxide removal. Both go beyond the modelled frontier and sit outside the HPA family, described in Chapter 3.

Deeper methane reductions. A deeper methane pathway for agriculture and waste, taken from IAM results, is substituted into HPA-2025, while the energy-sector methane pathway of HPA-2025 is left unchanged. The total emissions of both HPA-2025 and the modified pathway are visualised in Figure 19.

Methane: what deeper cuts could add to HPA-2025

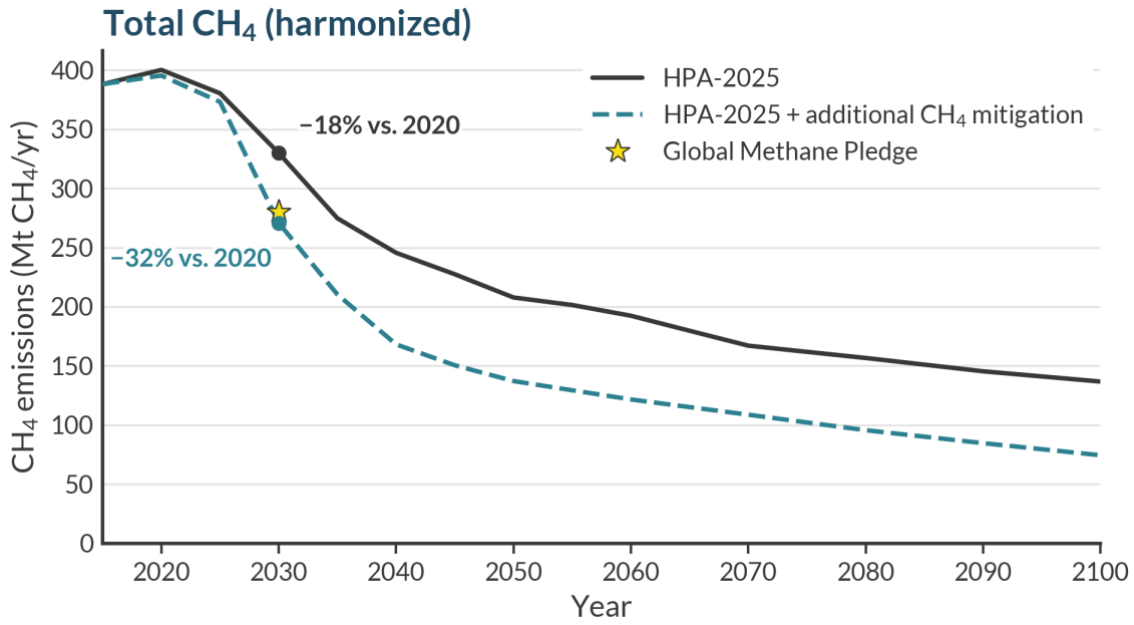


Figure 19: Methane emissions in HPA-2025 (black) and for HPA modification with deeper methane emission reductions for agriculture and waste (dashed purple). The latter pathway explores how coordinated action on methane across sectors can increase methane action in line with the Global Methane Pledge (-30% emissions by 2030 compared to 2020; yellow star).

HPA-2025 assumes little change in agricultural and waste methane to 2030 (Climate Analytics, 2026, *Cutting methane, limiting overshoot*). To explore the potential of increased near-term methane mitigation in these sectors, deeper methane mitigation pathways from IAMs are drawn upon (Hou et al., 2026). A combination of these sectoral pathways results in a Global Methane Pledge compliant pathway to reduce global methane emissions below those of HPA-2025, to 30% below 2020 by 2030.

Additional carbon dioxide removal. Building on the deeper-methane case, and as a thought experiment, additional negative CO_2 emissions are added to determine how much would be needed to bring end-of-century warming back to around 1.2–1.3°C. The thought experiment is visualised in Figure 20.

How much additional CDR a hotter climate would require

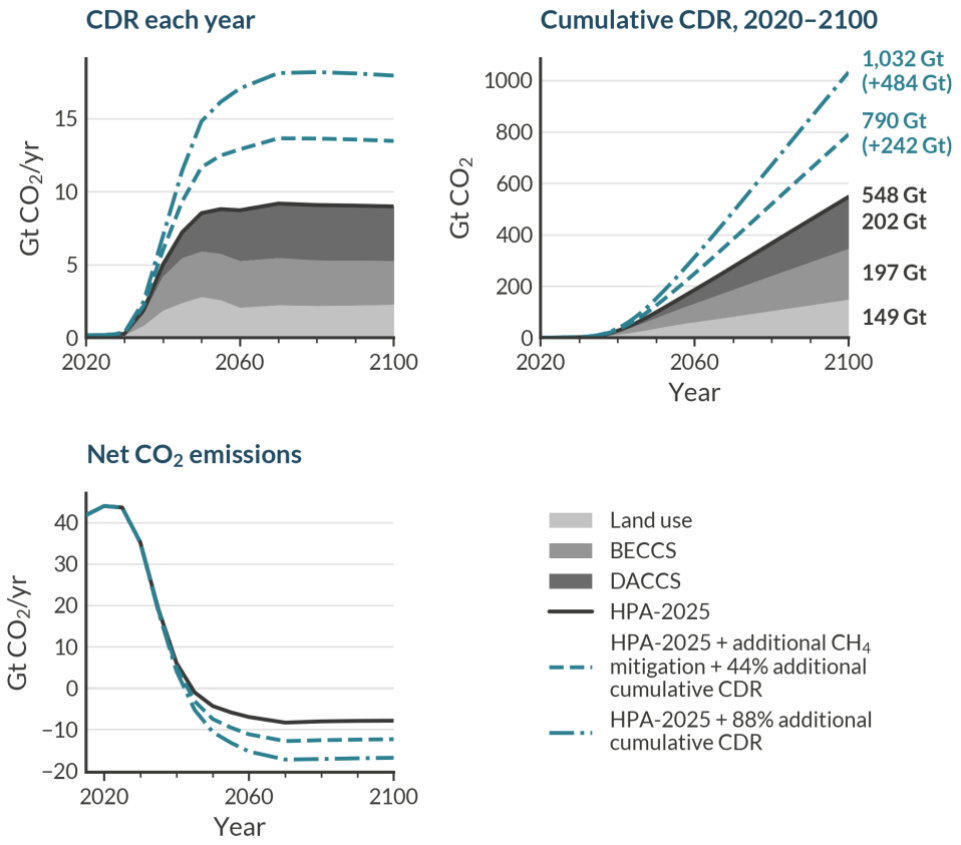


Figure 20: Carbon dioxide removal (CDR) in HPA-2025 combined with additional removals. The first plot shows stacked annual removals, where the coloured areas represent CDR as modelled in HPA-2025 (LULUCF, BECCS, DACCS) and the dashed lines represent the additional CDR in the thought experiment. The second plot visualises how much additional CDR is cumulatively removed in the thought experiments. The third plot shows the net carbon dioxide emissions in the experimental setup.

Unlike the methane case, this thought experiment does not show what is likely to be possible, only what would be required. Whether that is achievable remains an open question for future modelling.

Figure 21 shows how these additional mitigation action options can impact the warming level of the HPA-2025 both under standard and high transient climate response.

Impacts of additional mitigation actions in HPA-2025

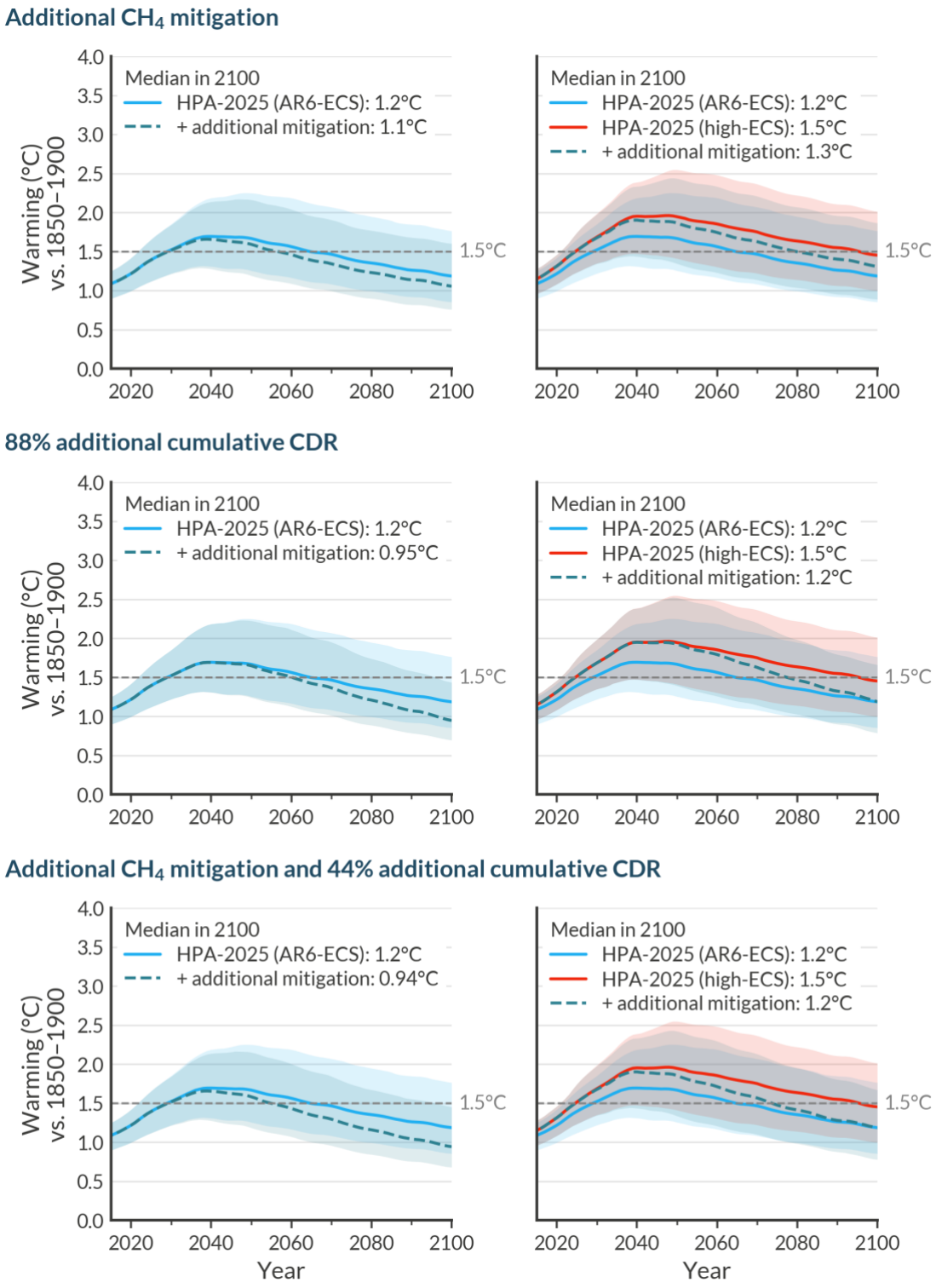


Figure 21: Impacts of additional mitigation actions in HPA-2025: Subplots on the left show the impact on warming under standard assumptions on climate sensitivity. Subplots on the right additionally show the high transient climate response. The amount of CDR is chosen in such a way that an end of century warming of close to 1.2°C is achieved.

Deeper methane reductions in agriculture and waste lower peak warming from 2°C to 1.9°C, and reduce warming in 2100 from 1.5°C to 1.3°C. This means that bringing end-of-century warming back to 1.2°C would require additional carbon dioxide removal (CDR).

If CDR is applied by itself, without additional reduction in methane, an additional 484 $GtCO_2$ would need to be sequestered to bring end-of-century temperatures down to 1.2°C again. This would increase the total amount of CDR deployed across the century from 548 $GtCO_2$ in HPA-2025 to 1032 $GtCO_2$. These additional removals mainly affect the decline after the peak; they would lower peak warming only if deployed at scale well before it.

If both the deeper methane reduction and CDR are deployed in parallel, the amount of additional CDR needed to bring end-of-century temperatures down to 1.2°C again decreases to 242 $GtCO_2$. In this combination, peak warming is also kept at 1.9°C instead of 2°C in the high transient climate response settings.

Figure 22 visualises a thought experiment which explores how much CDR would be required to bring end-of-century warming back to 1.2°C for the Climate Action Tracker's "Policies & action" pathway.

Current policies with 590% additional cumulative CDR

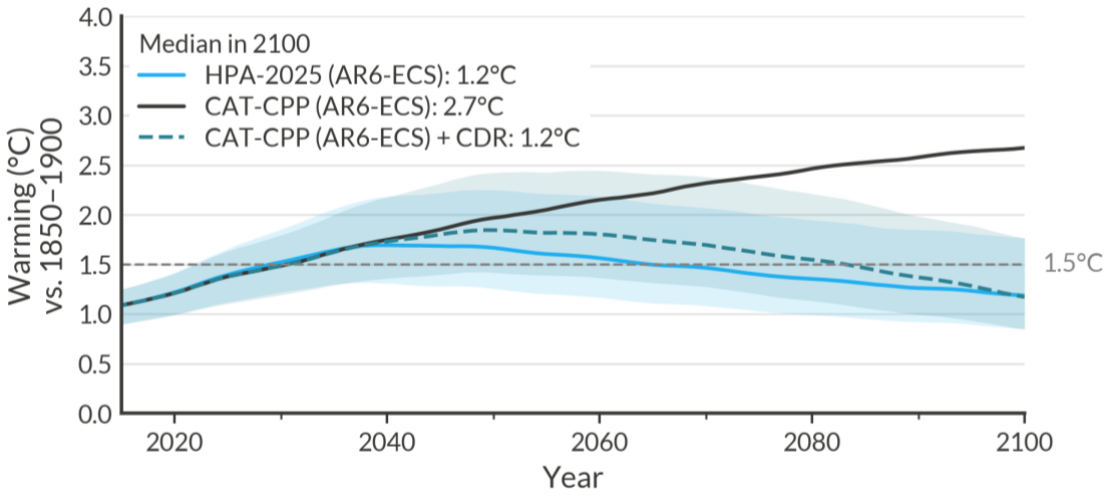


Figure 22: Hypothetical amount of carbon dioxide removal needed to bend the Climate Action Tracker's "Policies & action" pathway back to 1.2°C at the end of the century under a standard climate response.

An additional 3230 $GtCO_2$ captured is required to bring warming back down to 1.2°C again, around six times the total CDR in HPA-2025.

A more sensitive climate strengthens the case for faster emission reductions, deeper methane cuts and early investment in carbon dioxide removal. It does not make the case for solar radiation modification (see Annex B). The methane variant also indicates where the frontier of highest possible ambition could move. Full modelling of deeper methane reductions and of a realistic CDR portfolio is planned for future versions of the HPA family.

Annex B: Solar radiation modification: A dangerous distraction

Solar radiation modification (SRM) or solar geoengineering is gaining prominence as an apparent option to limit global warming, given the imminence of overshoot.

Various SRM options have been proposed, with Stratospheric Aerosol Injection (SAI) the most prominent. SAI would reduce incoming solar radiation, mimicking the natural cooling effect of major volcanic eruptions. Other options include Marine Cloud Brightening and Cirrus Cloud Thinning or even space-based mirrors. Crucially, no mature technology exists today (Lee et al., 2023).

If coordinated globally and deployed safely, SRM would in all likelihood lower global average surface temperatures. However, it would not reverse or halt climate change but create a different, engineered climate (O'Neill et al., 2022). Different pathways to the same global temperature target achieved through mitigation vs through SRM may lead to fundamentally different climate outcomes (Hwong et al., 2026). Meanwhile, de-coupling mitigation, temperatures, and climate impacts could erode the foundations of climate agreements.

SRM deployment would create new impacts and risks for human and natural systems, driven by changes in temperature, precipitation, and extremes, distributed unequally across the globe. The potential impacts and risks of different SRM methods are complex, and many are not well understood or deeply uncertain. Temperature or rainfall patterns could diverge from the intention of the intervention, and there is a risk of residual or overcompensating climate change at the regional or seasonal level (Lee et al., 2023).

Reducing the amount of incoming light could impact biodiversity and plant growth (Trisos et al., 2018), renewable energy (Kumler et al., 2025); (M. St. M. Williams et al., 2025), and even mental health (Tanaka & Matsubayashi, 2026). SAI would change atmospheric chemistry and could delay recovery of the ozone hole (WMO, 2022). Uneven regional temperature patterns could emerge, including less cooling in polar regions, especially with uneven injection (Duffey et al., 2023); (Irvine et al., 2010). Reducing incoming solar radiation could cut global average rainfall and change water availability, with regionally diverse patterns, depending on the deployment strategy (Rezaei et al., 2025); (Visioni et al., 2021).

The benefits and risks would be unevenly distributed, creating regional "winners" and "losers," with the most vulnerable likely to be disproportionately affected. Regionally diverse impacts on temperature, rainfall, and extremes would have implications for

climate-dependent sectors and livelihoods including agriculture, forestry, fisheries, and tourism.

Since SRM does not address greenhouse gas emissions, the root cause of climate change, it does not address their non-temperature related impacts. These include continued ocean acidification as the ocean absorbs CO_2, changing ocean chemistry. This has severe impacts on biodiversity, food webs, fisheries, and coastal livelihoods. Observations indicate that the planetary boundary for ocean acidification has been transgressed (Caesar et al., 2026);(Canadell et al., 2021); (O'Neill et al., 2022). Any chance of recovery requires reducing CO_2 emissions and lowering CO_2 concentrations through the phase-out of fossil fuels.

The climate system would respond quickly, on a timescale of years, to any changes in SRM deployment. This would leave little time to respond with policy. The changes would require new or shifted efforts on adaptation and loss and damage responses, as well as associated costs, especially for climate-dependent sectors.

If SRM deployment were halted for any reason – such as technological failure, political instability, or geopolitical conflict (Sanderson et al., 2026) – this would, within a few months to a few years, suddenly unmask the warming from the years or decades of greenhouse gas emissions that continued during SRM deployment. This sudden rise in temperatures would lead to rapidly unfolding impacts, known as the "termination shock"(O'Neill et al., 2022). These could be too fast to adapt or respond to.

Major **uncertainties** remain around SRM deployment, its effects, and how its impacts could be attributed (Haywood et al., 2025); (Lee et al., 2023);(Siegert et al., 2025); (The Royal Society, 2025). Difficulties in attributing responsibility for impacts of SRM deployment or of its termination pose new challenges for liability and compensation for damages (Proelss & Steenkamp, 2023); (The Royal Society, 2025). This could undermine the scientific basis of the Loss and Damage Fund. Because SRM research is largely based on models and scenarios that assume idealised deployment conditions without taking into account real-world socio-political dynamics, impacts of globally uncoordinated, inconsistent deployment are scarcely studied (Sanderson et al., 2026). Ultimately, therefore, we would all be living the global experiment.

There is some debate around what SRM would mean for the achievement of climate goals, co-benefits with sustainable development and just transitions, and whether or not it would create a "moral hazard" for mitigation and adaptation and lead to their deterrence (Heyen & Tavoni, 2024); (Shue & Hartzmark, 2026). Without strong and simultaneous emissions cuts, SRM may need to be deployed for over a century to avoid any sudden impacts, creating governance and financial commitments for generations (Baur et al., 2023).

Even if physical science uncertainties could be reduced, this would do little to address the bigger issues at play including ethics, governance, security, and costs. Uncertainties and risks concern governance of deployment and governance failure, the potential unilateral control of the global thermostat, equitable decision-making, a possible

weaponisation of the technology, creating or locking in a certain kind of society with little pressure for structural change, and the responsibility for adverse impacts. Motivations for developing and deploying solar geoengineering could be driven by neither the actual risks of the climate crisis, nor the latest science(Young, 2023). Those deploying SRM would gain a potent political and economic lever over those for whom continuing deployment was existential. Recent research suggests that attempts at a global cooperative approach to SRM deployment could fail due to misinformation and distrust, national security concerns and rivalries, the role of commercial interest-driven actors, and a lack of global rules (Young et al., 2026).

Several governments and intergovernmental blocs have positioned themselves against SRM, reaffirming the de facto moratorium under the UN Convention on Biological Diversity on outdoor activities, and calling for a moratorium, non-deployment agreement, or ban. These include the African Ministerial Conference on the Environment, the government of Vanuatu, and the EU (Bronkalla & Ruddigkeit, 2025); (EPRS, 2026); (SAPEA, 2024).

Rather than promoting potentially dangerous real-world experiments, both climate policy and action must follow the best available science, which is clear on the need for urgent and strong cuts to greenhouse gas emissions if we are to meet the Paris Agreement objectives.

By not addressing greenhouse gas concentrations directly, SRM methods provide no real avenue to achieve the UNFCCC's ultimate objective which is the "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Rather, global SRM methods themselves constitute an intentional "dangerous anthropogenic interference with the climate system".



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