This is a non-peer-reviewed preprint submitted to EarthArXiv.

A realistic climate strategy

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Abstract

The international climate strategy is failing. Current policies will act too slowly to prevent rising temperatures from crossing critical climate tipping points. IPCC assessments underestimate the non-linear risks and catastrophic costs of overshooting Paris Agreement targets.

Although solar geoengineering opponents cite concerns about moral hazard and other potential risks, at this juncture cooling interventions are the only feasible way to stop dangerous climate change.

Worsening impacts will force many climate sceptics to address the crisis. They will increasingly support solar geoengineering, as these methods will allow global temperatures to be rapidly lowered without reducing emissions.

Major powers are already researching climate geoengineering. In the near future one or more countries may make unilateral climate interventions to prevent increasingly extreme weather from causing massive crop failures and other deadly disasters.

To prevent rising temperatures causing irreversible environmental and social damages, and forestall the unilateral deployment of untested technologies, an international program is urgently needed to research safe climate cooling methods and develop effective global governance.

Solar geoengineering can reduce temperatures to safe levels, but will not stop rising concentrations of atmospheric greenhouse gases from acidifying the oceans and destroying critical marine ecosystems. Cooling interventions are imperative, but they must be used as supplements for existing strategies to reduce and remove greenhouse gases, not as substitutes.

To ensure constructive outcomes, international dialogue and research must immediately begin on a new, viable climate strategy: supplementing greenhouse gas emission reduction and carbon dioxide removal with cooling interventions. There is no realistic alternative.

Keywords

climate change strategy, climate overshoot, climate tipping points, cooling interventions, climate geoengineering, climate governance

Introduction

The Paris Agreement's climate targets will certainly be missed with current climate policies. There is no longer a credible pathway to keeping temperature increases below 1.5°C (WMO 2024; Fig. 1). This threshold has already been passed (Bevacqua et al. 2025; Cannon 2025); average global temperatures for 2024 were 1.6°C above 1850-1900 averages (the pre-industrial reference period) (Rohde 2025).

Many leading climate scientists expect global temperatures to rise by at least 2.5°C (Carrington 2024). There is a very high likelihood of 2.0 °C of warming by 2040 for the majority of land regions, along with a likelihood of 3°C by 2060 or earlier (Barnes et al. 2025). Hansen et al. (2025) estimate that global heating is likely to reach 2°C by 2045, unless solar geoengineering is deployed.

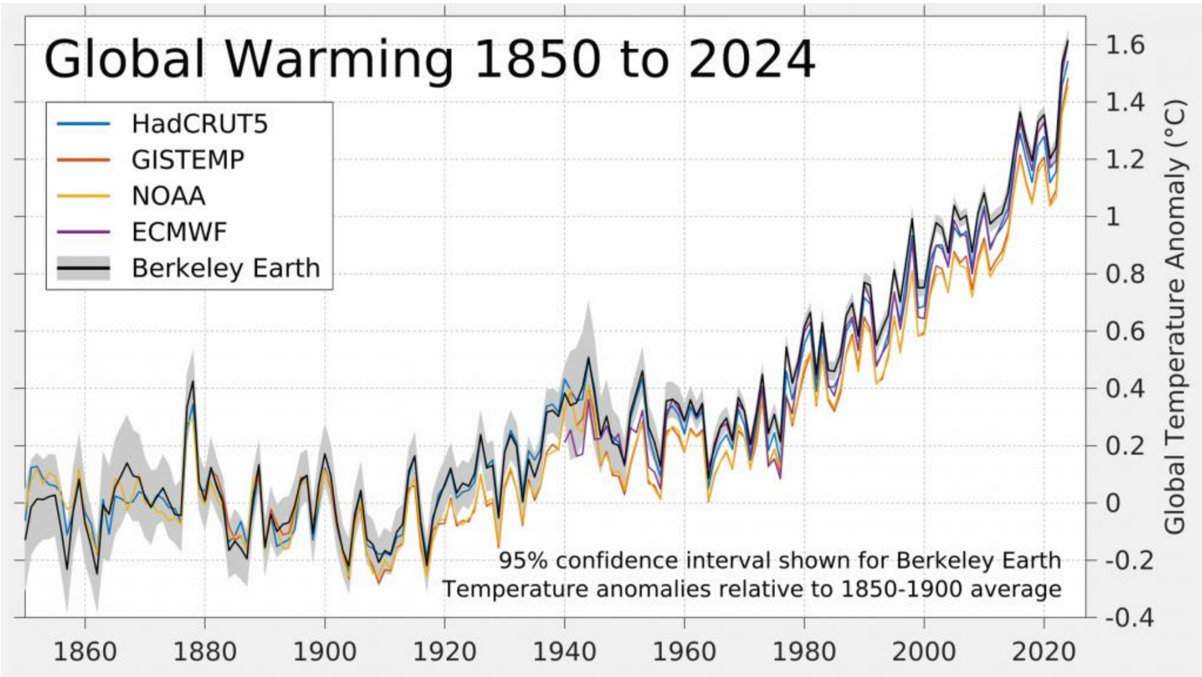

Figure 1. © Berkeley Earth, 2025.

While estimates vary on when and by how much rising temperatures will overshoot climate targets, it is clear that current international climate strategies are failing to moderate this trajectory. In this critical situation, scientists and policy makers need to ask: If current mitigation strategies are not working, what new approaches are needed to ensure safe outcomes? This article examines that question and outlines the requirements for a viable climate strategy.

Our intention is not to denigrate the hard-won scientific and diplomatic achievements of UN organizations, but rather to make these crucial points:

- International climate change strategies are failing. Rapidly rising temperatures are causing ever more dangerous climate change.

- Emission reductions can only limit the rate of temperature increase, and carbon dioxide removal methods act slowly. These strategies alone (even if expedited) will not lower greenhouse gas atmospheric concentrations quickly enough to prevent critical climate feedbacks from accelerating, and numerous earth systems tipping points from being triggered.
- Current strategies for managing climate change risks are fundamentally flawed because they underestimate non-linear risks and the unacceptable costs of failure.
- Achieving Net Zero Emissions will not stabilize the climate at manageable levels:
since the global climate is neither safe nor stable now, it cannot be safely stabilized at a higher temperature.
- Solar geoengineering can rapidly lower global temperatures to safe levels. These methods are the only feasible way to stop dangerous climate change in the near term (Fig. 2). Solar geoengineering opponents have not proposed any viable alternative strategy.
- Climate interventions have lower risks and costs than failing to intervene. A viable strategy will involve the simultaneous deployment of a wide range of approaches, each carefully targeted to maximize safety and effectiveness while minimizing risks and costs.
- Worsening impacts will compel many climate sceptics to address the crisis. They will increasingly support solar geoengineering, as these methods will allow global temperatures to be rapidly lowered without reducing emissions.
- However, solar geoengineering will not stop rising concentrations of atmospheric greenhouse gases from greenhouse gases acidifying the oceans and destroying critical marine ecosystems. These cooling interventions are urgently needed, but not as substitutes, but as supplements to more robust strategies for reducing and removing greenhouse gases.
- Major powers are already researching climate geoengineering. In the near future, one or more countries may make unilateral climate interventions to prevent increasingly extreme weather from causing massive crop failures and other deadly disasters.
- To forestall the unilateral deployment of untested technologies, an international program is urgently needed to research safe climate cooling methods and develop effective global governance.
- Overshoot risks—that rising temperatures may cause inadaptable and/or irreversible damage--must be assessed to determine the requirements for preventing dangerous climate change and restoring a safe, stable climate. All mitigation options should be evaluated in relation to these requirements in order to determine the comparative benefits, risks and costs of using or not using different mitigation strategies. These risk-risk assessments are prerequisites for developing a safe, realistic climate risk management plan (Fig. 3).
- To ensure constructive outcomes, international dialogue and research must immediately begin on developing a comprehensive and effective climate strategy: supplementing greenhouse gas emission reduction and carbon dioxide removal with cooling interventions. There is no realistic alternative.

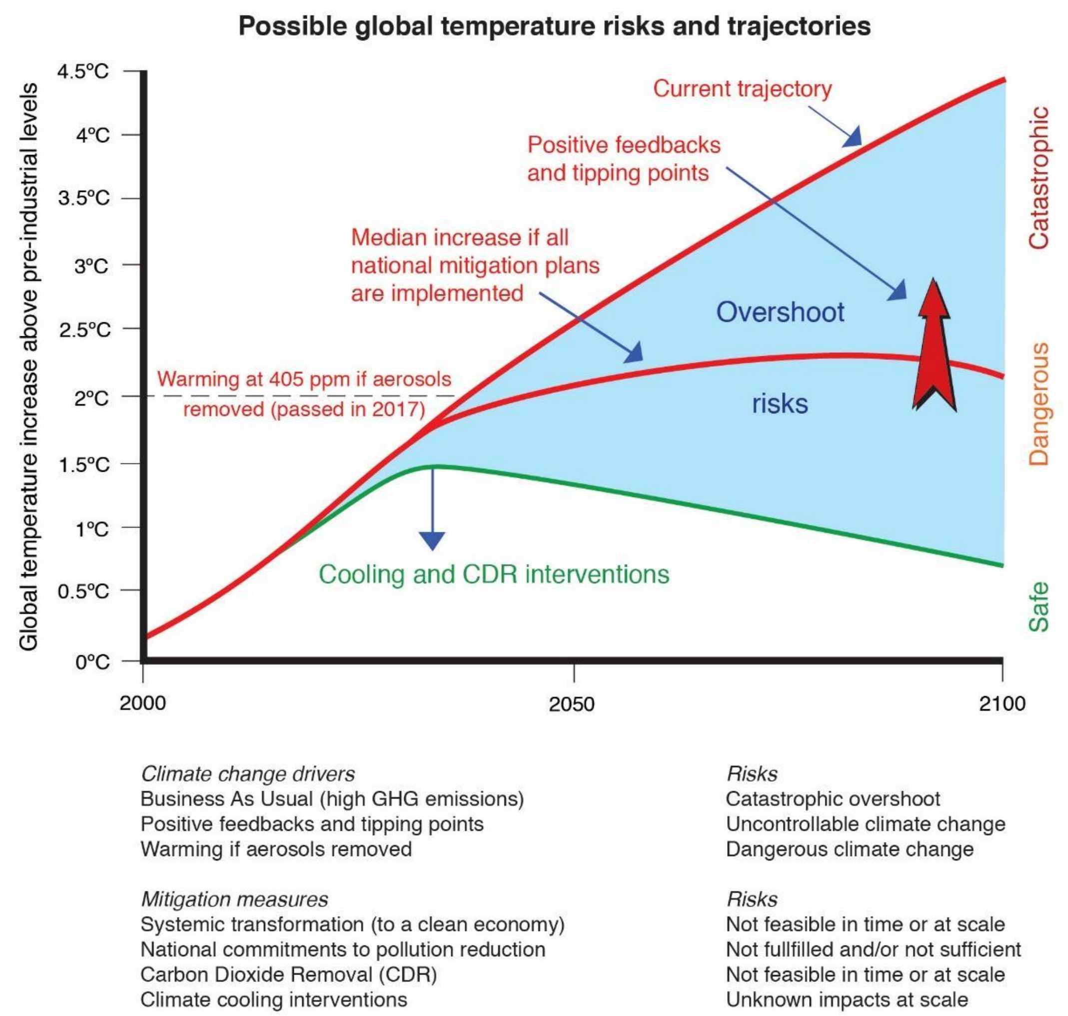

Figure 2. Possible global temperature risks and trajectories. © G. Taylor, 2024.

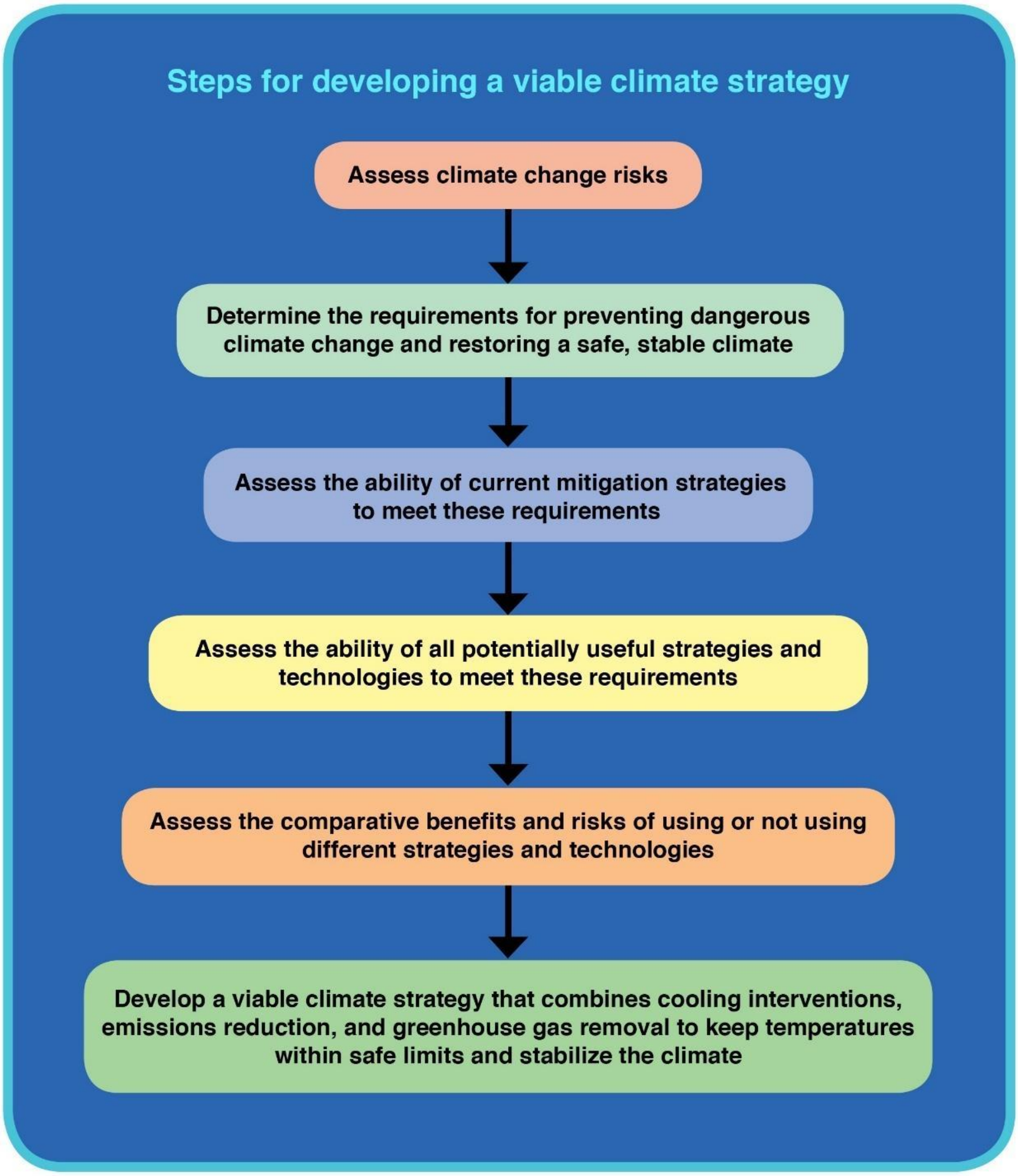

Figure 3. Steps for developing a viable climate strategy. ⓒ G. Taylor, 2025

2. Current climate strategies are failing

2.1. Rising temperatures will overshoot +2°C [Fig. 4].

Recognizing that human-made greenhouse gases (GHGs) are causing global warming, in 1992 one hundred and ninety-seven governments signed an international treaty to reduce emissions—the United Nations Framework Convention on Climate Change (UNFCCC). UNFCCC is the parent treaty to the 2015 Paris Agreement in which parties pledged to limit average global temperature increases to no more than 1.5°C–2°C above pre-industrial levels (UNFCCC 2015).

Notwithstanding these commitments, emissions have increased over the last three decades. Atmospheric concentrations of carbon dioxide, methane and nitrous oxide have constantly risen and are expected to grow further (NOAA 2024a; Nisbet et al. 2019). Few IPCC authors now believe that it will be possible to limit global warming below 2°C (Wynes et al. 2024).

In July 2023, the world's average temperature exceeded 17°C for the first time in 120,000 years (Rannard et al. 2023). Rising temperatures are causing increasingly extreme and destructive weather (e.g., Milman and Witherspoon 2023; Goreau and Hayes 2024; Romanello et al. 2024). For example, global sea ice cover hit a historic low in February, 2025; on February 2 temperatures at the North Pole were above freezing—20°C higher than normal (Macnamara 2025; Niranjan 2025).

Current international climate mitigation strategies rely almost exclusively on reducing emissions and removing carbon dioxide. Current strategies are failing to constrain rising temperatures and even if accelerated, these strategies alone will not prevent dangerous climate change.

2.2. National pledges are insufficient and it will take decades for renewable technologies to replace existing infrastructure.

The feasibility of current efforts is problematic: though many countries have pledged to reduce their emissions to net zero by 2050 or 2060, not only is the aggregate of national goals insufficient to keep global warming below 2°C (Harvey 2021; Liu and Raftery 2021; Fig. 4), but actual plans will not decrease emissions by 2050 (SEI et al. 2023). Further analysis finds deep decarbonization by 2050 improbable (Stammer et al. 2021; Zioga et al. 2024; Smil 2024). As of February 11, 2025, the official deadline has passed for countries to submit their revised NDCs; only 13 of the 195 parties have done so.

The 2025 withdrawal of the United States from the Paris Agreement will further weaken efforts. Following the Trump administration's declaration of war on the "climate hoax" and calls for increasing fossil fuel production, many oil and gas majors are slashing their green investments (Jack 2025). These developments make low emission pathways highly unlikely.

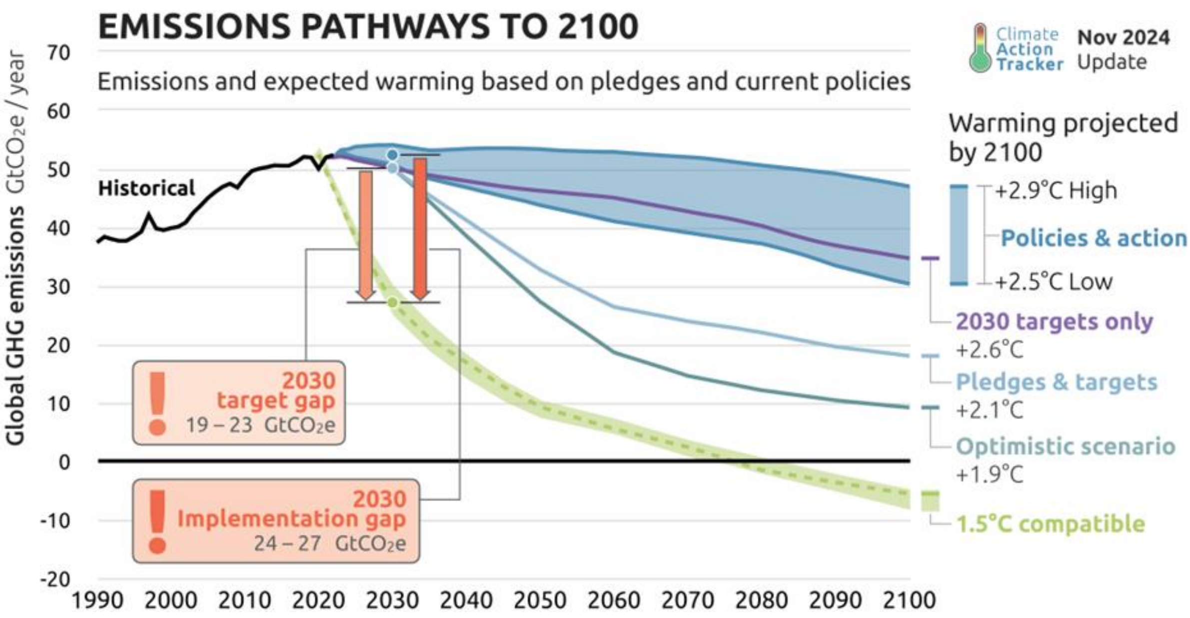

Figure 4. Climate Action Tracker, 2024. © Climate Analytics and NewClimate institute.

Even under the most optimistic scenarios, decarbonization cannot occur quickly enough to mitigate climate inertia and delays caused by committed warming from previous emissions. There will be delayed impacts from existing warming (Samset et al. 2020; Brown et al. 2019), from cultural and political inertia, and from resistance from fossil fuel producers and other vested interests (Westervelt 2022; Brown et al. 2023). For example, fossil fuel investment in 2023 was more than double the levels required to achieve net zero emissions (NZE) by 2050 (IEA 2023a).

Renewable capacity is rapidly increasing (Bond et al. 2024; IEA 2023b). Yet, only one out of 42 clean energy technologies and sectors—sales of electric cars—is currently on track to help hit international emissions reduction targets (WRI 2023) Technologies are not yet available for rapid decarbonization of the global economy in many sectors including agriculture (Costa et al. 2022) and aviation (Bergero and Davis 2023). The inertia of existing institutions, long lifespan of infrastructure, and reluctance to create stranded assets contribute to the challenge of rapid decarbonization.

Other sectors are highly resistant to change: e.g., forestry and land clearing (WRI 2022) and agrifood systems, which together are responsible for almost one-third of all emissions (FAO 2022).

Global inequity is another issue. In 2019 developed countries committed to mobilising USD $100 billion per year by 2020 to support climate action in developing countries, yet little real aid has materialised (Oxfam 2023; Harvey et al. 2024).

2.3. Heating from warming oceans, existing GHGs, and the removal of aerosols will raise temperatures above 2°C.

Between 1971 and 2020, GHGs trapped roughly 380 zettajoules of extra heat (von Schuckmann et al. 2020), which is 25 billion times the energy emitted by the Hiroshima nuclear bomb. The global net radiative flux imbalance means that oceans are now warming at the equivalent of more than five atomic bombs every second (Lubben 2020; Abraham 2022). Since the climate system is currently far from equilibrium, the long life of CO2 and the large thermal inertia of the oceans make long-term future warming inevitable (Rae et al. 2021; Snyder 2016).

Global heating is also masked by anthropogenic air pollution, which creates aerosols that reflect sunlight and lower global mean surface temperatures by 0.5°C– 1.5°C (Lelieveld et al. 2019; Rogelj et al. 2020; Nair et al. 2023; Hansen et al. 2023). Surface temperature warming is accelerating as pollution from burning fossil fuels is reduced (Hodnebrog et al. 2024; Wang et al. 2024).

CO2 concentrations are projected to be 426.6 ppm in 2025 (Betts et al. 2025). If there were no reinforcing feedbacks, doubling CO2 from pre-industrial levels (280 ppm) to around 550 ppm would produce a global warming of about 1°C. However, these feedbacks, which include increased water vapour concentrations due to higher CO2 levels in the atmosphere, as well as other major feedbacks such as reduced global cloud cover, ice sheet melting, and reduced pollution, have reduced earth's albedo by 2% since 2000. A CO2 doubling combined with these feedbacks will amplify the long-term average warming to around 3°C. This 'fast climate sensitivity' is estimated by various climate models as between 2°C and 4.5°C (Raupach and Fraser 2011).

These are massive, long-term problems: the energy imbalance caused by elevated greenhouse gas (GHG) concentrations will continue to drive warming and sea level rise for centuries to millennia (Wadhams 2016).

3. The dangers of overshooting safe temperatures

3.1. It will not be possible to manage or adapt to overshoot risks and impacts

3.1.1. Tipping points are already being passed. Accelerating climate change is a real and existential risk.

Climate tipping points (CTPs) are irrevocable changes to critical Earth systems, such as melting ice sheets, coral reef demise, or rainforest dieback (Fig. 5). These are points of no return: once glaciers and ecosystems like coral reefs have disappeared, they cannot be restored on any reasonable time scale.

Tipping elements have been identified in all earth systems including cryosphere, ocean circulation systems and the biosphere. A growing risk is that even if the Paris Agreement targets are met, a cascade of positive feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway (Steffen et al. 2018; Klose et al. 2020). During the last glacial period, abrupt climate changes sometimes occurred within decades, with temperatures over the Greenland ice-sheet warming 8°C to 16°C each time (Corrick et al. 2020).

We are nearing or have already crossed CTPs; we see catastrophic fires in rainforests, accelerated desertification, collapsing ecosystems, and shrinking sea ice. For example, warming oceans now make the collapse of the West Antarctic Ice Sheet unavoidable (Naughten, Holland and De Rydt 2023).

Six tipping points are likely to be crossed at temperatures within the Paris Agreement targets of 1.5°C - 2°C of warming (McKay et al. 2022):

- Greenland Ice Sheet collapse
- West Antarctic Ice Sheet collapse
- Coral reef die-off at low latitudes
- Sudden thawing of permafrost in northern regions
- Abrupt sea ice loss in the Barents Sea
- Collapse of the Labrador Sea current

More tipping points may be passed at the 2.5°C-2.9°C of warming expected under current policies.

Crossing these climate tipping points will generate feedbacks with cascading effects that increase the likelihood of crossing other CTPs (Laybourn et al. 2023). There is still considerable uncertainty over the likely timing and impacts of CTPs (e.g., Tsakali et al. 2025). Nevertheless, the extreme risks associated with these fat tail events need to be examined and incorporated in climate assessments (Dunlop and Spratt 2017; Kemp et al. 2022).

Arctic permafrost may thaw permanently even if warming stays in the current 1.1°C to 1.5°C range. It is now in a self-sustaining melt cycle that will continue until all carbon is released from permafrost and all ice is melted (Randers and Goluke 2020).

The Greenland Ice Sheet is melting 20% faster than previously estimated: it has lost over a trillion tonnes of ice since 1985 (Greene et al. 2024). The accelerating rate of melt and the positive feedbacks of increasing rainfall and reducing albedo are not represented in IPCC models.

This massive influx of fresh water is slowing the Atlantic meridional overturning circulation (AMOC) (Pontes and Menviel 2024; van Westen et al. 2024). Although Ditlevsen and Ditlevsen (2023) argue that it could collapse between 2025 and 2095, recent modelling suggests that while it will slow between 20% and 80%, it is unlikely to collapse this century (Baker et al. 2025). Impacts are likely to be significant as a weakening AMOC cools the Northern Hemisphere and warms the Southern Hemisphere (Liu et al. 2020). A collapse would have catastrophic impacts in many regions, increasing storms and severely disrupting the rains that billions of people depend on for food in India, South America and West Africa (Boers 2021; Akabane et al. 2024).

Aixue Hu observes, “Even just a 50% reduction in strength would result in a large drop in heat transport that would alter regional and global climates. There is therefore no reason to be complacent about AMOC weakening, and every effort must still be made to combat the global warming that drives it.” (Carrington 2025)

Melting ice sheets will also slow the Antarctic Circumpolar Current (ACC) by up to 20% by 2050 (Sohail et al. 2025), further accelerating Antarctic ice sheet melting and sea level rise and increasing the likelihood of cascading tipping points in Antarctica and the Southern Ocean (Kubiszewski et al. 2025). These risks need to be assessed: a brief episode of meltwater-induced weakening of the Atlantic meridional overturning circulation (AMOC) resulted in a massive CH_4 release 125,000 years ago (Weldeab et al. 2022).

Rapid global warming and accompanying ocean oxygen loss led to the Permian-Triassic mass extinctions (Penn et al. 2018); carbon emissions are likely to overstep the tipping point for the next catastrophic mass extinction event by 2100 (Rothman 2017).

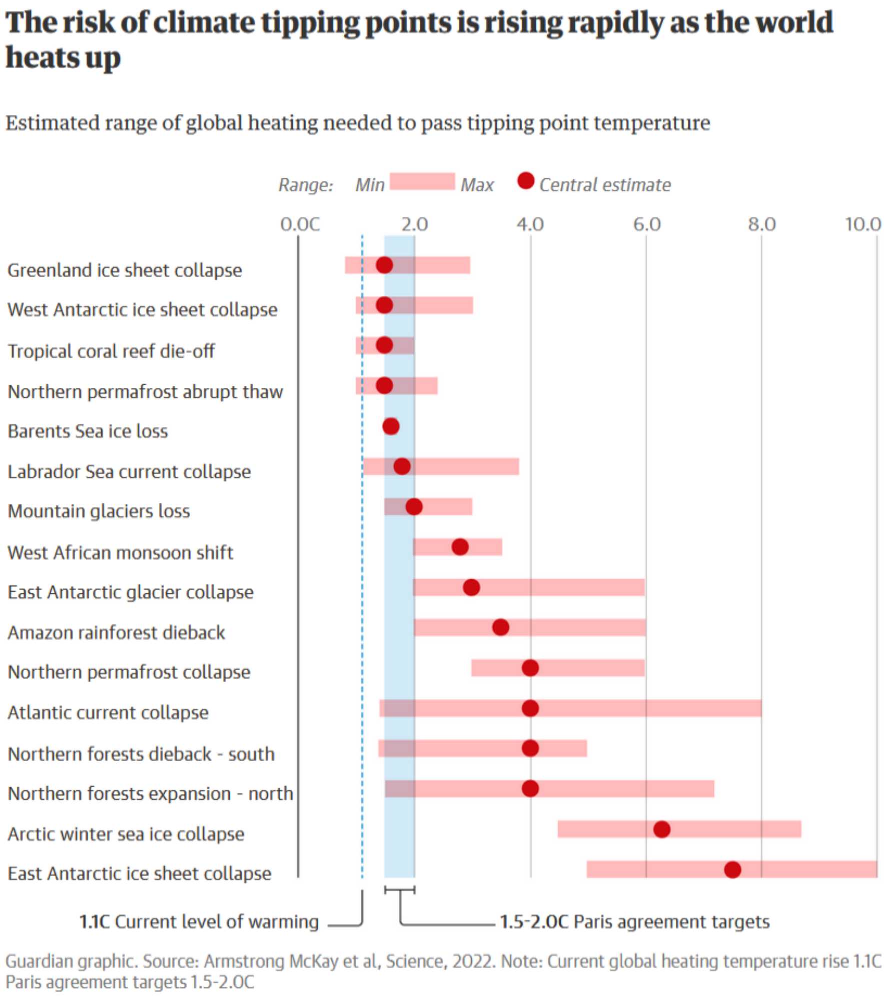

Figure 5. The risk of climate tipping points is rising rapidly as the world heats up. ©The Guardian.

Alarms should be ringing as the current trajectory of emissions is very close to the IPCC's highest GHG concentration pathway, RCP 8.5. This pathway may become a likely scenario due to missing carbon cycle climate feedbacks (Schwalm et al. 2020). These cascading feedbacks include emissions from thawing permafrost (Madaj 2025), methane releases from the ocean floor in the Arctic and Antarctic (Climate Emergency Forum 2025), changes in soil carbon dynamics (Huang et al. 2024), changes to forest fire frequency and severity, the removal of forest cover (Seymour et al. 2022), the destruction of peatlands (Austin et al. 2025), and warming tropical wetlands (Voosen 2022).

IPCC's most recent high-emission pathways suggest 4°C increases are "very likely" for 2081 through 2100, temperatures that many scientists believe pose a significant threat to the stability of civilization (Steel et al. 2022). Under SSP5-8.5, by 2100 world GDP may decrease by around 40% (Neal et al. 2025).

In general, the IPCC has been cautious about climate tipping points, e.g., discounting chances of incipient tipping points in Amazonia and other ecosystems being impacted by multiple interacting threats, like water stress, degradation and pollution. However, because tipping points amplify and accelerate one another, more than a fifth of ecosystems worldwide, including the Amazon rainforest, are at risk of a catastrophic breakdown within a single human lifetime (Klose et al. 2020; Willcock et al. 2023; Flores et al. 2024).

An OECD report concludes that "that current scientific understanding of climate system tipping points challenges the generally accepted notion that tipping points have a low probability of being crossed under moderate levels of warming, which adds further urgency to the climate challenge and requires a shift in how tipping points are treated in climate policy today (OECD 2022)."

3.1.2. It is impossible to adapt to irreversible, catastrophic impacts like species extinction, glacier loss, rising sea levels, and methane release from warming permafrost and oceans.

IPCC scenarios assume if overshoot occurs, temperatures can return to safe levels by 2100 through large-scale carbon dioxide removal. Policy makers also assume most human and environmental systems will adapt to a few degrees of higher temperatures without serious consequences. Both assumptions are questionable and unsupported by the available evidence (Anderson 2015).

For example, at 1.6°C warming, most of the Greenland Ice Sheet will eventually melt; it will take another ice age to replace the lost ice (Bochow et al. 2023). Climate change will also drive many species and ecosystems towards tipping points (Román-Palacios and Wiens 2020; Malanoski et al. 2024). The median values for percentage of species at likely risk of extinction range from 14% at 1.5°C to 48% at 5°C (IPCC 2022).

For a preview of the future, we can look at how climate change has already increased wildfire season length, wildfire frequency, and burned area (Cunningham et al. 2024). Australian megafires in 2019–2020 killed 60 billion invertebrates (Gibb and Porch 2023): complex forest ecosystems cannot adapt to fires of this scale and intensity.

Extinction is forever, and losing many keystone species and critical ecosystems will do catastrophic damage not only to the environment, but also to our human societies, which utterly depend on the biosphere for health and sustenance.

3.1.3. Current policies underestimate the non-linear costs of overshooting safe global temperatures.

The scientific consensus is that climate change is likely to push most natural and human systems into increasingly dangerous and irreversible states (IPCC 2020). Warming above 1.5°C will make much of the tropics unliveable (Zhang et al. 2021; Sherwood and Ramsay 2023); 20% to 30% of the world's land surface will become arid at a 2°C temperature rise (Park et al. 2018). Climate is a growing factor in population displacement and migration (IOM 2022; Huang 2023), and conflicts over shortages of food and water will increase (Farinosi et al. 2018).

3.2 NZE will not stabilize climate at manageable levels

3.2.1. Since the global climate is neither safe nor stable now, it cannot be safely stabilized at a higher temperature.

The world is already experiencing dangerous climate change, and temperatures of +1.5°C - +2°C will cause much more disruptive and irreversible impacts. Unprecedented climate changes are occurring in every region of the world. More frequent and dangerous heat waves are causing disappearing mountain glaciers, retreating sea ice, terrestrial and marine ecosystems degradation, rising sea levels, desertification, and ever more intense wildfires. For example, between 1990-2020 more than three-quarters of all land on Earth became drier, with the number of people living in drylands doubling to 2.3 billion (Vicente-Serrano et al. 2024). At the same time extreme precipitation events are increasing floods and soil erosion and decreasing crop yields (IPCC 2023).

The global climate is neither safe nor stable now, and will become even more unstable at a higher temperature. Unless temperatures are reduced to levels that stop climate change, reaching net zero will not produce a safe and stable climate.

At this time, it is generally assumed that safe temperatures can be overshot and then reversed. However, Schleussner et al. (2024) point out: “For a range of climate impacts, there is no expectation of immediate reversibility after an overshoot. This includes changes in the deep ocean, marine biogeochemistry and species abundance, land-based biomes, carbon stocks and crop yields, but also biodiversity on land. Overshoot will also increase the probability of triggering potential Earth system tipping elements. Sea levels will continue to rise for centuries to millennia even if long-term temperatures decline.”

Planning to overshoot climate targets may make climate model simulations and political negotiations easier, but it doesn’t solve the problem of irreversible impacts. As the International Cryosphere Climate Initiative says, “We cannot negotiate with the melting point of ice” (ICCI 2024).

3.2.2. Because of the Earth Energy Imbalance, NZE will not stop temperatures and sea levels from rising.

Overshoot doesn’t begin after we pass the Paris targets: overshoot began decades ago when rising concentrations of GHGs created the radiative imbalance driving global warming – the Earth Energy Imbalance (EEI) (Harris 2025; Fig. 6). To achieve radiative balance and prevent dangerous climate change, atmospheric CO2 concentrations will have to be reduced and kept below 350 ppm (Breyer et al. 2023). However, GHGs and other warming agents passed 534 parts per million carbon dioxide equivalents (CO2e) in 2023 (NOAA 2024a).

Long-term climate stabilization requires reducing the EEI to approximately zero (von Schuckmann et al. 2020).

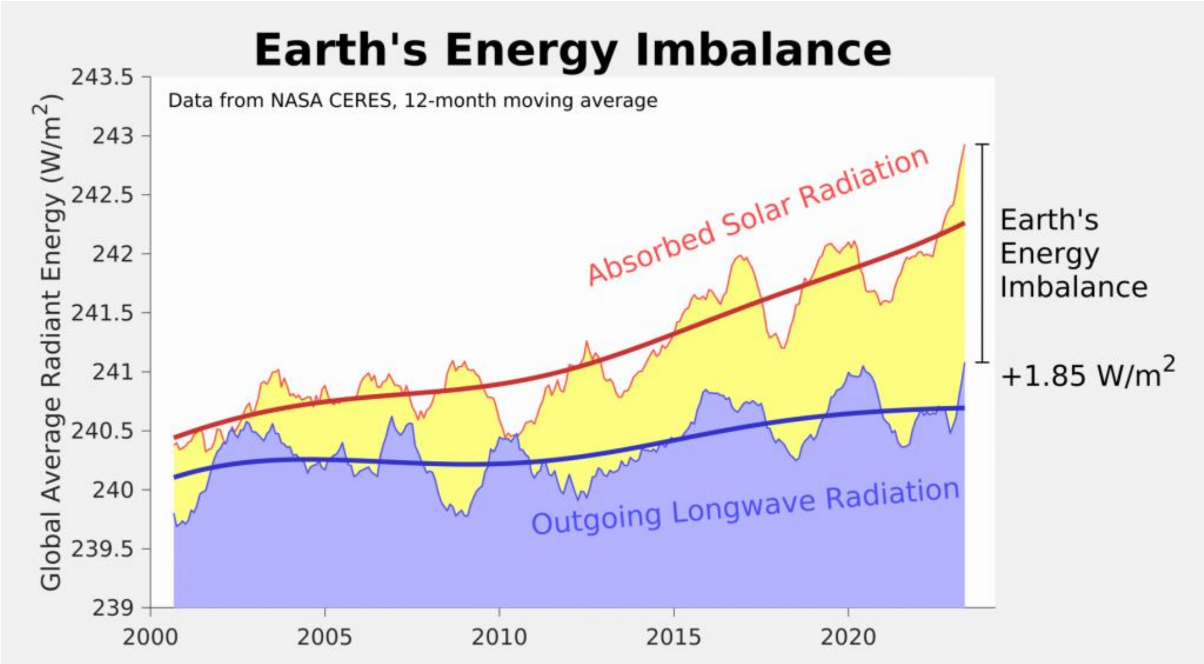

Figure 6. Earth's Energy Imbalance. 🅭 Berkeley Earth. (Rohde 2025)

The IPCC contends that once NZE is reached, warming will eventually end as radiative forcing is diminished by a combination of ocean and biosphere CO2 absorption and large-scale CDR (Dessler and Hausfather 2023). This assumes that Earth's albedo will increase and climate tipping points will not have been passed, triggering cascading positive feedback loops.

However, the ESCIMO climate model indicates that the world is already past the point-of-no-return for global warming (Randers and Goluke 2020). Without cooling interventions, even if all emissions of human-made GHGs end immediately, self-sustained permafrost thawing will continue due to declining surface albedo, increasing atmospheric water vapour, and release of sequestered GHGs to the atmosphere. Irreversible ice cap melting is underway in Greenland and West Antarctica, and may be imminent in East Antarctica.

3.2.3. NZE requires large-scale CDR, but no feasible and affordable technologies exist at needed scale.

The IPCC Illustrative Mitigation Pathways (IMPs) require removing from 450 to 1,100 GtCO2 between 2020 and 2100 (Smith et al. 2023), but no feasible plans exist for deploying CDR at the scale required because of high costs and difficult trade-offs such as converting croplands to forests. Two extensive reviews conclude that it is implausible for CDR technologies to be implemented by 2050 at the scale envisaged (Lawrence et al. 2018; Nemet et al. 2018).

CDR mitigation requires new carbon sinks with a capacity similar to ocean sinks (Rockström et al. 2016). However, many CDR approaches are constrained by cost, land, water, nutrient limitations and environmental concerns (Kramer 2020; Larkin et al. 2018; Friedmann 2019; Schenuit et al. 2021; Fajardy et al. 2019).

High costs and limited storage capacity have restricted deployment of Carbon Capture and Storage (CCS) technologies. Global CCS capacity is only 0.1% of annual global emissions from fossil fuels. Projected mitigation pathways for bioenergy with carbon capture and storage (BECCS) use 25% to 80% of current global cropland (IEA 2022). Currently, only around 2 Mt/yr of biogenic CO2 are captured, far short of the 250 Mt/yr that needs to be removed by 2030 (Lakhani 2023).

In addition, many carbon offsets and credits do not produce genuine carbon reductions (Greenfield 2023; Peng et al. 2023). Counting 'biofuel' as a clean, renewable source of energy doesn't make sense (Haberl et al. 2012). The UK Drax biomass plant is the 3rd biggest single emitter of CO2 in Europe (Proactive 2021).

It will not be possible to achieve net zero emissions without large-scale carbon dioxide removal. At least 1,300 times more technical CDR and twice as much from natural sinks are needed to limit temperatures below 2°C by 2050 (Smith et al. 2023). Natural carbon sinks mitigate ~30% of anthropogenic carbon emissions; however, the rate of natural sequestration of CO2 from the atmosphere by the terrestrial biosphere peaked in 2008 and is now declining (Curran and Curran 2025). Because excessive temperatures shut down plant photosynthesis, at current emissions rates land sinks may be almost halved by 2040 (Duffy et al. 2021).

As CO2 would be removed slowly, CDR methods will have small effects on global climate for decades. Nonetheless, limiting the duration of international climate target overshoot to less than two centuries requires ambitious decarbonization and CO2 removal (Ricke et al. 2017).

3.2.4. Massive scale and long-term impacts will require mitigation for centuries after NZE is reached.

Climate impacts including deep ocean warming, ocean acidification, and sea level rise will continue long after temperatures stabilize. Paleoclimatic records show that attaining thermal equilibrium lags forcing due to internal response feedback time delays. Climate responses to past hyperthermal events lasted up to hundreds of thousands of years, and evolutionary responses took millions of years.

Paleoclimatic data suggest that existing greenhouse gas levels may have already committed Earth to an eventual warming of 5°C or more (Snyder 2016; Hansen et al. 2023). Such temperature increases are an existential threat to civilization. The last time CO2 concentrations were this high was 4.3 million years ago, when sea levels were 22m higher than now and forests covered much of the Arctic and Antarctic (NOAA 2024b).

We need a new mitigation strategy based on the reality of the risks and consequences we already experience and that are destined to become worse (e.g., Sivaram 2025). If a safe and stable climate is to be achieved in the 21st century, climate cooling interventions need to be applied and maintained as long as required to constrain temperature rise while GHG emissions are reduced and sufficient atmospheric carbon is removed to restore concentrations to pre-industrial levels.

4. Climate cooling interventions are necessary

4.1. Climate interventions have lower risks and costs than not intervening.

Mitigation efforts need to focus on accelerating the global transition to a net-zero carbon emissions economy: it is much cheaper and less risky to avoid GHG emissions than to emit them with the expectation that they will be later removed from the atmosphere. Nevertheless, climate cooling interventions will also be needed to prevent temperatures exceeding safe limits during the long period that it will take to transition to an emissions-free global economy, reduce atmospheric carbon dioxide concentrations and re-establish a safe and stable climate.

The climate crisis is the result of massive interventions by humanity. Even if their impacts were unintended, deforestation, desertification, and burning fossil fuels are having devastating consequences for the climate, ecosystems, and life on Earth. For example, the rise of human civilization has destroyed almost 3 trillion trees--reducing their numbers by 46% (Crowther et al. 2015). Countervailing interventions are now necessary to restore temperatures to safe levels.

Although most people support stronger action on climate change (Andre et al. 2024), there is widespread opposition to direct cooling interventions (often called “solar geoengineering”, or “solar radiation modification”) (McLaren and Corry 2024). While it could be dangerous to deploy untested methods that are either ineffective or do more damage than good, if climate cooling interventions are not deployed in time to avert significant overshoot, the consequences of worsening climate change will be disastrous. The precautionary principle means both that risks of dangerous and potentially catastrophic climate change justify action rather than inaction (King et al. 2015), and that more research is needed before geoengineering methods can be deployed at climate-altering scales (Climate Overshoot Commission 2023; Committee on Geoengineering Climate 2015a; Committee on Geoengineering Climate 2015b).

NZE is unlikely to be reached by 2050. By then global temperatures will have risen more than 2°C and passed significant climate tipping points. Cascading feedbacks and growing radiative forcing will further increase temperatures by 3°C or more by century’s end. Climate cooling interventions have the potential to rapidly reduce temperatures to safer levels: opposing them means accepting that temperatures will rise at least 2°C above pre-industrial levels within decades, with catastrophic, irreversible impacts.

4.2.1. Climate change is a risk management issue.

Policymakers need to understand climate change as an issue of risk management: since all options involve risks, the challenge is to develop strategies that minimize likely risks and costs while maximizing benefits (Scientific Advisory Board 2016). The precautionary principle suggests that it is simple good sense to plan for a broader range of scenarios than just optimistic ones (Pasztor and Turner 2018).

To prevent dangerous climate change, researchers should focus on capping peak warming at safe levels (Rogelj et al. 2019). Rockström et al. (2023) argue that a safe temperature limit is around +1°C. This will require cooling interventions.

Research by Smith and Wagner (2018) suggests that solar radiation modification (SRM) methods are viable and cost-effective. While much more research is needed, climate models indicate that a well-designed SRM deployment could potentially reduce surface temperature increases and reduce changes to the hydrological cycle associated with climate change (Irvine et al. 2019; Honegger et al. 2021). These positive assessments of solar geoengineering contrast with concerns raised by opponents about potentially dangerous side-effects including changes to hydrologic cycles.

Another objection is that lowering temperatures will give fossil fuel producers excuses to continue polluting ("moral hazard") (Collins 2024; Asayama and Hulme 2019; Wagner and Merk 2019). To prevent oil, gas and coal interests from using climate cooling as an excuse to keep polluting, governments can pass regulations mandating phased reduction of fossil fuel production.

While climate interventions have some risks, the risks and moral hazards of not intervening are not only much greater (Schoenegger and Mintz-Woo 2024; Bledsoe and Zaelke 2024), but existential (Dyer 2024). Blocking emergency climate cooling on the basis that it is a moral hazard would be equivalent to denying a diabetic patient insulin on the grounds that it might reduce his incentive to adopt a healthy lifestyle.

Climate cooling methods do not appear to pose unmanageable risks. At present GHG warming is partially offset by anthropogenic aerosol discharge into the atmosphere. This pollution needs to stop because of serious health and environmental impacts, but it should be possible to replace its beneficial cooling effects with a wide range of smaller, cleaner, targeted interventions designed to maximise benefits and minimise risks. However, solar geoengineering will not prevent rising CO2 from acidifying oceans with catastrophic impacts on marine life (Eyre et al. 2018; Doney et al. 2020).

4.2.2. Climate interventions need to be assessed in comparison to the risks and costs of all possible policy options.

To evaluate risks, we need to weigh the risks of solar geoengineering against the risks of further climate deterioration in a world without it (Harding et al. 2020; Wiener et al. 2022; Parson 2021; Aldy et al. 2021; Crutzen 2006). Apart from preventing dangerous climate change, other geoengineering methods like afforestation and ocean fertilization may have co-benefits such as reversing desertification, improving water quality, promoting biodiversity, improving fisheries, enhancing food security, and reducing climate inequity.

Debates on solar radiation modification are based on relatively little evidence (Schipani 2023; Honegger et al. 2021a). Because there are still many unresolved questions about CDR and SRM (Visioni et al. 2023; Fuss et al. 2014; Vaughan and Gough 2016; Zarnetske et al. 2021; Visioni et al. 2021), research is urgently needed on the relative feasibility, benefits, risks and costs of all potential approaches (National Academies 2021). International Risk Governance Council guidelines could help evaluate the complex risks presented by these technologies (Grieger et al. 2019; AGU 2024).

The choice is not binary (Kerstein 2023). A limited solar geoengineering deployment that slows the increase of global temperatures might yield benefits that greatly outweigh associated risks. It would be wise to begin studying and trialling climate cooling methods in case the rapid onset of extreme climate scenarios accentuates the need for their deployment.

4.3. Research is needed on all potentially safe, viable geoengineering approaches.

Major climate intervention technologies are (1) direct climate cooling (DCC) technologies that reflect sunlight and directly cool Earth's surface; and (2) large-scale CDR technologies (also called Negative Emission Technologies or NETs) that drawdown atmospheric GHGs.

CDR geoengineering is required to support the transition to a net-zero carbon emissions economy. Cooling interventions are urgently needed to prevent temperatures overshooting safe limits during the long period it will take to transition to an emissions-free global economy, remove legacy atmospheric carbon, and re-establish a safe and stable climate.

Scientists have proposed a wide range of potentially safe, viable geoengineering approaches (e.g., Alfthan et al. 2023). All of these need to be urgently researched to determine their relative safety, effectiveness and cost.

4.3.1. Carbon Dioxide Removal

Scenarios that limit warming to 2°C or less by 2050 require reducing current emissions by 34 Gt per year plus carbon dioxide removal of 6–10 GtCO2 per year. Around 2 GtCO2 per year of CDR is taking place now. Almost all of this comes from conventional CDR methods, principally afforestation/reforestation. Novel CDR methods—which include direct air capture (DAC), CCS and large-scale BECCS—contribute less than 0.1% of total CDR (Smith et al. 2024). Because these approaches are slow to act, have limited capacity, and high costs, they are uneconomical at present (Young et al. 2023).

There is major potential for accelerating CO2 drawdown by ramping up natural climate solutions such as reforestation, land restoration, and regenerative agriculture (Conservation International 2022; Ellison, Pokorný and Wild 2024).

Researchers have found the ocean's capacity to function as a carbon sink has been diminished by climate change (Bunson et al. 2024). However, ocean sink drawdown capacity may be significantly increased by the deployment of marine permaculture and other practices, e.g., mimicking natural processes with ocean iron fertilization (Bonnet et al. 2023).

Other potential CDR technologies include enhanced atmospheric methane oxidation (EAMO), biochar, deepwater irrigation, enhanced silicate rock weathering, ocean alkalinization, ocean fertilization to grow diatoms, and synthetic limestone manufacture.

There is no chance of achieving NZE without developing large-scale CDR. Supportive policies are needed to develop and operationalize cost-effective CDR (Honegger et al. 2021b). However, even with strong mitigation efforts, carbon dioxide removal will not prevent overshoot.

4.3.2. Solar Radiation Management

In addition to carbon dioxide removal, solar radiation modification methods will be required to shave peak temperatures and limit climate damages (Baiman 2022; National Academies of Sciences, Engineering, and Medicine 2021; MacMartin et al. 2018; Tilmes et al. 2020). Such measures include stratospheric aerosol injection, marine cloud brightening, cirrus cloud thinning and mixed-phase cloud thinning (Redmond Roche and Irvine 2024), and increasing land, sea and ice surface albedo.

Solar radiation management is mostly discussed in relation to risks of a global application of stratospheric aerosol injection (SAI) technologies. While injecting sulphate aerosols into the stratosphere may be an effective and relatively inexpensive way to cool global temperatures, it poses new risks, including possible negative impacts on precipitation and ozone loss (Visioni et al. 2020). Using other mineral aerosols may overcome some of these problems (Dai et al. 2020; Hoback 2024; Vattioni et al. 2025).

An alternative approach would be to deploy SAI only in subpolar regions and only in the spring and summer months. This would curtail ice and permafrost melt at high latitudes with reduced costs and risks (Smith et al. 2022). Other climate cooling methods, such as marine cloud brightening (MCB) could be safely used with targeted application (Chen Y et al. 2024; Ahlm et al. 2017; Haywood et al. 2023; Chen C-C et al. 2024).

Additional potentially safe and useful direct climate cooling methods that should be evaluated include: stratospheric dehydration (Schwarz et al. 2024), atmospheric methane removal, buoyant flake ocean fertilisation, ice shields to thicken polar ice, and surface mirrors, as well as cooling urban areas with tree planting and reflective materials (Baiman et al. 2024).

Potential adverse effects have to be compared to the impacts being alleviated—e.g., less extreme weather and reduced risks of passing tipping points. Modelling indicates that to avoid passing dangerous climate tipping points like the collapse of the Atlantic Meridional Overturning Circulation, it will be much more effective to make gradual early-century interventions than rapid late-century interventions (Pflüger et al. 2024; Smith et al. 2024).

4.4. Climate interventions are needed to prevent mass extinctions and famines

Termination shock is a key argument of direct climate cooling opponents (Kemp and Tang 2022). If solar geoengineering masking high levels of global warming was suddenly stopped, temperatures would rise sharply. This would be a severe shock to many natural and social systems that are unable to adjust to rapid temperature increases.

Geoengineering opponents have the precautionary principle backwards. The biggest risks of mass extinction come from climate change (McPherson et al. 2022). Deploying solar geoengineering is precautionary as it will reduce risks of rising temperatures passing irreversible climate tipping points (Futerman et al. 2023).

It is highly unlikely any intergovernmental or scientific body would agree to deploy risky, untested climate cooling technology at global scale, or to suddenly terminate it (Parker and Irvine 2018; Rabitz 2018). Existing proposals are for careful research, followed by small-scale trials to ensure safety before gradually scaling up with limited, carefully targeted, monitored and supervised interventions (e.g., Tilmes et al. 2024; Keith and Smith 2024).

Direct atmospheric climate cooling methods should be used as long as needed to constrain dangerous temperatures and give emissions reduction and removal time to take effect. Regulatory procedures must include guardrails and ensure an orderly exit from the program. A smooth and safe transition would ramp down solar geoengineering at the same rate as natural carbon sinks and negative emissions technologies drawdown GHGs and reduce climate forcing. (MacMartin et al. 2014).

4.5. Cooling interventions must be used to supplement, not substitute, reducing and removing GHGs.

Present mitigation efforts rely on sharply reducing greenhouse gas emissions by mid-century, and achieving net zero emissions by deploying large-scale carbon removal technologies. Commitments to reduce emissions are inadequate. Even if strengthened, these methods will not be sufficient to prevent catastrophic climate change.

Because the climate is already unstable and dangerous, and will become more dangerous by the time NZE is reached, the Paris Agreement needs to be augmented with a third strategy: using climate cooling methods to rapidly lower global temperatures to safe levels.

In the long-term, cooling the planet is not a substitute for reducing greenhouse gases, but it buys the time needed for these measures to work. Equally, reducing GHGs cannot substitute for direct cooling.

A realistic overshoot management plan will have to simultaneously apply direct cooling, GHG reduction, and GHG removal. This “Climate Triad Strategy” will (a) use climate cooling technologies to keep temperatures within safe limits until GHG concentrations have been reduced to a level that stabilizes the climate; (b) rapidly reduce GHG emissions; and (c) deploy large-scale negative emission technologies to draw down atmospheric carbon (Baiman et al. 2023).

5. The need to forestall untested and ungoverned unilateral interventions

5.1. In response to increasing climate costs, conservative opponents will support SRM interventions

Though many conservative policy-makers deny climate change and/or downplay climate risks, worsening impacts and increasing costs will force them to address the crisis (e.g., Feinman 2025). In response, they are likely to be increasingly attracted to solar geoengineering (Hunt and Fitzgerald 2025) as a quick and relatively cheap way to mitigate rising temperatures.

This is the moral hazard environmentalists rightly fear, as these technologies will allow global temperatures to be rapidly lowered without reducing emissions. The critical problem is that solar geoengineering will not stop rising concentrations of atmospheric greenhouse gases from acidifying the oceans and destroying vital marine ecosystems.

5.2. To forestall unilateral actions, international research is needed to develop safe climate cooling methods and effective global governance

Opponents of climate interventions believe that even testing new technologies is dangerous, as it will legitimize their use. To reduce the risks of negative side effects, they are calling for an international moratorium on all climate geoengineering research. This position is mistaken for two reasons:

- First, the genie is already out of the bottle. Australia, China, the US, India, Russia, the UK and several EU member states as well as private companies are already researching climate geoengineering (Dragonfly Intelligence 2023; Simon, McDonald and Brent 2023; Skibba 2025). As temperatures rise, major powers are likely to make unilateral climate interventions to prevent increasingly extreme weather causing massive crop failures and other disasters within their borders.

- Second, without scientific research and testing, we can't evaluate the relative benefits and risks of using various geoengineering measures. Dozens of potentially useful technologies have been proposed for cooling the climate and removing greenhouse gases: to increase effectiveness and reduce risks, it is likely that a viable mitigation strategy will deploy a wide range of methods at different scales in different regions.

Banning research will not stop SRM from being used—it will only ensure that if it is, it will happen without knowledge, preparation, or ethical safeguards (Talati and Peterson 2025). To forestall the deployment of untested technologies by individual countries, an international program to research safe climate cooling methods is urgently needed (UNEP 2023; Pezzoli et al. 2023).

Governance must be addressed before undertaking large-scale testing and deployment (AGU 2022; Abnett 2023). Safe, effective strategies require internationally coordinated research on all potentially useful mitigation methods, including large-scale GHG removal technologies and climate cooling interventions (Buck 2022).

At this time international negotiations are gridlocked among countries that are opposed to researching and deploying SRM under any conditions and countries that might be agreeable to a constrained and monitored R&D program under certain conditions and with the information that is gathered freely shared (Lo 2024).

Current disagreement notwithstanding, one critical question must be answered before it is too late: "Is it safer to continue on the present trajectory and allow global temperatures to rise to +2.7°C (Ellis et al. 2024) or higher, with the impacts and associated risks and costs of passing irreversible tipping points, or to use solar engineering to reduce temperatures to + 0.5°C - +1°C?" This is not an abstract question. International climate agreements need to address it in a manner that will result in timely, effective action.

6. Developing a realistic climate strategy

6.1. The process for developing a viable climate strategy

Geoengineering approaches must be compared to risks and costs of other mitigation options, including business as usual. “Risk vs. risk” framing (Goklany 2002) allows policymakers to determine the suitability of different geoengineering methods and other approaches for preventing dangerous temperature increases.

Research is urgently needed on the comparative risks of overshooting safe temperatures versus the risks of various mitigation approaches (Climate Institute 2018). All mitigation options should then be evaluated in relation to the requirements for preventing dangerous climate change and restoring a safe, stable climate in order to determine the comparative benefits, risks and costs of using or not using different mitigation strategies. These assessments are prerequisites for developing a viable climate strategy (Taylor and Vink 2021, Fig. 7.]

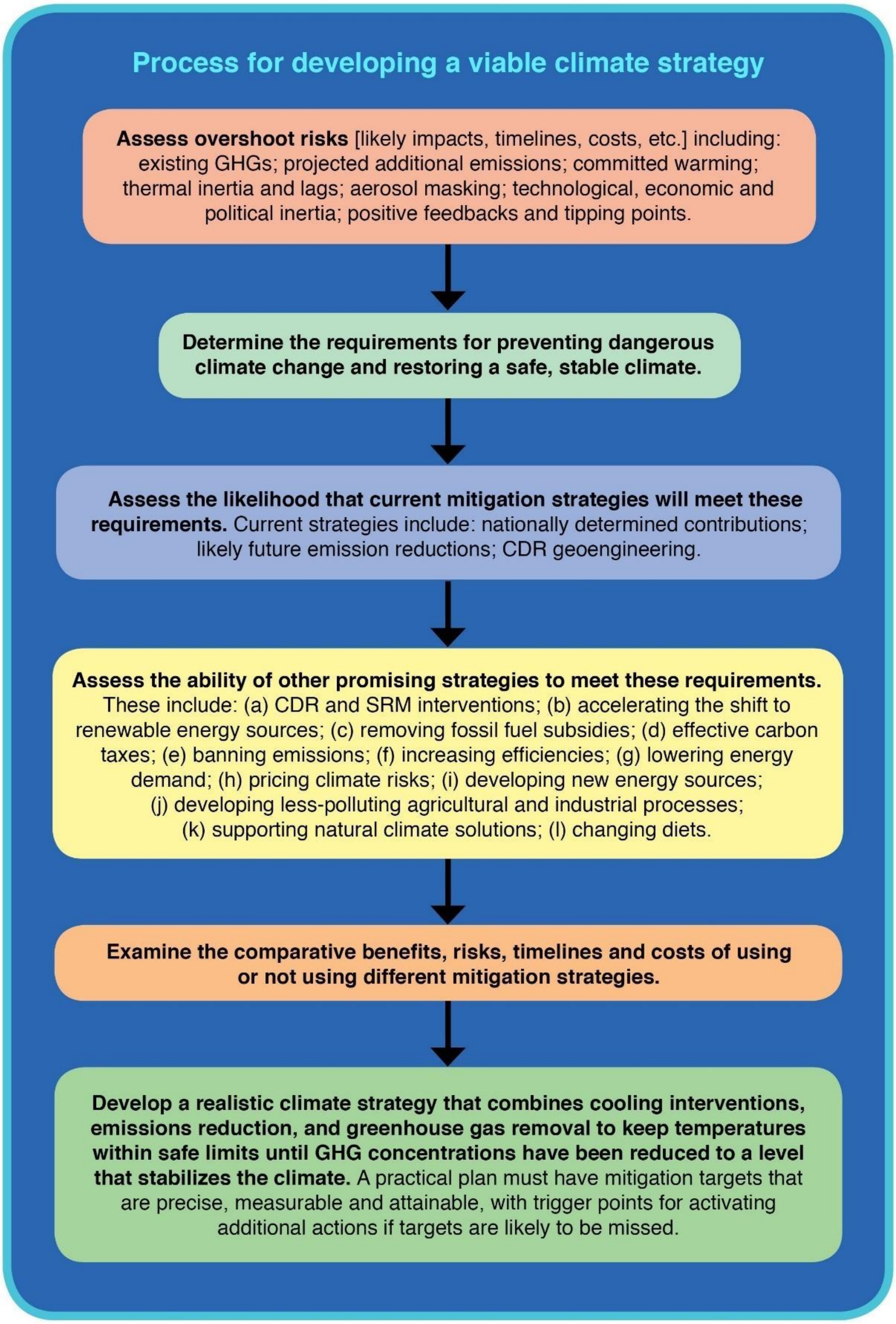

Fig. 7. Process for developing a viable climate strategy. 🅭 G. Taylor, 2025.

This evaluation of countervailing risks needs to take into account not only linear developments and their impacts, but also likely non-linear developments (Kopp et al. 2016; Stern 2016). An alternative approach is needed that explicitly embraces deep uncertainty, and in which modelling exists in an iterative exchange with policy development (Workman et al. 2020).

The research should invite and encourage inclusive public dialogue on the relative costs and risks of using or not using various types of climate engineering (OSTP 2023; Honegger et al. 2017; Lawrence et al. 2018; Buck et al. 2020; Pasztor 2021). The goal should be to both strengthen the Paris Agreement and develop a complementary overshoot risk management plan.

A study of 1,500 climate policies found that only 63 have delivered significant benefits (Stechemesser et al. 2024). For policy-makers to be accountable, mitigation targets must be precise, evaluable and attainable, with clear constraints on the magnitude and duration of overshoot and the feasibility of mitigation methods (Geden and Löschel 2017). The plan must contain metrics, timelines and trigger points for initiating actions.

Ambitious change is obstructed by the UNFCCC's consensus requirement (Verkuijl and Lazarus 2020). To accelerate change, a two-track approach could be used, with UNFCCC agreements complemented by climate "coalitions of the willing" (Nordhaus 2020), e.g., agreements among nations willing to impose meaningful internal carbon taxes matched by tariffs on all imported goods and services (Cramton et al. 2017). A two-track approach will allow simultaneous application of both the Paris Agreement and a supplemental plan for managing overshoot risks.

6.2. The real moral hazard

While there are bad actors, the climate crisis is ultimately a wicked problem: a tragedy of the commons exacerbated by the obsolete, dysfunctional design of the global system. This crisis has developed because generations of people, businesses, and communities at all scales have created economic and social structures that use the environment, and in particular the atmosphere, as a free waste dump.

The crisis is not only the product of the duplicity of the fossil fuel sector, and the preference of many states to put the burden of action on others' shoulders: it is also the result of a widespread failure of society at large to understand that there is a cost to maintaining the health and productivity of the environment on which all our flourishing depends.

Most policy makers still do not understand the catastrophic risks of rising temperatures. An example of this is that the current carbon price—on average less than $18 per tonne in the 71 countries that tax emissions (OECD, 2022)—is far too low to deter businesses from polluting. In Tim Flannery's words, there is a "kind of madness" to the global approach to carbon pricing. "We know at the moment it costs about $250 a tonne to remove it. In a saner world it would cost more to dump the stuff in the atmosphere than suck it out." (O'Malley and Hannam, 2021)

In practice, most countries are delaying major emissions cuts until closer to their net-zero target year, on the assumption that technological breakthroughs will sharply reduce the costs of transitioning away from fossil fuels (National Intelligence Council, 2021). Kevin Anderson (2021) believes that this approach is dangerously immoral: "It is the reliance on these future technologies that is the moral hazard not the technologies themselves…. But to rely on those, rather than actually reducing our emissions today, that is the moral hazard."

There are many win-win climate solutions. For example, an Oxford University study challenges the pessimistic predictions by the IPCC that the cost of keeping global temperatures rises under 2 degrees would lower GDP by 2050. In reality, switching from fossil fuels to renewable energy could save the world as much as $12tn by 2050. A rapid green transition would also avoid climate damages, reduce air pollution, and lower energy price volatility (Way et al. 2022).

Unfortunately, these analytical errors are not confined to economics. Leading political, scientific and environmental organizations have not only greatly underestimated the benefits of making a rapid green transition, they have also seriously underestimated the dangers of continuing with the current climate strategy (Bawden, 2016).

As we argue in this paper, our failing climate strategy is the result of multiple mistakes, omissions, delays and compromises. While each of these can be explained and perhaps forgiven, in combination they have created a deadly delusion. Now, reassured that climate change is being safely managed, humanity is staggering blindly towards collective disaster.

Our children will pay for these mistakes with their futures—unless we find the courage and voices to demand a new, effective climate strategy.

6.3. Research on a viable "Climate Triad" strategy must be prioritized. There is no realistic alternative.

In reality, the world is still many decades away from ending greenhouse gas emissions, let alone deploying viable carbon removal technologies. A realistic overshoot risk management plan will need to combine three approaches in a "Climate Triad" strategy: (a) rapidly reducing GHG emissions; (b) deploying large-scale CDR to draw down atmospheric carbon; and (c) using SRM technologies to keep temperatures within safe limits until CO_2e levels have been reduced to a level that stabilizes the climate.

Doom is not inevitable. Disaster will only occur if we fail to urgently develop and deploy cooling interventions. Opponents to researching and deploying solar geoengineering need to recognise that the alternative is to leave all efforts to limit temperature increases to reducing emissions, a strategy that would be almost certain to fail (Aldy and Zeckhauser 2020).

The authors see no viable alternative. If opponents of cooling interventions cannot propose one, they should change their position.

At this critical time, the international community must prioritize developing a feasible overshoot risk management plan that deploys the most effective climate cooling strategies or risk irreversible, catastrophic damage to the biophysical, physicochemical, and social systems that support human civilization.

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Acknowledgements

A number of respected natural and social scientists reviewed advance drafts of this paper. We appreciate their valuable contributions.

Conflicts of Interest

The authors researched and wrote this paper pro bono and have no conflicts of interest.