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A safe climate means cooling an overheated planet

A framework for reversing dangerous warming and restoring climate safety

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Summary

- Climate risks are cascading, non-linear and underestimated. Tipping points are happening faster than forecast; some have already occurred at less than the current 1.5°C of warming.
- To provide maximum protection for the places and peoples we care about requires returning to a climate similar to the relatively stable Holocene conditions of the last 9000 years when carbon dioxide (CO_2) levels did not exceed 280 parts per million (ppm) prior to 1900.
- A "three levers" approach — "reduce, remove and repair" is required:
  - Reducing emissions to zero at emergency speed;
  - Removing carbon by drawdown to return atmospheric conditions to the Holocene zone; and
  - Urgent research to identify safe interventions that cool and protect and repair vital systems and, in the shorter term, aim to prevent warming reaching a level that triggers a cascade of calamitous tipping points that are irreversible on human timescales.
- The harsh reality is that the first two levers alone — zero emissions and drawdown — are not sufficient to stop the Earth system charging passing 1.5°C, nor 2°C in all likelihood, regardless of the emissions path.
- Even if the world moves to zero emissions, and CO_2 levels start to decrease by natural processes and by CO_2 removal, albedo modification to create active cooling for a limited period may flatten the level of peak warming — and perhaps help avoid existential climate impacts and extreme damage — until the other processes fully kick in.

The new climate crisis

The wave of record-smashing climate extremes in recent years is shocking. But it should not have been unexpected. In the 2023 paper *Faster, higher, hotter*, we noted:

> "System-level change and tipping points are happening faster than forecast, with a number of crucial climate system elements already passed tipping at the current level of warming. Risks are cascading, non-linear and underestimated; prudent risk management requires consideration of the bad-to-worst-case-scenarios."[1]

In September 2022, Stockholm University's David Armstrong McKay and his colleagues concluded that even global warming of 1°C risks triggering some tipping points,[2] just one data point in an alarming mountain of research on tipping points presented in the last three years. Clearly, even the current level of warming of around 1.5°C is unacceptably dangerous.

To protect small-island states, the Great Barrier Reef, Antarctica, Greenland, the Amazon — and the many places and peoples we care about — requires returning to a climate similar to the relatively stable Holocene conditions of the last 9000 years and fixed human settlement, during which time CO_2 levels did not exceed 280 ppm. It also requires preventing a cascade of tipping points in the meanwhile.

For example, in 2022 a group of Australian scientists suggested that from a geologic perspective: "a justifiable aim for a future climate is one akin to pre-industrial conditions".[3] Other evidence points to the need to return to pre-industrial levels of 280 ppm, for example in relation to the polar regions.[4]

If this were the goal, activists and policymakers would advocate a "three levers" approach to reversing global warming: a strategy to rapidly "reduce, remove and repair".[5] That means:

1. Reducing emissions to zero at emergency speed;
2. Removing carbon by drawdown (in addition to natural processes) to return atmospheric conditions to the Holocene zone; and
3. The urgent research to identify safe cooling interventions that protect and repair vital systems and, in the shorter term, aim to prevent warming reaching a level that triggers a cascade of calamitous tipping points that are irreversible on human timescales.

1 breakthroughonline.org.au/papers
2 science.org/doi/10.1126/science.abn7950
3 nature.com/articles/s41558-022-01446-x
4 iccinet.org/wp-content/uploads/2015/11/ICCI_thresholds_v5_151128_high_res1.pdf
5 static1.squarespace.com/static/60ccae658553d102459d11ed/t/60d421c67f1dc67d682d8d29/1624515027604/ CCAG+Launch+Paper.pdf

Emissions reduction is not enough

The harsh reality is that first two levers by themselves — zero emissions and drawdown — are not sufficient to stop the Earth system charging past 1.5°C, regardless of the emissions path,[6] and to significantly higher temperatures — more than 2°C well before mid-century — with truly catastrophic impacts for some peoples, regions and natural systems. In essence:

- Warming to date plus the observed Earth Energy Imbalance (EEI) at the top of the atmosphere adds up to more than 2°C for today's level of greenhouse gases. EEI is rising at an alarming rate which suggests the amount of warming in the pipeline is increasing.[7] And the paleoclimate record suggests the current level of CO_2 is sufficient for 3°C or more of warming in the longer term.[8] Thus a strategy of emissions elimination only will not prevent catastrophic outcomes.
- A safe-level of greenhouse gases to preserve and restore vital climate systems likely requires returning to the pre-industrial CO_2 level of around 280 ppm. On top of a zero-emissions regime, large-scale carbon drawdown is essential in achieving this goal, but this cannot be done at a scale and speed fast enough to prevent more tipping points being activated in the near term and the possibility of a cascade of consequences leading to enhanced warming.
- Thus a 'third lever' of action is required: the urgent scaling up of research and investigation into an additional range of climate interventions that aims to rapidly cool the planet is required by changing the Earth system's reflectivity, known as albedo management. This includes solar radiation management (SRM) cooling which, if shown to be efficacious, could play a vital role in flattening the warming peak whilst allowing time to achieve zero emissions and carbon drawdown on a path back to a safe, liveable climate.[9]

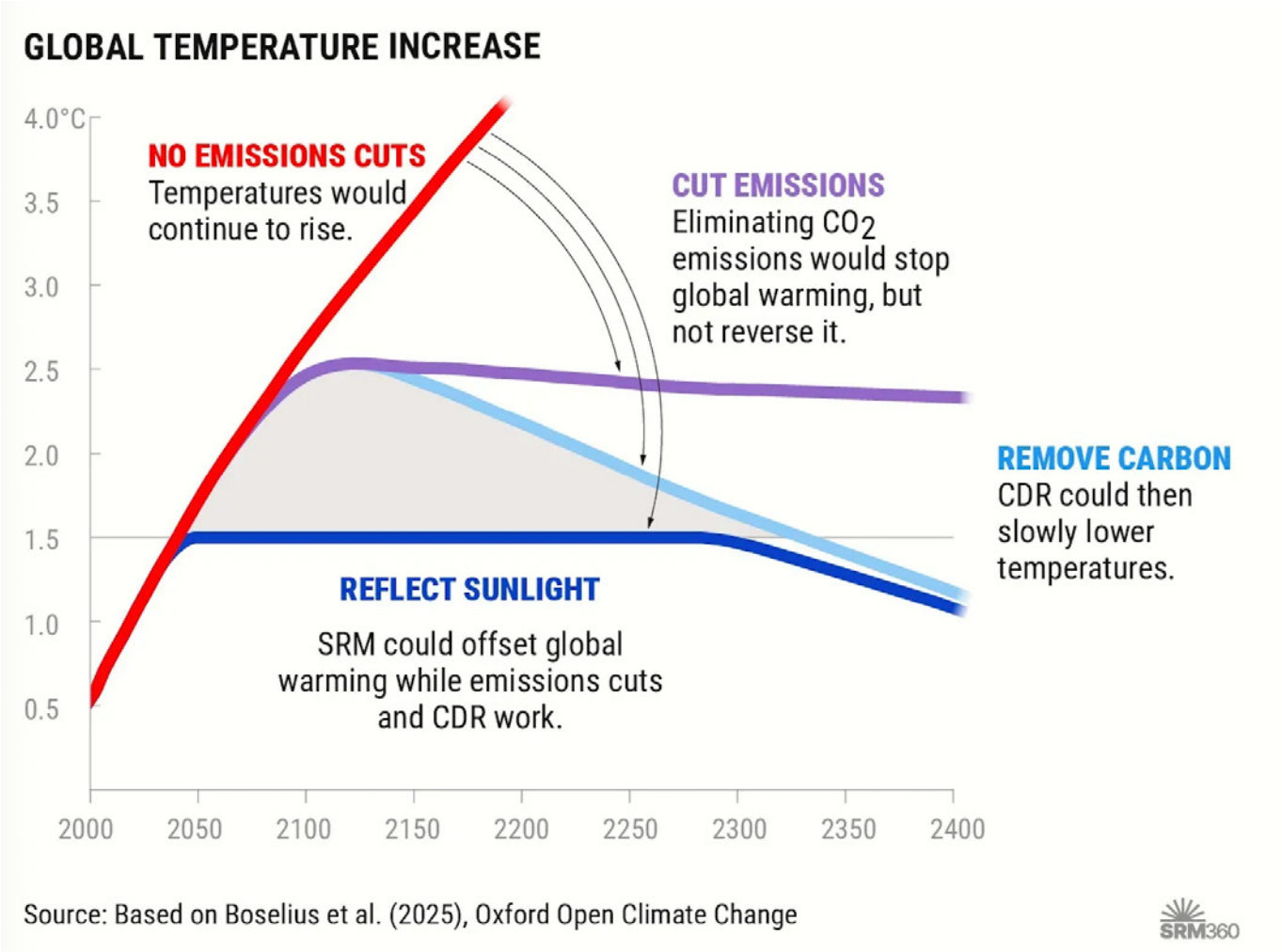
There is a near-term risk that warming may also trigger the "Hothouse Earth" scenario, in which climate system feedbacks and their mutual interaction drive the Earth System climate to a "point of no return", whereby further warming would become self-sustaining (that is, without further human-caused perturbations). Scientists have warned that this is possible even in the 1.5–2°C range.[10]

Even at 1.5°C, "we're at risk of crossing irreversible thresholds on unique and threatened systems", says Johan Rockström, director of the Potsdam Institute for Climate Impact Research.[11]

As illustrated,[12] as the world moves to zero emissions, and CO_2 levels start to decrease by natural processes and by carbon dioxide removal (or drawdown), albedo modification can flatten the level of peak warming — and perhaps help avoid existential climate impacts and extreme damage — until the other processes fully kick in.

6 See for example, Table SPM.1, ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers
7 twitter.com/LeonSimons8/status/1522342203481370625
8 pnas.org/doi/10.1073/pnas.1809600115
9 annualreviews.org/doi/abs/10.1146/annurev-earth-042711-105548
10 pnas.org/doi/10.1073/pnas.1810141115
11 phys.org/news/2022-06-irreversible-shifts-climate-experts.html
12 Adapted from royalsocietypublishing.org/doi/10.1098/rsta.2016.0454

Reduce, remove, repair



The three levers. Emission cuts and carbon dioxide removal (CDR) tackle the root cause of climate change, and sunlight reflection methods (SRM) could limit warming while they work. (Based on Boselius et al (2025), Oxford Open Climate Change/SRM360).

Climate intervention is the "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change".[13] Climate interventions fall into two broad categories: CO_2 removal and albedo modification.

13 royalsociety.org/topics-policy/publications/2009/geoengineering-climate

Carbon dioxide removal

Carbon dioxide removal (CDR) involves taking the excess CO_2 out of the atmosphere and the ocean, and storing it safely and securely in biomass, soils or rock formations, or in neutralised or stable forms in the oceans. CDR techniques may be classified as nature-based solutions and technical solutions, and include:

Nature-based solutions

- Ecosystem sequestration, in which ecosystems can be restored or created to use photosynthesis to capture CO_2 and store it in biomass, for example in peatlands, terrestrial forests and shallow saltwater ecosystems such as mangroves, kelp and seagrass. Reforestation and wetlands restoration is well-established, safe and the most cost-efficient CDR option at present.
- Regenerative land management practices that enhance water retention and soil carbon, which are proven and cost effective, including the use of biochar to store carbon and rejuvenate soils.
- Marine up-welling, which extends the scale of marine kelp, sea grasses and seaweed farms, offering new carbon sinks, plus production of food for cattle which increases milk yields whilst lowering methane emissions from livestock. Biomass allowed to drift down to the deep ocean would remain for hundreds of years or millenia.
- Ocean iron fertilisation, in which fertilising deep ocean areas with light sprinklings of iron dust can generate, in a matter of months, green, plankton-rich forests, accompanied by burgeoning fish stocks and a huge variety of marine wildlife. One result is more organic matter settling in the deep ocean.
- Enhanced mineralisation, mimicking a process in nature where silicate rock weathering on land binds CO_2. Crushed carbonate rock can also be exposed to CO_2 dissolved in water to create bicarbonate ions that can be stored in the ocean. This has been demonstrated in the laboratory and in small scale field trials, but has yet to be demonstrated at scale.

Technical solutions

- Negative emissions construction, the increased use of plantation timber (and potentially new forms of concrete and road materials) to store carbon in the built environment.
- Ocean alkalinization, the adding of alkaline substances — minerals such as olivine, or artificial substances such as lime or some industrial byproducts — to seawater to enhance the ocean's natural carbon sink by converting dissolved CO_2 into stable bicarbonate and carbonate molecules. This idea is at an early stage of development.
- Direct chemical capture by machines, to store in geological formations or in immobile form in the ocean or ocean sediments, which is now at the demonstration stage, but cost and energy use are currently prohibitive.
- Bioenergy with carbon capture and storage (BECCS), the use of crops to manufacture bioenergy, with underground storage of CO_2. This technology is unproven at scale or cost, but a favourite of policymakers and incorporated into Integrated Assessment Models and the Paris Agreement as a means of justifying a longer life for the fossil fuel industry via bioenergy with carbon capture and storage (BECCS) "offsets" for continuing carbon pollution.

Some of these techniques have well-known safety profiles and are at a high technical readiness level, whilst others are unproven at scale and cost, or speculative, and need technological development, safety testing and suitability evaluation.

Until emissions reach zero, CDR complements decarbonisation in mitigating the rate of increase of CO_2. After that point, CDR can reduce the absolute level of CO_2, but it is a relatively slow process, and not a primary tool in countering a locked-in temperature rise of 1.5°C by around 2030, and likely warming of 2°C before 2050 unless there is a radical reduction in emissions far beyond current national commitments.

Repair with albedo modification

Albedo modification (AM) is the reflection of more sunlight away from the planet. Proposed methods include:

- Enhancing surface reflection with mirrors, such as the Mirrors for Earth's Energy Rebalancing (MEER) project which is at an early stage of research development, but appears to not be bounded by material or energy use constraints. MEER addresses the imminent urgency of climate change due to temperature increase and weather extremes while reshaping energy production and consumption to renewable energy.[14]
- Marine cloud brightening (MCB) to increase reflectivity, in which saltwater spray is added to the lower atmosphere which has a high water vapour content, making existing clouds whiter (more reflective) or helping new clouds to form in a clear sky. Field research on MCB to protect the Great Barrier Reef is under way,[15] and the Centre for Climate Repair at Cambridge is urgently researching MCB as a means of cooling the Arctic.
- Solar radiation management (SRM), more accurately described as stratospheric aerosol injection (SAI), which increases the amount of stratospheric aerosols to reduce incoming solar radiation. This in a way mimics the cooling effect of major volcanic eruptions that inject sulphur dioxide gas into the stratosphere creating small particles of sulphuric acid that reflect some sunlight back to space; when Mount Pinatubo in the Philippines exploded in volcanic eruption in 1991, it cooled the planet by 0.6°C for about 15 months due to the particulate matter released. There is strong evidence that SAI, if applied at a scale, could significantly reduce or fully eliminate the earth's overheating in a relatively short period of time. SAI is the most studied form of albedo modification, with hundreds of published research papers, but with potentially significant risks.
- Increasing reflection of the terrestrial surface, everything from ice whitening to more reflective human infrastructure such as roofs.
- Decreasing the amount of high-altitude cirrus clouds to allow more out-going radiation.
- Space-based methods, which are highly speculative.

Some of these methods are at the early stage of research, whilst others have been more extensively researched, such as SAI. Most are at a relatively low level of technical readiness.

Unlike CDR, albedo modification does not aim to reverse warming by reducing the CO_2 level, nor does it have a direct effect on ocean acidification caused by rising levels of CO_2. However, as an interim measure, it could, in theory, "reduce some harm done by climate change during the time it takes for societies to implement deep cuts in greenhouse gas emissions while also potentially developing and deploying CDR systems. It could also, in theory, cool the climate quickly and thus prove highly valuable should society at some point face rapid changes in climate that cause unacceptable damage."[16]

Debate over stratospheric aerosol injection

Research on albedo modification and especially SAI is expanding rapidly. So are the number of NGOs focused on research, funding, advocacy and governance, including Operaatio Arktis, Arctic Circle, The Degrees Initiative, Silver Lining, Climate Crisis Advisory Group, Climate Overshoot Commission, MEER, SRM 360, Geoengineering Research Governance Project, Carnegie Climate Governance Initiative, and the Australian Forum for Climate Intervention Governance, to name but a few.

Since SAI has become highly politicised, how should its efficacy be assessed? The central question is whether SAI is of net social and environmental benefit. Some people object that it is "interfering with nature". Whilst a nature conservation approach invokes a "hands off nature" response to proposed climate interventions, the reality is that "hands off" will no longer protect nature in a rapidly-heating world, as a traditional conservation paradigm assumes.

A second line of opposition is that it may do damage to particular systems, regions and vulnerable people, compared to the status quo. But that is not the real-life choice. The real choice is the impacts of SAI versus the impacts in a significantly hotter world without SAI.

Unfortunately there is no ideal path away from climate disruption, so every tool at our disposal must be explored, and there needs to be an evidenced-based assessment of what is the least-worst option to protect what is at great risk.

14 prweb.com/releases/harvard_faculty_ye_tao_presents_a_solution_to_the_climate_change_crisis_at_nanoscientific_ symposium_nov_19_2019/prweb16688571.htm

15 nature.com/articles/d41586-021-02290-3

16 agu.org/Share-and-Advocate/Share/Policymakers/Position-Statements/Climate-Intervention-Requirements

In 2024, Gwynne Dyer reported that: "Almost nobody in the climate science community really believes anymore that we can stop the warming at a place that is relatively safe without direct human intervention of some sort in the climate system."[17] And a landmark 2024 study showed the Global South is more supportive of SRM interventions.[18] In 2021, the prestigious journal Nature ran an editorial titled: "Give research into solar geoengineering a chance".[19]

Delaying a high-level global mission on climate interventions is dangerous. Michael MacCracken, former chief scientist for climate change programs with the Climate Institute in Washington DC, provides a compelling case for prioritising intervention without delay, identifying the most urgent case as the potential for moderating amplified Arctic warming. [20]

He says that to date, there has been no high-level interest among international decision-makers in organizing a mission-focused climate intervention research and deployment program aimed at preventing temperature increases exceeding the 1.5–2°C Paris band. Instead, intervention "seems to be viewed as a potential emergency response that could be resorted to some decades in the future as a possible remedy after substantial impacts are widely evident and the consequences are becoming unacceptable".

But time is not on our side. MacCracken says that insufficient attention is being given to the inability of a delayed intervention to reverse disruptions of the landscape, undo the irreversible losses of biodiversity, or substantially slow the accelerating pace of sea level rise from the loss of ice sheets. Delay research too long and interventions may no longer work as well or at all: "Putting off initiation of actual climate intervention until there is much greater understanding might well lead to a situation where the transient conditions associated with restoring the past's milder conditions might themselves be unacceptably disruptive."

MacCracken also notes that many of the ethical analyses have been primarily focused on evaluating the relative risks and benefits of climate intervention on its own rather than as compared to the risks of projected changes without climate intervention. The relevant question is not what would be the risks of SRM or other interventions compared to the current climate, but the costs and benefits compared to a climate 2–4°C hotter.

MacCracken has identified how climate interventions are necessary to ensure the ongoing plausibility of achieving the UN Sustainable Development Goals. [21] He also suggests that the UN structures for sustainable development could be the overseeing climate interventions governance mechanism, given that the low-latitude nations are the most vulnerable and it was mainly the developed nations that put them in this predicament.

A lack of governance has not been a hindrance to research. State actors including the UK, the European Union, Russia, China, India, the USA and Australia have or are funding albedo modification research including SAI and cloud brightening, and funds are now also being made available by the Degrees Initiative to developing nations so they can better understand the issue. China, for example, has a weather modification program that already employs an estimated 35,000 people, and in 2020 announced plans that would increase fivefold the world's biggest cloud-seeding operation. And it is a leading nation in climate intervention research.

In the UK, the government is supporting small-scale climate intervention experiments as part of a £50m government-funded programme, through the Advanced Research and Invention Agency (Aria), to provide "critical" data needed to assess the potential of the technology.[22]

As circumstances become more desperate, and in the absence of agreed upon global governance, affected states may simply take unilateral action. Kim Stanley Robinson's prophetic 2020 cli-fi book, The Ministry for the Future, starts with a mega-heatwave in India that kills thousands in the state of Uttar Pradesh, and then tells of the global consequences. In such circumstances, asks Robinson, can others have an objection to such an impacted state taking unilateral action:

> "Throwing dust up into the atmosphere would be, I think, an emergency gesture on a temporary basis, in effect imitating a volcanic eruption and hoping that five years of slightly lower temperatures would save us from brutal heat waves. And if one nation suffers a catastrophic heat-death event and then decides to go this route, no other nation will have any legal or moral standing to object to it. Nor is it clear that it would be bad for civilization or the biosphere. Arguments about moral hazard become irrelevant in such an emergency, and worries about secondary effects are speculative and not supported by what has actually happened after real volcanic explosions."[23]

17 thewalrus.ca/seven-truths-climate-crisis/
18 peteirvine.substack.com/p/landmark-study-shows-the-global-south
19 nature.com/articles/d41586-021-01243-0
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23 nytimes.com/2021/06/22/magazine/ezra-klein-climate-crisis.html

What scientists say

—Prof. JAMES HANSEN

"We will need to return to a global climate no warmer than the middle of the 20th century, and likely somewhat cooler, for the sake of maintaining global shorelines."[24]

—Prof. JOHAN ROCKSTRÖM

"I just get tired...Tired of hearing that 1.5°C is a "target" or "goal". IT IS NOT. It is a limit. The only real goal is 0°C. And not bad 1.5°C, when we LIKELY tip GIS, WAIS, Tropical Coral Reefs and Abrupt Boreal Permafrost, and get more floods, droughts, heat, disease, storms."[25]

—Prof. WILL STEFFEN

"It is clear from observations of climate change-related impacts in Australia alone—the massive bushfires of the 2019-2020 Black Summer, the third mass bleaching of the Great Barrier Reef in only five years, and long-term cool-season drying of the country's southeast agricultural zone—that even a 1.1°C temperature rise has put us into a dangerous level of climate change."[26]

—Prof. HANS JOACHIM SCHELLNHUBER

"Our survival would very much depend on how well we were able to draw down CO2 to 280 parts per million."[27]

—Prof. NERILIE ABRAM

"People and ecosystems are already suffering from the impacts of climate change across the world, and these impacts will worsen unless we move quickly to radically reduce global greenhouse gas emissions. But we've also let this problem get to the point where rapid emission reductions alone won't be enough—we also need to develop ways to remove large amounts of carbon dioxide from the atmosphere and to preserve critical parts of the Earth system while we still can."[28]

—Sir DAVID KING

"Today the level of greenhouse gases (GHGs) in the atmosphere is already so high that rapid emissions reduction is no longer sufficient to avoid an unmanageable future for mankind. We also must have the capability to remove GHGs at scale from the atmosphere, and to repair those parts of the climate system, such as the Arctic Circle, which are passing or have passed their tipping point."[29]

Conclusion

In practical terms, the world has reached 1.5°C of global heating. The average for 2023 to 2026 will be above 1.5°C, and an unprecedented El Niño may push 2027 to 1.7°C. The rate of warming is accelerating and will likely continue on that path for several decades, especially given the failure so far to bend the emissions curve down fast. That means 2°C by 2040 or shortly after, and the emergence of vast zones of unlivable heat two decades after that on the present course of grossly inadequate action. Tipping points have been passed or are close at hand for some of the biggest elements of the climate system, including polar ice sheets and vast forest and permafrost carbon stores; and system inertia and hysteresis make preserving and restoring those systems very challenging. Scientists are increasingly alarmed that we may be heading towards Atlantic Meridional Overturning Circulation collapse by mid-century.

Any rational response would be an emergency "All hands on deck" rallying cry. Reducing emissions, even very fast, is not enough to stop the systemic changes that are under way. Drawing atmospheric carbon dioxide levels back to safe, near pre-industrial levels, is a necessary but slow process; and in the meantime actively cooling the planet must be on the agenda if it can be done safely. This is what the Climate Crisis Advisory Group has termed the "Reduction, Removal and Repair" strategy.

Avoiding civilisational collapse means governments and nations making climate the first priority of economics and politics, especially for the world's largest and high-polluting economies. It would mean making human security, not national security, the focus of geopolitics. It would mean the rich providing the capacity for developing nations to make a fast transition. It would recognise that disruption is inevitable, dislocation is necessary and this is not a period for business and politics-as-usual.

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