BREAKTHROUGH
National Centre For Climate Restoration

BRIEFING NOTE

The heat is on: Lessons from an "extraordinary" 2023 about future warming

FEBRUARY 2024

Summary

- A year of record-breaking heat in 2023 and global average warming for the year of 1.5˚C shocked scientists, with some events and extremes beyond model projections.
- The 2023 events and new research published during the year point to a dramatically hotter and unliveable future if the current high-emissions path is maintained.
- Major fossil fuel producers plan to pump even more oil and gas, putting Earth on a path of 3–4˚C of warming and social collapse.
- Key issues are the tipping points and system boundaries which, once exceeded, result in irreversible damage, even with subsequent cooling envisaged in "overshoot" scenarios.
- A strategy to avoid major irreversible impacts requires actions to actively cool the planet and protect vital systems in addition to a rapid drive to zero emissions and large-scale carbon drawdown.

> "Staggering. Unnerving. Mind-boggling. Absolutely gobsmackingly bananas. As global temperatures shattered records and reached dangerous new highs over and over the past few months, my climate scientist colleagues and I have just about run out of adjectives to describe what we have seen."
> — Dr Zeke Hausfather[1]

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[1] dtnext.in/edit/clear-and-present-danger-climate-change-data-tells-us-something-new-741788

For climate change, 2023 was an "unprecedented" year, "absolutely gobsmackingly bananas", "scary" and "frightening". And that was what climate scientists said! The UN Secretary General called it the year in which humanity crossed into a new climate era — an age of "global boiling".[2]

What happened in 2023, and new research published during the year, point to a dramatically hotter and unliveable future if the current high-emissions path is maintained. Key issues are the tipping points and system boundaries which, once exceeded, result in irreversible damage, even with subsequent cooling such as envisaged in the "overshoot" scenarios fondly embraced by policymakers.

A new approach to avoiding the irreversibility of many climate impacts is now essential, and urgent.

Scientists in shock

Climate disruption shocked climate scientists in 2023. "Surprising. Astounding. Staggering. Unnerving. Bewildering. Flabbergasting. Disquieting. Gobsmacking. Shocking. Mind boggling," said Ed Hawkins when the September 2023 warming exceeded the previous September record by a huge 0.5°C.[3]

The decline in Antarctic sea-ice extent was much greater than model projections, leading Walt Meier of the National Snow and Ice Data Center to exclaim: "It's so far outside anything we've seen, it's almost mind- blowing."[4]

The sea-ice decrease also staggered Cecilia Bitz from the University of Washington: "The last three or four months now is nothing like we've seen before, or would have expected, ever… This tells me that the climate change we're seeing is outside our range of experience and can't be explained by natural variability."[5]

Many records were set for new climate extremes — record heat, rainfall and floods — with some of it driven by the destabilisation of the polar jet stream. "We are hitting record breaking extremes much sooner than I expected. That's frightening, scary, and concerning, and it really suggests that we're not as aware of what's coming as we thought we were," said Sarah Perkins-Kirkpatrick of the University of NSW.[6]

Another scientist proffered: "Staggering, unnerving, mind-boggling", saying that "as global temperatures shattered records and reached dangerous new highs over and over the past few months, my climate scientist colleagues and I have just about run out of adjectives to describe what we have seen".[7]

Records broken everywhere

With devastating extreme heat and storms and floods, 2023 was the first year 1.5°C warmer than the 1850-1900 baseline, and both Antarctic sea-ice loss and record northern hemisphere sea-surface temperatures were way beyond the ranges projected by climate models.

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[2] news.un.org/en/story/2023/07/1139162

[3] twitter.com/ed_hawkins/status/1709825752705753105

[4] bbc.com/news/science-environment-66724246

[5] earth.org/antarctic-sea-ice-sets-record-low-maximum-extent-by-wide-margin-new-analysis-shows/

[6] theguardian.com/environment/2023/aug/28/crazy-off-the-charts-records-has-humanity-finally-broken-the-climate

[7] dtnext.in/edit/clear-and-present-danger-climate-change-data-tells-us-something-new-741788

Datasets of global temperatures vary a little depending on method, but two of the most significant are Berkeley Earth which put 2023 at 1.54˚C above the pre-industrial (1850-1900) level,[8] and Copernicus/ECMWF at 1.48˚C.[9]

Berkeley said that "a single year exceeding 1.5˚C is a stark warning sign of how close the overall climate system has come to exceeding this Paris Agreement goal. With greenhouse gas emissions continuing to set record highs, it is likely that climate will regularly exceed 1.5˚C in the next decade."[10]

2023 was notable for:

- Global average warming hitting the 1.5˚C mark, and new monthly records for global temperature every month from June to December. The October to December period was 1.74˚C.
- New national record high annual averages for an estimated 77 countries, including Bangladesh, Brazil, China, Germany, Japan, and Mexico.
- The first year that global average ocean surface temperature warming exceeded 1˚C, with once-in-a-century levels of warmth in the North Atlantic.
- The warmest year on record for ocean heat content, which increased notably between 2022 and 2023 and is increasing at an accelerating rate.
- Record low sea ice extent during the Antarctic winter. Physical oceanographer Edward Doddridge explained: "For those of you who are interested in statistics, this is a five-sigma event. So it's five standard deviations beyond the mean. Which means that if nothing had changed, we'd expect to see a winter like this about once every 7.5 million years."[11]

A useful discussion on "Approaching 1.5˚C: How will we know we've reached this crucial warming mark?", was published in December 2023.[12]

Extreme events included:

- Two days in November when global average temperature, for the first time, reached 2˚C above the pre-industrial levels.
- Catastrophic flooding from China to Africa, and earlier in the year major flooding in New Zealand associated with a rain bomb and then cyclone Gabrielle.
- Floods in Greece which obliterated one-quarter of farming land,[13] and olive oil yields plummeting across the Mediterranean due to extreme conditions, doubling the oil price in a year.
- More than 5000 people killed when storm Daniel hit Libya; and Freddy, one of the longest-lasting tropical cyclones on record, killed more than 1000 people in southeast Africa.
- Severe wildfires in Europe, Russia, Maui and North America; fires in Canada burned 18.5 million hectares of land.
- A new national temperature record in China of 52.2˚C, and a reading in Death Valley National Park in the USA of 53.9˚C.

[8] berkeleyearth.org/global-temperature-report-for-2023
[9] climate.copernicus.eu/copernicus-2023-hottest-year-record
[10] berkeleyearth.org/global-temperature-report-for-2023/
[11] abc.net.au/news/2024-01-10/2023-earths-hottest-year-on-record/103258396
[12] nature.com/articles/d41586-023-03775-z
[13] twitter.com/99blackbaloons/status/1705576597883916546

- In the south-west United States city of Phoenix, 31 straight days were greater than 43.3˚C (110˚F), breaking the previous record of 18 consecutive days.

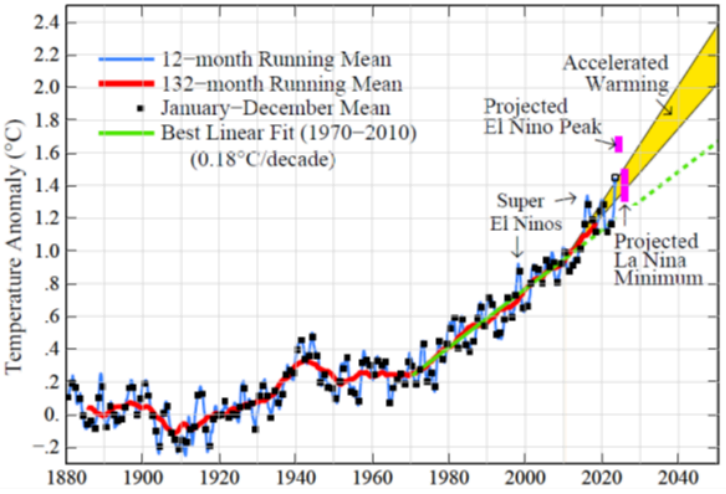
The 2023 extremes highlighted modelling limitations. Prof. Katharine Hayhoe told the *Guardian* that: "We have strongly suspected for a while that our projections are underestimating extremes, a suspicion that recent extremes have proven likely to be true… It is difficult to model something that you have almost no physical evidence for and, in the case of unprecedented extremes, no physical evidence. We are truly in uncharted territory in terms of the history of human civilisation on this planet."[14]

Explanations for 2023 are incomplete, but warming is accelerating and 2024 is likely to be hotter

In August 2023, Berkeley Earth outlined the factors, additional to the effect of global warming and a strengthening El Niño, that were likely aiding the extraordinary heating.[15]

But what happened in 2023 was not what scientists' models anticipated at the beginning of the year and fell well outside the confidence intervals of any of the estimates.[16] Carbon Brief says that "while there are a number of factors that researchers have proposed to explain 2023's exceptional warmth, scientists still lack a clear explanation for why global temperatures were so unexpectedly high… researchers are just starting to disentangle the causes of the unexpected extreme global heat the world experienced in 2023."[17]

One person who has a clear view is James Hansen, the former NASA climate chief, who says that "the 1.5 degree limit is deader than a doornail"[18] and warns that warming will accelerate to 1.7˚C by 2030 and "2˚C will be reached by the late 2030s"[19] (see illustration of Hansen's projections). It should be noted that the mean of the latest generation of climate models with a current-policy-type scenario show a warming of more than 2˚C by 2050.[20]



For a long time Hansen has been saying that the impact of sulphate aerosols — which are a byproduct of burning fossils fuels, cause acid rain, and have a strong but short-term cooling effect by reducing incoming radiation — is much greater than generally stated, so producing less of them under "clean air" policies will contribute to accelerated warming as the cooling mask is removed.

[14] theguardian.com/environment/2023/aug/28/crazy-off-the-charts-records-has-humanity-finally-broken-the-climate

[15] berkeleyearth.org/AUGUST-2023-temperature-update/

[16] theclimatebrink.com/p/2023s-unexpected-and-unexplained

[17] carbonbrief.org/state-of-the-climate-2023-smashes-records-for-surface-temperature-and-ocean-heat/

[18] youtube.com/watch?v=NXDWpBlPCY8

[19] mailchi.mp/caa/how-we-know-that-global-warming-is-accelerating-and-that-the-goal-of-the-paris-agreement-is-dead

[20] twitter.com/hausfath/status/1720177510531633297?s=43&t=dD_XOlpiO_e_ECnmTgND6A

Whilst the orthodox estimates for the aerosol impacts are around 0.5°C of cooling, Hansen and his colleagues say it is likely above 1°C. More on Hansen's analysis may be found in the 2023 paper "Global warming in the pipeline",[21] which former UK Chief Scientist Sir David King says is "one of the most important published on the state of the climate crisis in years".[22]

The "Pipeline" paper warns that "we are in the early phase of a climate emergency" and that acceleration in warming is "dangerous in a climate system that is already far out of equilibrium. Reversing the trend is essential – *we must cool the planet – for the sake of preserving shorelines and saving the world's coastal cities*" (emphasis added).[23]

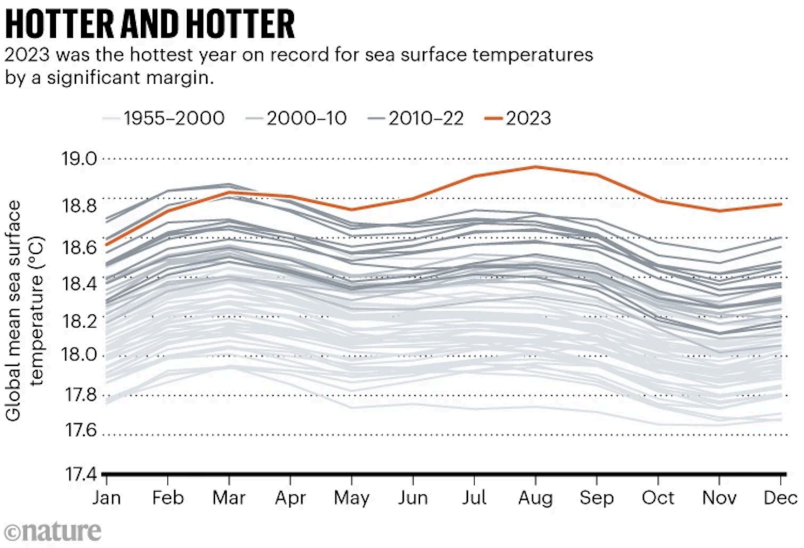
In Hansen's view, the efforts to clean up maritime shipping emissions by mandating fuel with much lower sulphur content resulted in the "Faustian bargain" being exposed: as the sulphate cooling impact has reduced, greater warming has been revealed. This was allied with continuing high human greenhouse emissions, and the effects of the developing El Nino, to produce the 2023 heat records.

Berkeley says there is a 58 percent chance that 2024 will be warmer than 2023, and the recent climate record shows the second year of an El Nino is warmer than the first.

Whether warming is accelerating has caused sharp differences between scientists, but Hansen's view is gaining more support. Prof. Stefan Rahmstorf says warming "has accelerated over the past 40 years",[24] based on NASA data. And a paper published four days before the end of 2023 showed a "robust acceleration of Earth system heating observed over the past six decades", and the "long-term acceleration of Earth warming aligns qualitatively with the rise in carbon dioxide (CO_2) concentrations and the decline in aerosol concentration during the same period, but further investigations are necessary to properly attribute these changes".[25]

Two key indicators — an acceleration in the rate at which the ocean is absorbing heat, and a spike in Earth's Energy Imbalance — suggest Hansen is on the right track.

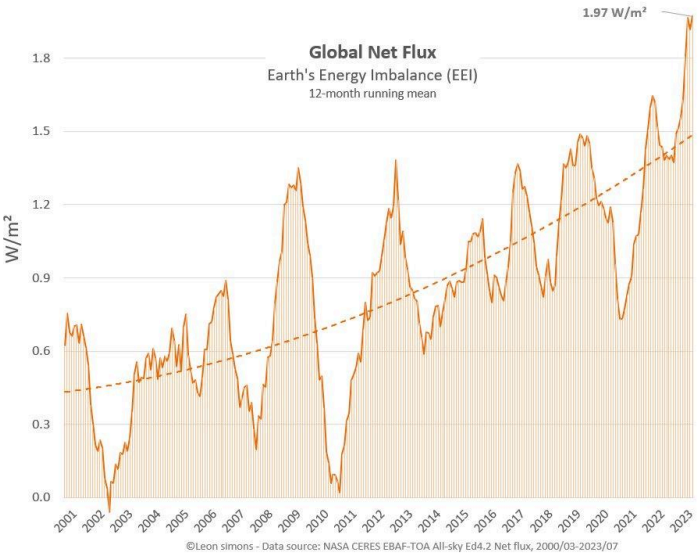
Ocean heat content: 90 percent of the heat generated by the greenhouse effect warms the oceans (with only 2 percent to the atmosphere, and the balance melting the polar ice and warming the land). With this great store of heat, it is oceans and their surface temperature that drive atmospheric warming. 2023 was the hottest year on record for sea-surface temperatures by a significant margin (see illustration). Research published in 2023 showed that the rate of increase in ocean heat content has accelerated over recent decades.[26] Ocean temperatures started spiking in March-April 2023, and global temperatures in June.



[21] academic.oup.com/oocc/article/3/1/kgad008/7335889
[22] twitter.com/sir_david_king/status/1722693289378259294
[23] academic.oup.com/oocc/article/3/1/kgad008/7335889
[24] twitter.com/rahmstorf/status/1746587002512761278
[25] nature.com/articles/s41598-023-49353-1
[26] nature.com/articles/s41467-023-42468-z

The heat stored in the world's oceans increased by the greatest margin ever in 2023, absorbing more heat than in any other year since records began.[27] Associated with the onset of a strong El Niño, the global sea surface temperature was an astounding 0.3˚C above 2022 values for the second half of 2023.[28]

Earth's Energy Imbalance: Earth's energy imbalance (EEI) is the difference between incoming energy from the sun and the amount of heat radiating from Earth back into space. Data from the CERES project, which uses satellites to estimate EEI, suggests that EEI has more than doubled since 2000 (as illustrated), resulting in an acceleration of global warming's impact on the Earth system.[29]

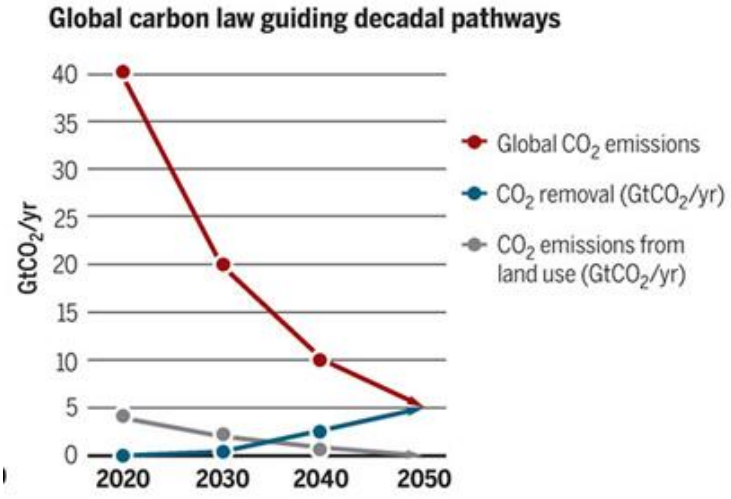


If EEI is increasing over time, it should drive an increase in the world's rate of warming, says Zeke Hausfather: "As countries around the world have begun to clean up the air, the cooling effect provided by these aerosols has fallen by around 30 percent since 2000. Aerosols have fallen even more in the past three years, after a decision to largely phase out sulphur in marine fuels in 2020. These reductions in pollution on top of continued increases in atmospheric greenhouse gas concentrations mean that we are encountering some of the unvarnished force of climate change for the first time."[30]

These two lines of evidence — ocean heat content and EEI — support Hansen's assessment that warming has and will accelerate.

Earth will fly past 2˚C

Given current trends in the climate system and in human greenhouse emissions, the world will fly past 2˚C. Climate model scenarios similar to current policies project 2˚C of warming before 2050; if Hansen is right and warming sharply accelerates, it could be a decade sooner. These outcomes will be driven by the energy imbalance, continuing high emissions, the accelerating accumulation of heat in the oceans, and decreases in short-term aerosol cooling.



Several years ago a group of eminent scientists described a "carbon law", which said that keeping warming to 2˚C required emissions to be

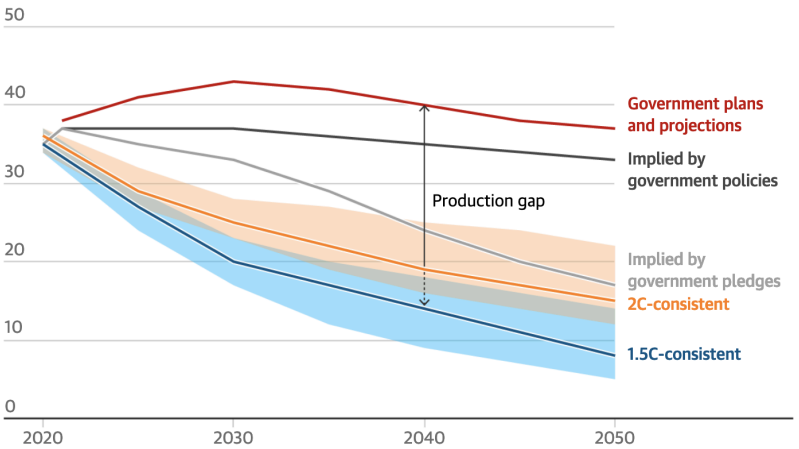
[27] nature.com/articles/d41586-024-00081-0
[28] link.springer.com/article/10.1007/s00376-024-3378-5
[29] berkeleyearth.org/global-temperature-report-for-2023/
[30] dtnext.in/edit/clear-and-present-danger-climate-change-data-tells-us-something-new-741788

halved *every* decade from 2020 onwards, including a halving between 2020 and 2030, plus some carbon drawdown (see illustration).[31]

But instead, the level of greenhouse gases and coal use both hit record highs in 2023. And the largest national fossil fuel producers plan to keep on expanding production. Hence current government plans worldwide will likely result in emissions in 2050 almost as high as they are today, according to the UN Environment Programme's 2023 *Production Gap* report (see illustration).[32]

Countries are planning double the fossil fuel production in 2030 than is consistent with 1.5C warming

Billions of tonnes of CO_2 equivalent per year



Guardian graphic. Source: The Production Gap: SEI, Climate Analytics, E3G, IISD and UNEP 2023

Other analyses are broadly consistent with this. For example:

- The US Energy Information Administration projects US emissions in 2050 will be 80percent of today's levels.[33]
- The International Energy Agency finds that stated national policies will result in oil and gas production in 2050 as high as 2020; with coal halved.[34]
- The OECD finds that a world economy four times larger than today is projected to need 80 percent more energy in 2050; and without new policy action and the global energy mix in 2050 will not differ significantly from today, with the share of fossil energy at about 85 percent, renewables including biofuels just over 10 percent, and the balance nuclear.[35]
- A study of three dozen plans found 90 percent of national targets were not credible and unlikely to be achieved.[36]

The intentions of the world's five largest fossil fuel producers are clear — and civilization-threatening — as reported by the UN:[37]

- In China, oil production is projected to be flat to 2050, but gas will increase more than 60 percent from 2020 to 2050, while coal use will remain high till 2030 then decline sharply to about 30-40 percent of current levels by 2050.

[31] https://www.science.org/doi/10.1126/science.aah3443
[32] unep.org/resources/production-gap-report-2023
[33] eia.gov/outlooks/aeo/narrative/index.php#ExecutiveSummary
[34] iea.org/reports/world-energy-outlook-2023
[35] oecd.org/env/indicators-modelling-outlooks/oecdenvironmentaloutlookto2050theconsequencesofinaction-keyfactsandfigures.htm
[36] theguardian.com/commentisfree/2023/jun/15/from-the-oceans-to-net-zero-targets-were-in-denial-about-the-climate-crisis
[37] unep.org/resources/production-gap-report-2023

- In the United States, oil production will grow and then remain at record levels to 2050, and gas is projected to significantly increase to 2050; coal production in 2050 will be about half the current level.
- Projections for Russia are available only to 2035, with coal and gas production projected to increase significantly, while oil remains flat. Oil and gas production constitute 19 percent of the economy.
- Saudi Arabia's plan is to increase oil and gas capacity: Oil production is projected to grow by 26 to 47 percent by 2050, with gas up 40 percent between 2019 and 2050. Oil and gas production make up half of the Saudi economy.
- And Australia is one of the world's top two liquified natural gas and coal exporters. Gas production is projected to stay above the current level for the next 15 years, with coal remaining high over the same period, above 450 million metric tons annually.

Earth is heading towards 3–4˚C.

This emissions outlook suggests that the Earth is heading towards 3˚C of warming and perhaps a good deal more, in part because current climate models which project warming of around 2.7˚C do not adequately account for all the system-level reinforcing feedbacks.

The pre-eminent UK international affairs think-tank, Chatham House, says a "plausible worst-case scenario" is 3.5˚C this century, and says this could be an underestimate if tipping points are reached sooner than the orthodox science suggests.[38] This now seems to be the case.

A clear majority of scientists expected warming of more than 3˚C, and 82 percent expected to see catastrophic impacts of climate change in their lifetime, according to a 2021 survey by the journal *Nature.*[39]

Questions about the size of the aerosol forcing, and the related issue of how sensitive the climate is to changes in greenhouse gases, remain an issue of scientific contention. [Higher climate sensitivity implies higher aerosol forcing, and vice versa.]

Two years ago there was discussion that a subset of the new generation of general climate models (CMIP6) which implied higher committed warming and higher climate sensitivity[40] were running "too hot". But the events of 2023, and recent research, suggest these models may be on the money.

New climate history research published in December 2023, based on a study of the last 66 million years, concluded that global temperature may be more sensitive to CO_2 levels than current models estimate.[41] It showed that the last time CO_2 levels were as high as today was around 14 million year ago, which is longer than previous estimates, and that climate sensitivity — the amount of warming resulting from a doubling of atmospheric CO_2 — may be between between 5˚C and 8˚C, compared to the Intergovernmental Panel on Climate Change (IPCC) orthodoxy of 1.5–4.5˚C.

[The Hansen at el. "Pipeline" paper finds that climate sensitivity is 4.8˚C ± 1.2˚C per doubling of CO_2, based in part on an analysis that the temperature change between the last ice age and today was 7˚C ± 1˚C, which is much greater than is generally thought.]

[38] chathamhouse.org/2021/09/climate-change-risk-assessment-2021

[39] nature.com/articles/d41586-021-02990-w

[40] link.springer.com/article/10.1007/s10584-020-02849-5

[41] science.org/doi/10.1126/science.adi5177

The level of the "well-mixed" greenhouse gases is currently around 560 parts per million, double the pre-industrial level. Now some of those gases such as methane are short-lived so this level of forcing is not written in stone, but nevertheless if Hansen et al. are right that a doubling may lead to around 5˚C or warming, then another 30 years of high emissions means humans will face an increasingly unliveable planet in the second half of this century.

Has the impact of aerosols been widely understood? In what the *New York Times* described as "an eye-opening *Nature* commentary",[42] Geeta Persad and her colleagues wrote in late 2022 that "overall, vast emissions of aerosols since the start of the industrial age have had a profound cooling effect" and that without them "the global warming we see today would be 30 to 50 percent greater", and warned that "the impacts of aerosols on climate risk are often ignored".[43]

Thus Chapter 2 on "Emissions trends and drivers" of the Working Group 3 report of the most recent IPCC assessment discloses in a footnote (on p. 226) that "Emission metrics also exist for aerosols, *but these are not commonly used in climate policy*. This assessment focuses on GHG [greenhouse gas] emission metrics only" (emphasis added).[44]

So UN Secretary General Antonio Guterres is justified in saying that the era of "global boiling" has arrived.

In 2018, a group of eminent scientists explored the potential — once warming had exceeded the 1.5–2˚C range — for self-reinforcing positive feedbacks in major elements of the climate system to push passed a planetary threshold that would prevent temperature stabilization, and drive the system to a "Hothouse Earth".[45] They warned that "we are in a climate emergency… this is an existential threat to civilization".[46]

Scientists at the University of New South Wales warn that "an equilibrium climate under *current* carbon dioxide concentrations would have a sea level 5–25 metres higher."[47] And we are still adding greenhouse gases to the atmosphere at a record rate!

The *2023 State of the Climate Report: Entering uncharted territory* warned that:

> Conditions are going to get very distressing and potentially unmanageable for large regions of the world, with the 2.6˚C warming expected over the course of the century, even if the self-proposed national emissions reduction commitments of the Paris Agreement are met. We warn of potential collapse of natural and socioeconomic systems in such a world where we will face unbearable heat, frequent extreme weather events, food and fresh water shortages, rising seas, more emerging diseases, and increased social unrest and geopolitical conflict.[48]

Whatever the words, the understanding is widely shared that contemporary nations and societies, and likely the global social system, are heading towards collapse. "If we carry on the way we are going now, I can't see this civilization lasting to the end of this century", says Professor Tim Lenton.[49] The US Defence Secretary Lloyd Austin III calls the risk "existential".[50]

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[42] nytimes.com/2023/08/30/opinion/columnists/the-faustian-bargain-of-reducing-air-pollution.html
[43] nature.com/articles/d41586-022-03763-9
[44] ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter02.pdf
[45] pnas.org/doi/10.1073/pnas.1810141115
[46] nature.com/articles/d41586-019-03595-0
[47] climateextremes.org.au/briefing-note-15-can-we-limit-global-warming-to-1-5c/
[48] academic.oup.com/bioscience/advance-article/doi/10.1093/biosci/biad080/7319571
[49] youtu.be/FKjVpyqOZ2w?si=jwFuOBbbQOIPw0Ty
[50] defense.gov/News/Transcripts/Transcript/Article/2582828/secretary-austin-remarks-at-climate-change-summit

Opening the Innovation Zero Congress in London in May 2023, Potsdam Institute Director Prof. Johan Rockström described the path we are on:

> There's one conclusion without any uncertainty whatsoever, and that is that 2.5°C global mean surface temperature rise is a disaster. It's something that humanity has absolutely no evidence that we can cope with. It would actually exceed the warmest temperature on Earth over the past four million years.
>
> Push ourselves to 2.5°C – we're in unknown terrain. It would lead to a complete melting of the big ice sheets, which would be a 10-metre sea-level rise.
>
> There would be a collapse of all the big biomes on planet Earth — the rainforest, many of the temperate forests — abrupt thawing of permafrost, we will have complete collapse of marine biology, we will have a shift of large parts of the habitability on Earth.
>
> Over one-third of the planet around the equatorial regions will be uninhabitable because you will pass the threshold of health, which is around 30°C. It's only in some parts of the Sahara Desert today that has that kind of average temperature.[51]

Chatham House's *Climate Risk Assessment 2021* concluded that by 2050 global food demand would be 50 percent higher, but crop yields may drop by 30 percent. As desertification spreads across the dry subtropics, and one-third of the planet experiences unprecedented heat, it is not difficult to see why it concluded that cascading climate impacts will "drive political instability and greater national insecurity, and fuel regional and international conflict".[52]

System boundaries are being exceeded as tipping points cascade

Several significant reports on tipping points and planetary boundaries were released during 2023.

The *Global Tipping Points Report* was launched at COP28 in December 2023, with Tim Lenton from the University of Exeter's Global Systems Institute leading a team of 200 researchers in 26 countries. It concluded that humanity faces "devastating domino effects" including mass displacement and financial ruin as the planet warms.[53]

It said that five important natural thresholds — for Greenland, West Antarctica, permafrost, coral systems and Atlantic circulation — already risk being crossed, but that may be an understatement. Co-author Sina Loriani said that crossing these thresholds "may trigger fundamental and sometimes abrupt changes that could *irreversibly* determine the fate of essential parts of our Earth system for the coming hundreds or thousands of years" (emphasis added).[54]

"Safe and Just Earth System Boundaries", published by Rockström and colleagues in May 2023, quantified safe and just Earth system boundaries (ESBs) for climate, the biosphere, water and nutrient cycles, and aerosols at global and subglobal scales.[55] They found seven of eight globally quantified safe and just ESBs and at least two regional safe and just ESBs in over half of global land area are already exceeded. Rockström said the boundaries can be seen as health indicators for people and

[51] aol.co.uk/news/current-climate-path-lead-collapse-103729716.html
[52] chathamhouse.org/2021/09/climate-change-risk-assessment-2021
[53] theguardian.com/environment/2023/dec/06/earth-on-verge-of-five-catastrophic-tipping-points-scientists-warn
[54] theguardian.com/environment/2023/dec/06/earth-on-verge-of-five-catastrophic-tipping-points-scientists-warn
[55] nature.com/articles/s41586-023-06083-8

the planet, but the science is "showing clearly that we are at risk of destabilising the entire planet and its life support systems".[56]

The *State of the Cryosphere Report 2023 — Two Degrees is Too High,* said that a number of new studies all point to a threshold for both Greenland and parts of Antarctica well below 2˚C, which would commit the planet to between 12–20 metres of sea-level rise if 2˚C becomes the new constant Earth temperature.[57] And on the present trends, we are going to fly past 2˚C! Two warnings about irreversibility were particularly sobering:

- "Many ice sheet scientists now believe that by 2˚C, nearly all of Greenland, much of West Antarctica, and even vulnerable portions of East Antarctica will be triggered to very long-term, inexorable sea-level rise, *even if air temperatures later decrease*. This is due to a warmer ocean that will hold heat longer than the atmosphere, plus a number of self-reinforcing feedback mechanisms, so that it takes much longer for ice sheets to regrow (tens of thousands of years) than lose their ice" (emphasis added).
- "If 2˚C warming is reached, projections show that nearly all tropical glaciers (north Andes, Africa) and most mid-latitude glaciers outside the Himalayas and polar regions will disappear, some as early as 2050. Others are large enough to delay complete loss until the next century, but have *already passed a point of no return*. Even the Himalayas are projected to lose around 50 percent of today's ice at 2˚C" (emphasis added).[58]

Whilst some scientists, donning a policymaker's garb, are tempted to say that tipping points *will* be a big issue *when* warming exceeds 1.5˚C or 2˚C, the evidence continues to accumulate that several such thresholds have already been passed, as surveyed in the report, *Climate Dominoes*.[59]

- 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.[60]
- Coral reefs have passed their tipping points and are dying. "Nearly all tropical reefs will become extinct even if global warming is kept to 1.5˚C", says the IPCC.[61]
- The 2022 *State of the Cryosphere* report concluded that more than four metres of additional sea level rise was locked in "with sections of the West Antarctic ice sheet potentially collapsing *even without any further emissions over the coming centuries*" (emphasis added).[62] And an ingenious look at the genetic history of Turquet's octopus and its population movement across Antarctica in past warm periods led to the conclusion that "even under global heating of 1.5˚C the West Antarctic Ice Sheet *could be consigned to collapse*" (emphasis added).[63]
- Antarctica is warming much faster than models predicted.[64] In "Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century", researchers found that rapid ocean warming, at approximately triple the historical rate, is likely committed over the

[56] abc.net.au/news/science/2023-06-01/health-report-card-for-the-planet-science-boundaries/102405754
[57] iccinet.org/statecryo23/
[58] iccinet.org/statecryo23/
[59] breakthroughonline.org.au/climatedominoes
[60] science.org/doi/10.1126/science.abn7950
[61] ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Chapter_3_LR.pdf
[62] theguardian.com/environment/2022/nov/07/melting-arctic-sea-ice-summer-report
[63] theguardian.com/world/2023/feb/05/clue-to-rising-sea-levels-lies-in-dna-of-4m-year-old-octopus-scientists-say
[64] nature.com/articles/s41558-023-01791-5

twenty-first century, with widespread increases in ice-shelf melting, including in regions crucial for ice-sheet stability: "These results suggest that mitigation of greenhouse gases now has limited power to prevent ocean warming that could lead to the collapse of the West Antarctic Ice Sheet."[65] In other words, West Antarctica will continue to melt this century regardless of how much the world slashes planet-warming emissions.

- A 2023 study concluded that ice-ocean dynamics lead to more rapid ice loss from Greenland glaciers ending in the ocean, a mechanism "not included in models, and if we were to include them, it would increase projections of sea level rise by up to 200 percent—not just for Petermann but for all glaciers ending in the ocean, which is most of northern Greenland and all of Antarctica".[66] Earlier, a 2020 study found that the Greenland ice sheet had "reached a tipping point 20 years ago",[67] with researchers showing that "widespread retreat between 2000 and 2005 resulted in a step-increase in discharge and a switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt".[68]
- In a ground-breaking 2021 paper, Katharyn Duffy and colleagues mapped the relationship between increasing temperatures and carbon uptake in Amazon forests by analysing more than 20 years of data on the transfer of carbon dioxide between plants, land, and the atmosphere; their analysis showed that in recent hot periods the thermal maximum for photosynthesis had been exceeded. At higher temperatures, the amount of CO_2 absorbed by plants (photosynthesis) will decline sharply, whilst CO_2 released by plants (respiration) will continue to rise.[69]

Perhaps the biggest tipping point story in 2023 was the Atlantic Meridional Overturning Circulation, or AMOC for short. This system has already slowed by 15 percent since the mid-20th century,[70] and in 2021 researchers concluded there is "strong evidence that the AMOC is indeed approaching a critical, bifurcation-induced transition" (in other words, a tipping point) but the timing was unclear.[71]

Then, in July 2023, a study again drew headlines and surprise when it estimated "a collapse of the AMOC to occur around mid-century under the current scenario of future emissions," with a high confidence (95 percent probability) of it occurring between 2025 and 2095.[72] This finding is contested, but eminent scientists have said it cannot be easily dismissed.

This is starkly different from the IPCC projection that the AMOC would weaken in the 21st century but "a collapse is very unlikely," with only a 50/50 chance of collapse by 2300 in a high-emission scenarios.[73]

Potsdam University's Stefan Rahmstorf said that while there is still "large uncertainty where the tipping point of the AMOC is… the scientific evidence now is that we can't even rule out crossing a tipping point already in the next decade or two",[74] and "the conservative IPCC estimate, based on climate models which are too stable… is in my view outdated now".[75]

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[65] nature.com/articles/s41558-023-01818-x
[66] phys.org/news/2023-05-rapid-ice-greenland.html
[67] phys.org/news/2020-09-greenland-ice-sheet-years.html
[68] nature.com/articles/s43247-020-0001-2
[69] science.org/doi/10.1126/sciadv.aay1052
[70] nature.com/articles/s41561-021-00699-z
[71] nature.com/articles/s41558-021-01097-4
[72] nature.com/articles/s41467-023-39810-w
[73] ipcc.ch/srocc/
[74] edition.cnn.com/2023/07/25/world/gulf-stream-atlantic-current-collapse-climate-scn-intl/index.html
[75] realclimate.org/index.php/archives/2023/07/what-is-happening-in-the-atlantic-ocean-to-the-amoc

A severe AMOC slowdown would bring more warming in the tropics and more extreme storms to the North Atlantic region, more frequent heat waves around the world, a shift in the rain belt in South Africa, causing droughts for millions of people, and sea level rises across the US East Coast.

Consistent with this analysis, Australian researchers in March 2023 published projections showing Antarctic deep ocean warming and changes in deep ocean circulation contributing to a slowing of the AMOC over the next few decades, with physical measurements confirming these changes are already well underway.[76] They explained:

> Climate change is to blame. As Antarctica melts, more freshwater flows into the oceans. This disrupts the sinking of cold, salty, oxygen-rich water to the bottom of the ocean. From there this water normally spreads northwards to ventilate the far reaches of the deep Indian, Pacific and Atlantic Oceans. But that could all come to an end soon. In our lifetimes.[77]

They said the currents "may even collapse" and, if this happens, this would "deprive the deep ocean of oxygen, limit the return of nutrients back to the sea surface, and potentially cause further melt back of ice as water near the ice shelves warms in response. There would be major global ramifications for ocean ecosystems, climate, and sea-level rise."[78]

Looking at the other pole, research published in June 2023 found that even if greenhouse gas emissions are sharply reduced, the Arctic will be sea-ice free in September in coming decades.[79] The *Guardian* headlined a comment from Dirk Notz that "unfortunately it has become too late to save Arctic summer sea ice",[80] but that seems to assume that no climate interventions (geoengineering) is possible. The *Washington Post* reported the story as: "A summer in which the Arctic Ocean features almost entirely open water could be coming even sooner than expected and may become a regular event within most of our lifetimes."[81]

We are entering the territory of irreversible harms

These stories about the Arctic and the Antarctic highlight new understandings about what may be termed "the territory of irreversible harms".

One big concern is the use of overshoot net-zero-2050 scenarios, favoured by integrated assessment modellers to inform policymakers, in which a given temperature goal — say 1.5°C — is exceeded (or overshot) for several or many decades, before negative emission policies — for example, zero emissions plus carbon drawdown (CDR) — reduce the level of greenhouse gases, and hence the global temperature.

In 2018, researchers said that "while it is possible that CDR, together with mitigation, could eventually return atmospheric CO_2 to previous levels, this would only *partially* return the climate and other Earth system parameters, such as ocean pH, to the corresponding previous state, due to hysteresis and other effects".[82]

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[76] nature.com/articles/s41586-023-05762-w
[77] theconversation.com/torrents-of-antarctic-meltwater-are-slowing-the-currents-that-drive-our-vital-ocean-overturning-and-threaten-its-collapse-202108
[78] theconversation.com/torrents-of-antarctic-meltwater-are-slowing-the-currents-that-drive-our-vital-ocean-overturning-and-threaten-its-collapse-202108
[79] nature.com/articles/s41467-023-38511-8
[80] theguardian.com/environment/2023/jun/06/too-late-now-to-save-arctic-summer-ice-climate-scientists-find
[81] washingtonpost.com/climate-environment/2023/06/06/arctic-sea-ice-melting/
[82] nature.com/articles/s41467-018-05938-3

Hysteresis is the bifurcation of a system, where it may be more difficult, or impossible, for a system to return to its previous state. Put more simply: the path from A to B is not the same as the path from from B to A. Ice sheets are a good example.

A chilling 2015 report on *Thresholds and Closing Windows: Risks of irreversible cryosphere climate change* warned that the Paris commitments will not prevent the Earth "crossing into the zone of irreversible thresholds" in polar and mountain glacier regions, and that crossing these boundaries may "result in processes that cannot be halted unless *temperatures return to levels below pre-industrial*" (emphasis added).[83] For example, the tipping point for the most vulnerable West Antarctic glaciers is probably between 0.5˚C and 1˚C, but cooling the planet back to that range may not create the conditions for their re-establishment.

In a 2023 paper, "Temporary overshoot: Origins, prospects, and a long path ahead", Andy Reisinger and Oliver Geden discussed the irreversible harm of overshoot and irreversibility:

> One simple reason is irreversibility: the extinction of species is a key concern under higher warming levels, but bringing warming back down again will not reverse such extinctions, even though the risk to surviving species would be reduced. Similar issues apply to near irreversibility of the loss of ice sheets and glaciers or rather the need for temperature to fall far below current levels for those ice masses to build up again. A related but more complex reason is that impacts, once manifested, leave behind an altered world that cannot be reversed by declining global warming levels… At best, many human and natural systems will exhibit a significant hysteresis in their recovery after global warming levels decline again, but often they will assume a permanently altered state that is difficult to return to the original condition…. if a tipping point is reached during the overshoot period, the consequences would generally not be reversible.[84]

In "Overconfidence in overshoot", Joeri Rogelj worries about "the ease with which this risky overshoot idea is being socialised is deeply concerning. Indeed, much of the overshoot discussion is characterised by stark overconfidence."[85]

He identifies three areas of overconfidence in the overshoot discourse: overconfidence in the geophysical characteristics of overshoot, overconfidence in effectively deploying technologies required to carry out an overshoot, and overconfidence in the resilience of institutions and societies in such a world. Specific issues include poor approaches to risk and uncertainty and the large likelihood of larger warming; the fact that reversing warming might be very hard; and high uncertainty about removing CO_2, with overshoot scenarios having a "reliance on CO_2 removal [which] is highly at odds with current development, scale-up and reliability of available measures".

In April 2023, US climate envoy John Kerry warned about reliance on overshoot, saying that: "The danger… which alarms me the most and motivates me the most, is that according to the science, and the best scientists in the world, we may be at or past several tipping points that they have been warning us about for some time. That's the danger, the irreversibility."[86]

[83] iccinet.org/thresholds/

[84] sciencedirect.com/science/article/pii/S2590332223005419

[85] granthaminstitute.com/2023/11/29/overconfidence-in-overshoot/

[86] theguardian.com/us-news/2023/apr/25/john-kerry-relying-technology-remove-carbon-dioxide-dangerous

Strategies for avoiding irreversible harms

In November 2023, the Climate Crisis Advisory Group (CCAG), led by Sir David King, called for "unprecedented interventions to mitigate 1.5˚C climate overshoot" through a "4R climate strategy", noting that:

- Above the critical 1.5˚C threshold, the latest science warns that the world will enter a realm of unacceptable risk and uncertainty, exposing humanity to potentially irreversible harms.
- Even at the current 1.1˚C decade averaged global temperature rise, many parts of the world are already experiencing the catastrophic effects of the climate crisis.
- Global warming must be kept to 1˚C to ensure safety as well as justice for the most vulnerable communities, who are already bearing the brunt of climate breakdown.[87]

In fact, a desirable goal is likely to be pre-industrial conditions, or at least those of the mid-20th century which would result in warming of less than 0.5˚C, which is about the maximum band of temperature experience by humans during the Holocene (the last 10,000 years of fixed human settlement). [See box on next page.]

The CCAG strategy is:

- Reduce: rapid reduction of emissions to limit the Earth's warming
- Remove: development, research and scaling of techniques to remove GHGs from the atmosphere
- Repair: finding solutions that could help repair parts of our damaged climate systems
- Resilience: strengthening our capacity to deal with the climate crisis.

Repair is a polite word for climate interventions or what may pejoratively be called geo-engineering.

Take a specific case: what can be done about future sea-level rise? Greenhouse gas levels today are likely higher than during a previous warm period, the Pliocene three million years ago, when temperatures were ~3˚C warmer than pre-industrial and sea levels 25 metres higher, driven by melting polar ice.[88]

New research shows that rising sea levels are likely to inundate twice as much land in developing countries than previously projected.[89] It is no wonder that in February 2023 the UN Secretary-General Antonio Guterres said that an increase in the pace at which sea levels are rising threatens "a mass exodus of entire populations on a biblical scale":

> It is a threat-multiplier. For the hundreds of millions of people living in small island developing states and other low-lying coastal areas around the world, sea-level rise is a torrent of trouble… Mega-cities on every continent will face serious impacts including Lagos, Maputo, Bangkok, Dhaka, Jakarta, Mumbai, Shanghai, Copenhagen, London, Los Angeles, New York, Buenos Aires and Santiago. The danger is especially acute for nearly 900 million people who live in coastal zones at low elevations — that's one out of ten people on earth… The consequences of all of this are unthinkable. Low-lying communities and entire countries could disappear forever. We would witness a mass exodus of entire populations on a biblical scale.[90]

[87] ccag.earth/newsroom/ccag-calls-for-unprecedented-interventions-to-mitigate-15c-climate-overshoot-new-report

[88] hpnas.org/doi/10.1073/pnas.1809600115

[89] agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022EF002880

[90] un.org/sg/en/content/sg/statement/2023-02-14/secretary-generals-remarks-the-security-council-debate-sea-level-rise-implications-for-international-peace-and-security

What scientists say about the climate goal

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."[91]

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 the Greenland Ice Sheet, West Antarctic Ice Sheet, Tropical Coral Reefs and Abrupt Boreal Permafrost, and get more floods, droughts, heat, disease, storms."[92]

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."[93]

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."[94]

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."[95]

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."[96]

Melting polar glaciers will be the largest driver of rising sea levels. Glaciologist John Moore says the only way of preventing the collapse of polar glaciers is to physically stabilise the ice sheets. A good example is West Antarctica's Thwaites Glacier which he says is in a state of "geometric instability... there is a ball at the top of the hill and it has started to roll down, it doesn't matter what the temperature is, the ball doesn't care...".[97]

In this case, system hysteresis means that a moderate cooling will not prevent further ice-mass loss, as discussed above. Conditions may have to return to pre-industrial conditions to halt ice-mass loss

[91] columbia.edu/~jeh1/mailings/2021/NovemberTUpdate+BigClimateShort.23December2021.pdf
[92] twitter.com/jrockstrom/status/1584811163329523712
[93] link.springer.com/chapter/10.1007/978-3-030-78795-0_2
[94] newscientist.com/article/mg20126971-700-how-to-survive-the-coming-century/
[95] phys.org/news/2021-06-carbon-emissions-expert.html
[96] breakthroughonline.org.au/dor
[97] climatecodered.org/2022/06/we-need-to-talk-about-climate.html

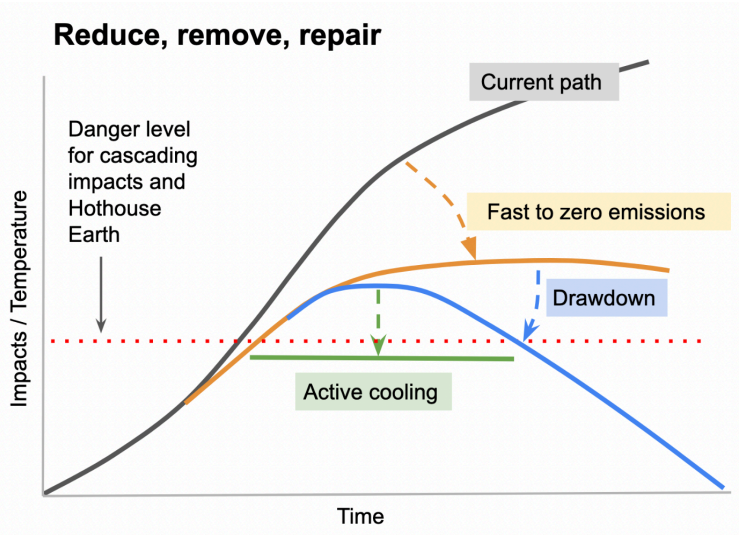
and stabilise the system. Thus the crucial short-term climate intervention, if it can be proved technologically safe and ready, may be glacial engineering to physically slow the processes leading to ice sheet disintegration.

On top of a zero-emissions regime, large-scale carbon drawdown is essential in achieving the goal of returning to the pre-industrial CO_2 level, 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 an additional 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 by changing the Earth system's reflectivity, known as albedo management. This includes options such as marine cloud brightening and solar radiation management cooling. The latter, 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.[98]

There are two big near-term risks that demand a path of rapid decarbonization to zero emissions **and** climate interventions to cool or preserve systems:

- Overshoot leading to irreversibility of major impacts and systemic changes.
- 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.[99]



As illustrated,[100] 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.

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 within the next decade (nor 2˚C in all likelihood), regardless of the emissions path.

There is no silver bullet. A diverse range of "reduce, remove, repair, reflect" actions are necessary to seek maximum protection for all people and species by preventing a cascade of adverse events, reversing global warming and returning to safe climate conditions.

[98] annualreviews.org/doi/abs/10.1146/annurev-earth-042711-105548
[99] pnas.org/doi/10.1073/pnas.1810141115
[100] Adapted from royalsocietypublishing.org/doi/10.1098/rsta.2016.0454

This is a complex and unfamiliar objective, with many potential risks and a large number of difficult scientific, technical, social and ethical questions. It is a matter of weighing benefits and costs, and of managing existential risks:

- Can a safe climate be achieved, in the next 100 years, if climate actions involve only the elimination of greenhouse gas emissions?
- Are unacceptable, dangerous near-term climate impacts likely in the absence of climate interventions?
- What measures and technologies could be safely deployed to return critical elements of the climate system to a viable and stable state? And under what circumstances would these need to be deployed?
- Are proposed climate interventions feasible in terms of their material and energy inputs?
- Will delay in researching and deploying climate interventions degrade their usefulness?
- Which authorities would need to allow the deployment of these measures, and what are, amongst others, the legal, economic, political and ethical implications of this?
- And finally, what are the risks in a world with albedo modification, and without, by relying on decarbonisation only?

Above all, we need new global leadership which accepts that climate change is real and that the risks have been badly underestimated; that historic inaction means that it is now uncontrollable without rapid collective action globally; and that it is the greatest threat facing humanity, far outweighing conventional geopolitics. Emergency action must be taken accordingly.