

Addendum B: Cooling to Save the Ice, and Lives

How much cooling the Arctic, Greenland, Antarctica and the Himalayas need, a suite of plausible measures, the lives at stake, and the risks of acting · October 2026

Overview

Addendum A showed that cutting emissions cannot save the lives of the next 25 years, and that net zero alone leaves the death toll stuck on a high plateau. This addendum asks the harder question. If the world deliberately cooled the planet, how much cooling would the frozen regions need, how many lives could it save, and what risks would today's residents of Earth have to accept to get there?

The published science is now good enough to answer the first question in rough terms. The ice sets three targets, which this addendum treats as a ladder. Holding **1.5 °C** keeps the Paris limit but leaves every ice region still shrinking. Returning to about **1.0 °C**, roughly the climate of the early 2000s, is what glaciologists now call the likely 'safe limit' for the ice sheets. Returning to about **0.6 °C**, the climate of the 1980s, is when Greenland was last near balance and the Arctic still had its old summer ice. On the realistic net-zero path, that means cooling the planet by 1.1 to 1.6 °C and holding it there indefinitely. With large-scale CO₂ removal underneath, the same cooling is needed for only a few decades, as a bridge.

The lives at stake are large. Cooling to 1.0 °C on the realistic path would save roughly 41 million lives by 2100 after allowing for the aerosols' own side effects, and cooling to 0.6 °C about 46 million. Unlike emission cuts, cooling also reaches the next 25 years, saving about 3.5 million of the lives Addendum A found otherwise locked in before 2050.

The risks are just as real. The most serious is the **termination shock**. If a cooling program on the realistic path stopped suddenly in 2070, the planet would warm about 0.9 °C in six years and some 19 million of the lives saved would be lost again. With CO₂ removal underneath, the same halt costs about 0.25 °C and about 1 million lives. Cooling is safest as a bridge to removal, not as a substitute for it.

This addendum does not price any of this; costs are endlessly debated and beside the point. It sets out what would be risked, what would be committed, and how many lives hang on the answer.

1. How much cooling does the ice need?

Each frozen region responds to warming differently and on its own timescale. Arctic sea ice responds within years and has no known tipping point, so it would regrow if temperatures fell. Ice sheets respond over centuries and may not regrow at all once lost. Mountain glaciers sit in between. The table summarizes what each region needs and what each rung of the ladder would buy.

Region	What the science says	Hold 1.5 °C	Return to 1.0 °C	Return to 0.6 °C
Arctic sea ice	Loss is reversible and tracks global temperature. Summer minimum was about 7 million km ² in the early 1980s; recent years are about 4–5 million km ² .	Summers with little ice remain possible; loss slows but continues.	Recovers toward the summer ice of the 2000s within a decade or two.	Recovers toward the 1980s, about 7 million km ² in September.
Greenland ice sheet	Near balance from 1972 to 1990; lost about 286 billion tonnes a year in the 2010s. Tipping estimated at about 1.5 °C (range 0.8–3 °C).	Heavy loss continues; sits on the central tipping estimate.	Loss slows but continues, roughly at the pace of the 2000s.	Close to balance, as in 1972–1990. Lost ice does not return for centuries.
West Antarctic ice sheet	Melting driven by warm ocean water. Faster melting this century is now unavoidable even at 1.5 °C (Naughten et al. 2023). Holds up to 5 m of sea level.	Melting roughly triples relative to the 20th century.	Slows the long-term rate; the ocean responds over decades to centuries.	Best chance of stabilizing, but recovery takes hundreds to thousands of years.
Himalayan glaciers	Feed rivers for more than 1.6 billion people. Glaciers lost ice 65% faster in the 2010s than the 2000s; worldwide, about 39% of glacier ice is already committed to melt at today's temperature.	Lose 30–50% of volume by 2100 (ICIMOD 2023).	Loss slows sharply; smaller glaciers still disappear.	Loss slows further, but glaciers have retreated since the 1800s; halting them fully needs near pre-industrial temperatures.

Three conclusions follow. First, **1.5 °C is not enough for the ice**: every region keeps losing mass. Second, **the Arctic and Greenland need roughly 0.6 °C**, about 0.8 °C cooler than today. Third, **West Antarctica and the Himalayas cannot be fully saved by cooling alone** on any human timescale; cooling slows the loss and buys time, which for coastal and mountain communities is worth a great deal.

2. The cooling ladder

How Much Cooling? A Ladder of Targets

Warming above 1850–1900 with cooling added from 2035 to hold 1.5, 1.0 or 0.6 °C, and the sulfur dioxide stratospheric aerosol program would need each year.

Cooling needed, realistic path

1.1–1.6 °C

to reach 1.0 or 0.6 °C; held indefinitely

Sulfur dioxide, realistic path

~10–14 Mt/yr

range 9–25; Pinatubo released ~15–20 Mt once

With CO₂ removal, 1.0 °C rung

ends ~2079

cooling is a bridge, not a permanent crutch

Greenland last near balance

~0.3–0.6 °C

1972–1990 (Mouginot et al. 2019)



Same coupled model as Addendum A. Cooling is a negative radiative forcing, ramped by at most 0.1 W/m² a year from 2035 and adjusted each year to hold the target. Sulfur dioxide uses ~0.11 °C of cooling per million tonnes a year (GeoMIP G6-1.5K-SAI, Lee et al. 2026; range 8–16 Mt per °C). Not modeled: regional patterns of cooling, rainfall changes, ice-sheet dynamics. Illustrative, not a forecast.

Figure B1 · Warming with cooling added, and the sulfur dioxide needed (full size on page 8)

Figure B1 runs each rung of the ladder through the same coupled model as Addendum A. Cooling starts in 2035, the year carbon removal begins in the second briefing, and is ramped up gradually and adjusted each year to hold the target.

- **On the realistic net-zero path** (panel 1), holding 1.5 °C takes about 0.6 °C of cooling, reaching 1.0 °C takes about 1.1 °C, and reaching 0.6 °C takes about 1.6 °C. Because CO₂ stays high, the cooling never ends: it must be maintained into the next century and beyond.
- **With CO₂ removal** (panel 2), less cooling is needed and it is temporary. On the 1.0 °C rung it peaks at about 0.9 °C in the 2050s and ends around 2079, as removal does the job for good. Only the 0.6 °C rung needs a small residual effort after 2085.
- **The scale** (panels 3 and 4). Using stratospheric aerosols, the realistic path needs about 10 million tonnes of sulfur dioxide a year for the 1.0 °C rung and 14 million for the 0.6 °C rung (range 9–25). Mount Pinatubo released about 15–20 million tonnes once in 1991 and cooled the planet about 0.5 °C for two years. The 0.6 °C rung amounts to most of a Pinatubo every year, indefinitely.
- **The pace.** Reaching 1.0 or 0.6 °C means cooling at about 0.4–0.5 °C a decade, faster than today's warming of about 0.27 °C a decade. Rapid change in either direction strains ecosystems and farming, so a slower descent would be wiser in practice and would save somewhat fewer lives.

3. A suite of plausible measures

No single measure can do all of this. Global cooling can only come from reflecting a little more sunlight; regional measures can add protection where the ice is most exposed. All of them remain experimental. The suite below is ordered from global to local; none is a substitute for cutting emissions and removing CO₂.

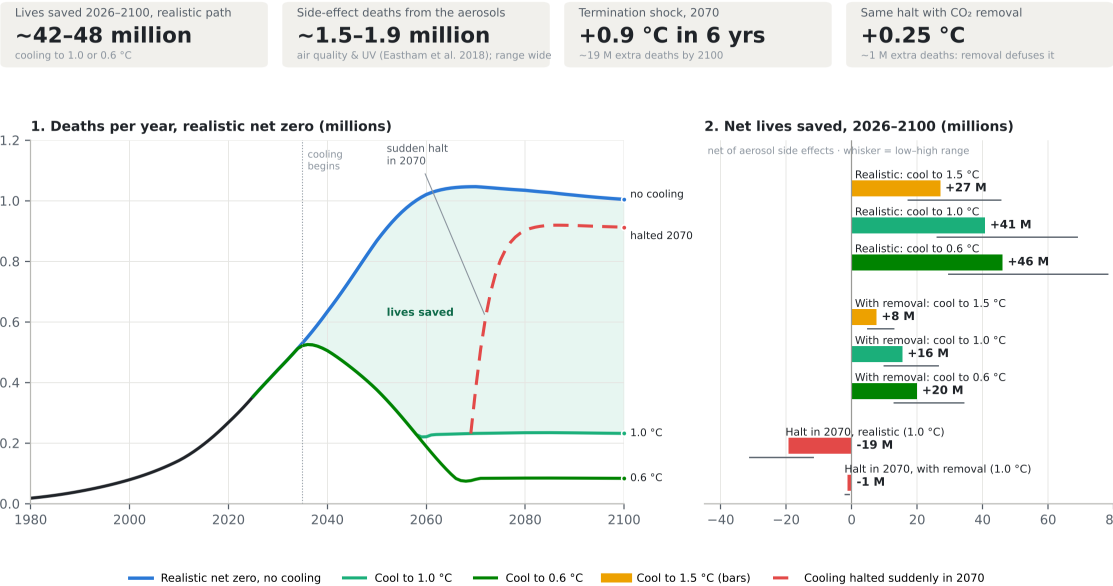
Measure	What it does	Reach	Readiness	Main concerns
Stratospheric aerosol injection	Aircraft release sulfur dioxide at 18–25 km; the resulting haze reflects about 1% of sunlight.	Global; the backbone of any program at this scale.	Computer models and volcanic analogues only; no outdoor tests at scale.	Termination shock, rainfall and monsoon shifts, ozone loss, governance.
Subpolar aerosol injection	The same haze released at around 60° north and south, at lower altitudes, to cool the poles.	Polar; studied as a way to cool the Arctic and Antarctic by about 2 °C (Smith et al. 2022).	Design studies only; needs a purpose-built aircraft fleet.	Same as above; spillover to rainfall in the tropics.
Marine cloud brightening	Ships spray fine sea-salt mist to make low clouds whiter and more reflective.	Regional; could target oceans upwind of ice or reefs.	Small field trials on the Great Barrier Reef.	Uncertain cloud response; regional weather effects.
Arctic sea-ice thickening	Pumps seawater onto winter ice so it freezes thicker and survives the summer.	Local; would need millions of pumps to matter Arctic-wide.	Field trials in Nunavut, Canada (UK ARIA program, 2025–).	Energy demand, scale, local ecology.
Seabed curtains and basal water removal	Barriers on the seafloor block warm water from Antarctic and Greenland outlet glaciers; pumping melt water from under glaciers slows their slide.	A few critical glaciers, such as Thwaites.	Concept and early engineering studies.	Extreme engineering in polar seas; unknown side effects.
Himalayan measures	Ice stupas (artificial winter glaciers), reflective covers on glacier tongues, protecting snow from soot.	Very local; protects water supply in valleys rather than whole glaciers.	Used in Ladakh and the Alps today.	Small scale; no effect on global warming.

A sober counterweight: a 2025 assessment of five polar engineering ideas by Siegert and colleagues concluded that none holds up as a fix. They found sea curtains, ice thickening and basal pumping technically infeasible at the scale needed and environmentally risky. In their view, cutting emissions remains the clearest way to protect the poles. Only the global measures can deliver cooling of the size this addendum describes, and they carry the largest risks.

4. The lives cooling could save

Lives Saved by Cooling, and the Risk of Stopping

Climate-attributable deaths (Addendum A method) with cooling added; a sudden halt in 2070 shows the termination shock.



Deaths = population × k × warming² (Addendum A; Bressler 2021 to Carleton et al. 2022). Treats cooled degrees like avoided degrees, which is optimistic; aerosol cooling does not reproduce a low-CO₂ climate region by region. Excludes rainfall and monsoon shifts, sea-level and tipping-point deaths. Illustrative, not a forecast.

Figure B2 · Lives saved by cooling, and the termination shock (full size on page 9)

Base path + cooling	Cooling needed	SO ₂ (Mt/yr)	Deaths 2026–2100	Net lives saved (range)
Realistic net zero, no cooling	–	–	66 M	–
+ hold 1.5 °C	0.6 °C, forever	~6	38 M	27 M (17–45)
+ return to 1.0 °C	1.1 °C, forever	~10	24 M	41 M (26–69)
+ return to 0.6 °C	1.6 °C, forever	~14	18 M	46 M (30–78)
Net zero + CO ₂ removal, no cooling	–	–	37 M	–
+ hold 1.5 °C	0.4 °C, ends ~2068	~4	30 M	8 M (5–13)
+ return to 1.0 °C	0.9 °C, ends ~2079	~8	21 M	16 M (10–26)
+ return to 0.6 °C	1.25 °C, small after 2085	~11	16 M	20 M (13–34)

Cooling and SO₂ are peak values. Net lives saved subtract the aerosols' estimated air-quality and UV deaths; ranges use the low and high mortality coefficients of Addendum A. M = million.

Key insights

- **Cooling is the only lever that reaches the next 25 years.** Addendum A found about 15 million deaths locked in before 2050 on every emissions path. Cooling from 2035 brings that down to about 11.5 million.
- **The first degree saves the most.** Going from 2.1 to 1.0 °C on the realistic path saves about 41 million lives; the next 0.4 °C adds about 5 million more. The case for the lowest rung rests on the ice, sea level and tipping points, which this count leaves out, rather than on heat deaths.
- **Removal plus cooling beats either alone.** Net zero with removal and cooling to 1.0 °C has the lowest toll of the paths that end their cooling, about 21 million, and the smallest termination risk.
- **The aerosols' own toll is real but small by comparison:** about 1.5–1.9 million deaths over the century from air pollution and UV changes (Eastham et al. 2018, a wide and uncertain range), against tens of millions saved.

5. The risks today's residents of Earth would take

Risk	What could happen	How large
Termination shock	If the program stops suddenly through war, collapse or political decision, the masked warming returns within a few years.	Realistic path, halt in 2070: about +0.9 °C in six years and some 19 million extra deaths. With removal underneath: about +0.25 °C.
Rainfall and monsoons	Dimming sunlight weakens the water cycle; poorly designed programs could shift monsoons that billions depend on.	Depends strongly on where and how aerosols are released; the largest scientific uncertainty.
Ozone layer	Sulfate particles speed up the chemistry that destroys ozone.	Could delay recovery of the Antarctic ozone hole by decades (Tilmes et al. 2008).
Air quality and UV	Aerosols eventually settle; thinner ozone lets in more UV.	About 26,000 net extra deaths a year per °C of cooling (range –30,000 to +79,000).
Ocean acidification	Cooling does nothing about CO ₂ itself; the oceans keep acidifying.	Unchanged unless CO ₂ is cut and removed.
Moral hazard	Cooling could become an excuse to slow emission cuts, making the dependence permanent.	Without removal, the realistic path needs cooling forever.
Governance and conflict	One country or coalition could set the planet's thermostat for everyone; harms from a drought or a failed monsoon would be blamed on it.	No international framework exists. UN talks in 2024 failed to agree; Mexico banned experiments in 2023.

At what treasure? The question for the present residents of Earth

Set the price tag aside. The real treasure such a program would demand is not money but **commitment and trust**. It would have to run, without a break, for decades if paired with CO₂ removal and for centuries if not. It would need institutions able to decide, for every nation, how cool the world should be. And it would pass to our children a planet whose climate depends on a program they did not choose and cannot safely stop.

Against that stands the ledger of lives. Roughly 40 million deaths could be avoided this century from heat alone, plus the ice, the coastlines and the water supplies that the death count leaves out. Today some 110 million people live on land below the high-tide line, protected by sea walls and pumps (Kulp and Strauss 2019); every meter of ice-sheet loss adds to them. The question this addendum leaves with its readers is whether the present generation is willing to take on a risk it can manage, in order to spare future generations a loss they could never undo. If it is, the evidence points to cooling only as a bridge: alongside deep emission cuts and large-scale CO₂ removal, never instead of them.

Caveats

- Cooled degrees are treated like avoided degrees. Aerosol cooling does not reproduce a low-CO₂ climate region by region, so lives saved may be overstated in some places and understated in others.
- The ice outcomes are judgments drawn from published thresholds, not ice-sheet model runs. Ice sheets respond over centuries, and some losses in West Antarctica may already be committed.
- Sea-level, flood, drought, crop and tipping-point deaths remain outside the count, as in Addendum A. All results are illustrative models built from published sources, not forecasts.

Sources

Stokes, C. R. et al., "Warming of +1.5 °C is too high for polar ice sheets," *Communications Earth & Environment* (2025). Mouginot, J. et al., "Forty-six years of Greenland Ice Sheet mass balance," *PNAS* (2019). Armstrong McKay, D. I. et al., "Exceeding 1.5 °C global warming could trigger multiple climate tipping points," *Science* (2022). Naughten, K. A. et al., "Unavoidable future increase in West Antarctic ice-shelf melting," *Nature Climate Change* (2023). Zekollari, H. et al., "Glacier preservation doubled by limiting warming to 1.5 °C versus 2.7 °C," *Science* (2025). ICIMOD, *Water, Ice, Society, and Ecosystems in the Hindu Kush Himalaya* (2023). IPCC AR6 WG I (2021). Met Office Hadley Centre, *A seasonally ice-free Arctic*. Lee, W. R. et al., GeoMIP G6-1.5K-SAI, *Atmos. Chem. Phys.* (2026). Smith, W. et al., "A subpolar-focused stratospheric aerosol injection deployment scenario," *Environ. Res. Commun.* (2022). Eastham, S. D. et al., "Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure," *Atmos. Environ.* (2018). Tilmes, S. et al., "The sensitivity of polar ozone depletion to proposed geoengineering schemes," *Science* (2008). Trisos, C. H. et al., *Nature Ecology & Evolution* (2018). Siegert, M. et al., polar geoengineering assessment, *Frontiers in Science* (2025). UNEP, *One Atmosphere* (2023). Royal Society, *Solar radiation modification* (2025). ARIA, *Exploring Climate Cooling programme (2025–2026)*. Kulp, S. A. and Strauss, B. H., *Nature Communications* (2019). Companion documents: *The Road to Net Zero, Net Zero Plus Carbon Removal* and *Addendum A: Climate-Related Deaths* (October 2026).

Figure B1 · How much cooling? A ladder of targets

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Warming above 1850–1900 with cooling added from 2035 to hold 1.5, 1.0 or 0.6 °C, and the sulfur dioxide a stratospheric aerosol program would need each year.

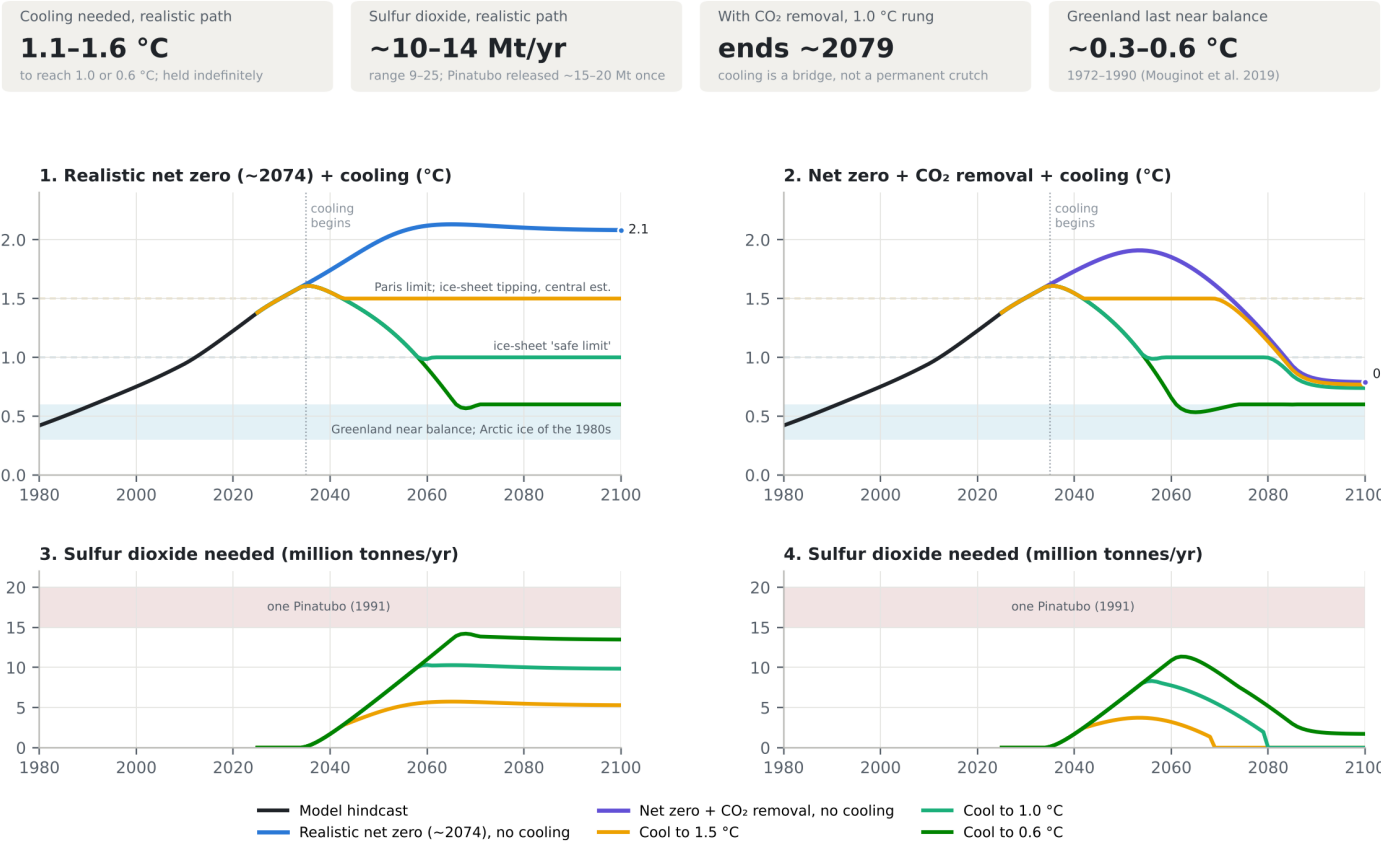
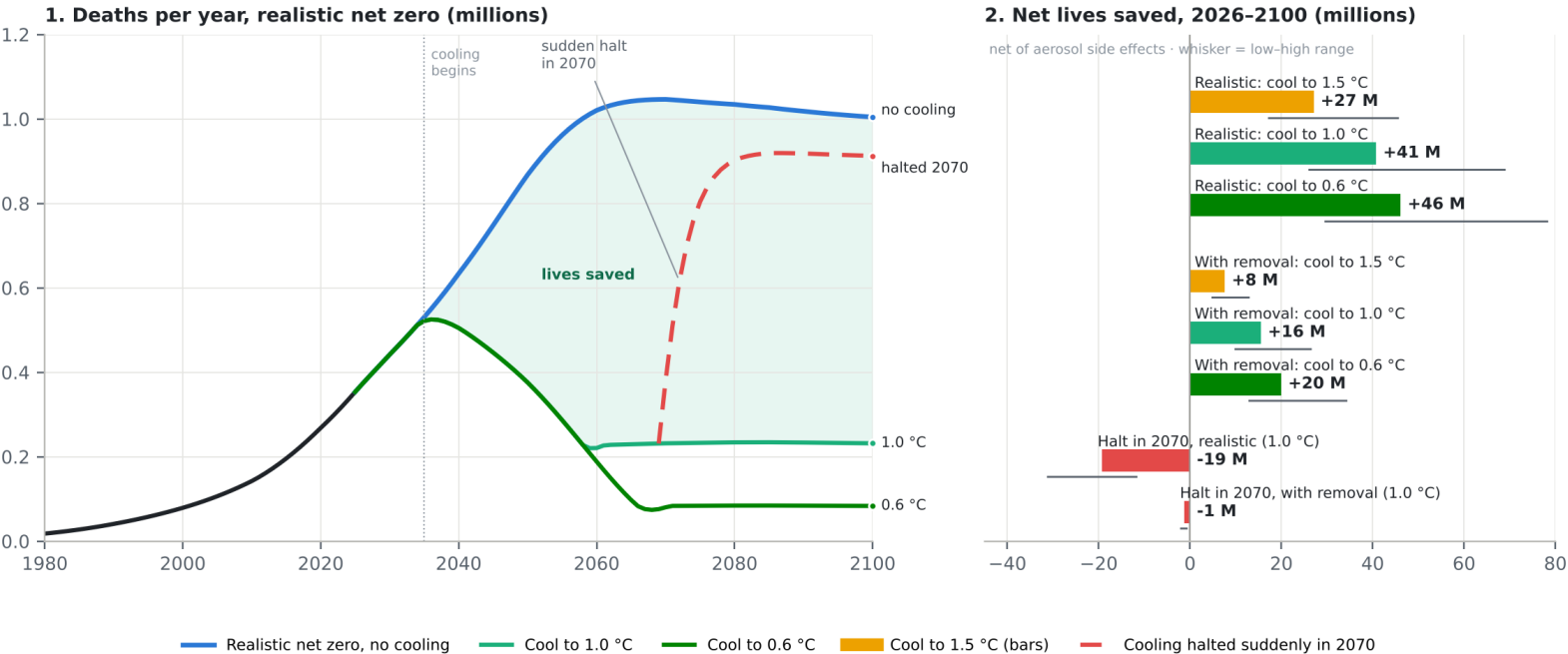
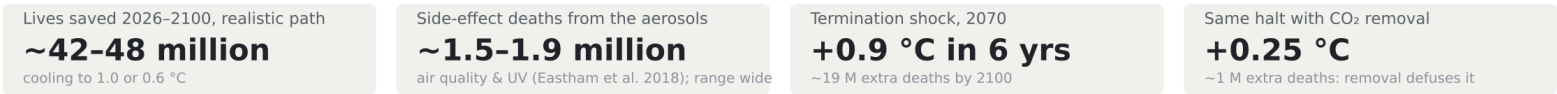


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