Solar radiation modification (SRM): technology and risks review

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Context

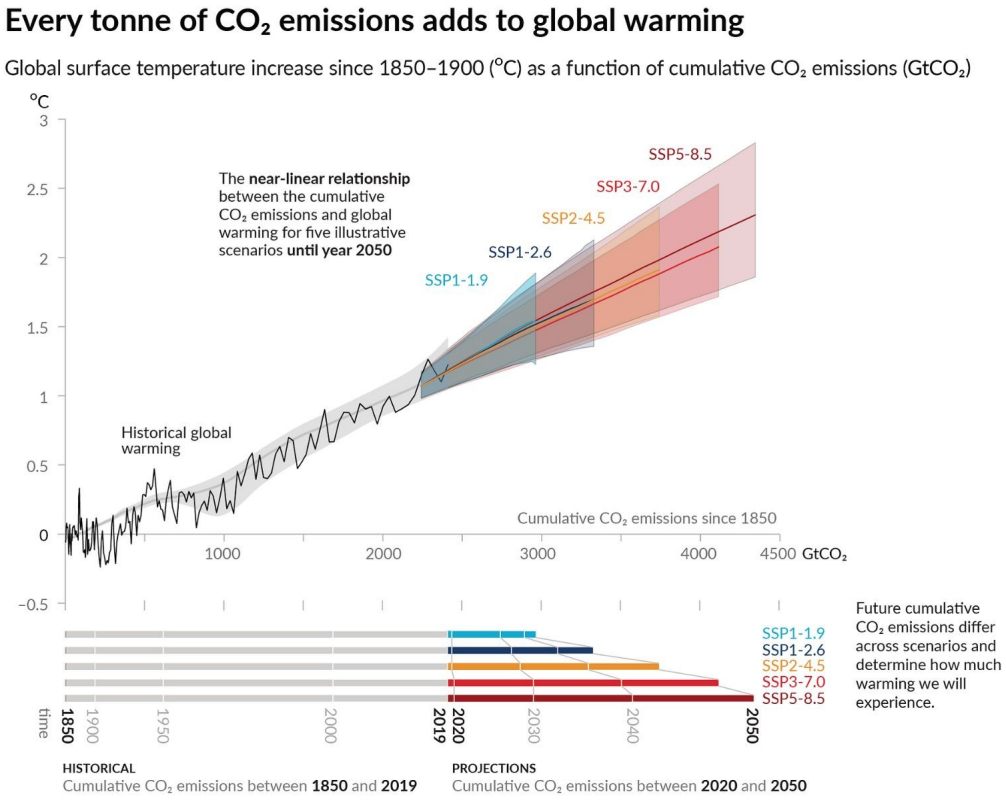
Impact of cumulative emissions

Transient Climate Response to cumulative Emissions (TCRE)

Global surface temperature increases near linearly with cumulative CO2 emissions. Every 1000 GtCO2 adds ≈ 0.45°C of warming.

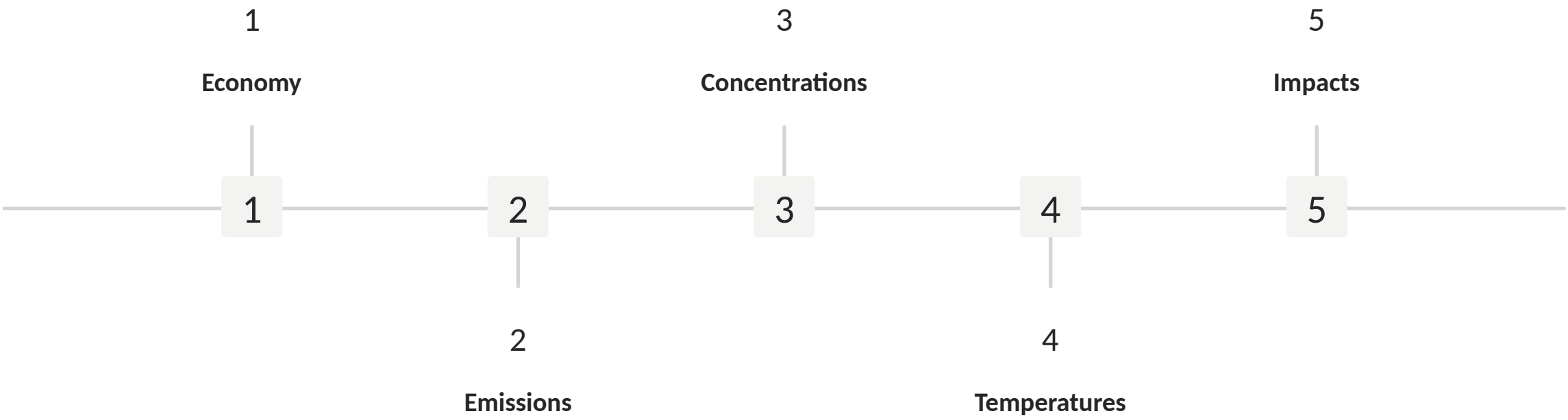
The bathtub

If we turn off the taps (emissions), the water level (concentrations) stops rising immediately, however the water level remains high (temperatures), and can still splash about and cause damage (impacts).



REF: IPCC AR6 Figure SPM.10

The causal chain of climate change



Key Climate Change Response Strategies

1. Decarbonisation

Energy (renewables, nuclear) and non energy related emissions generating activities (cement, agriculture) can break the link between the economy and future GHG emissions

2. Carbon removal

Technology (afforestation, enhanced weathering, ocean alkalinity, BECCS, DACS) can break the link between cumulative GHG emissions, and climate change

3. Solar radiation modification

in particular, sunlight reflection (stratospheric aerosols, marine cloud brightening) can break the link between atmospheric GHG concentrations and temperatures

4. Adaptation

Building infrastructure (sea walls, coastal defences, nature restoration, resilient infrastructure) can weaken the link between temperatures and impacts on human society and ecosystems

REF: Compton Lecture Series: Climate as a 4D Problem (David Keith)

Opportunities and risks for each response strategy

Strategy	Opportunities	Risks	Technological readiness
1. Decarbonisation	✓ Avoid worst impacts ✓ Economic innovation & jobs ✓ Health benefits	Transition disruption & stranded assets Political, economic and social impacts Fairness for developing countries	
2. Carbon removal	✓ Removes historical/residual emissions ✓ Potential ecosystem co-benefits	Moral hazard (license to continue burning fossil fuels) Permanence & land-use conflicts	
3. Solar radiation modification	✓ Rapid cooling potential in crisis ✓ Avoidance of tipping points	High uncertainty Governance risks & moral hazard Risk on rainfall patterns	
4. Adaptation	✓ Protects communities & assets ✓ Avoided damages > investment	Finance & capacity gaps Limits in extreme warming	

Solar Radiation Modification (SRM)

Natural phenomenon

Mount Pinatubo (1991)

The eruption of Mount Pinatubo (1991) in the Philippines was a catastrophic disaster and over 847 people lost their lives. Beyond the immediate devastation, the eruption had measurable global climate impacts.

Injection

The volcano blasted ≈ 20 million tons of sulfur dioxide straight into the Stratosphere (≈ 35 km).

Dispersal

The SO2 converted into a mist of sulfuric acid droplets (aerosols). This haze spread around the equator and then the globe.

Result

This aerosol layer reflected roughly 2.5% of incoming sunlight, causing average global temperatures to drop by 0.5°C (0.9°F) for about 15 months, almost identical to Krakatoa (in 1883).

REF: U.S. Geological Survey (via Wikipedia)

Human phenomenon

Shipping sulphates

The International Maritime Organisation (IMO) introduced limits to sulphur in fuels to protect against acid rain and related respiratory diseases. Sofiev et al. estimated ~400,000 premature deaths annually due to shipping fuels

Before 2020

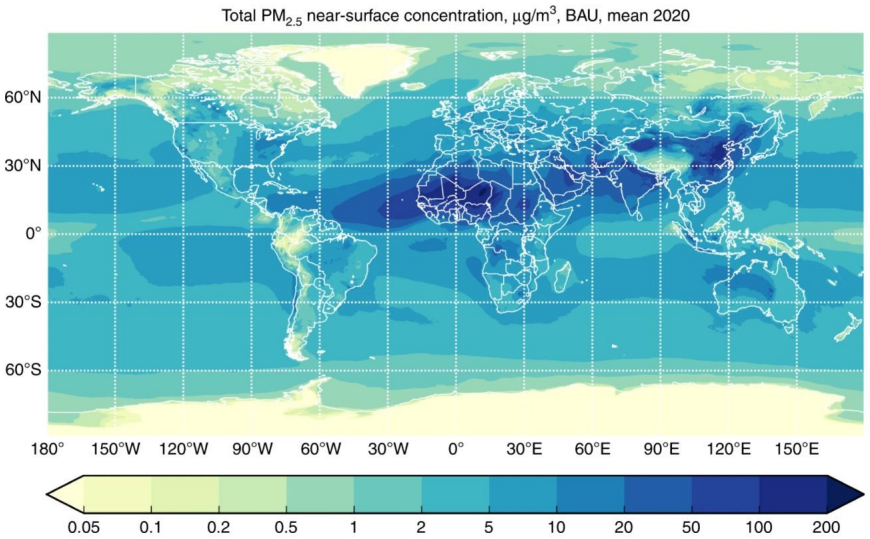
Ships burned high-sulphur fuel (up to 3.5% S). This emitted ~8 million tonnes of SO2 per year into the lower troposphere, producing reflective aerosols that had a measurable cooling effect, an unintended, unmanaged form of solar radiation modification.

After 2020

The IMO's 2020 regulation reduced sulphur limits to 0.5%, sharply cutting those emissions. Yuan et al. 2024 observed anomalous North Atlantic sea surface temperature increases shortly after, suggesting the regulation may have contributed.

Note: Extent of causal attribution to IMO 2020 is debated, 2023 North Atlantic temperatures also reflect El Nino and long-term warming.

From: Cleaner fuels for ships provide public health benefits with climate tradeoffs

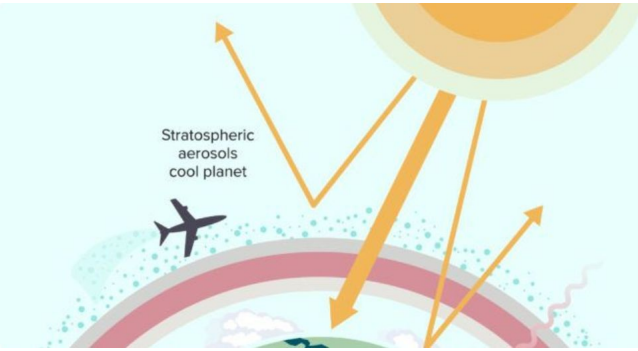


Mean annual $PM_{2.5}$ concentrations from all sources. Model results showing mean annual $PM_{2.5}$ concentrations in micrograms per cubic meter from all sources and with business-as-usual ship emissions in 2020

REF: Sofiev et al "Cleaner fuels for ships provide public health benefits with climate tradeoffs"

SRM technology

Stratospheric Aerosol Injection (SAI)



REF: Columbia Climate School

Mechanism

Aircraft inject SO2 or CaCO3 into the stratosphere (~20-25km). Oxidises to reflective sulphate aerosols, mimicking a volcanic eruption.

Scale and effect

Global. Stratospheric aerosols are swept around the world by atmospheric currents. Aerosols persist 1-2 years.

Reversibility

Requires continuous replenishment. Stopping abruptly causes rapid temperature rebound ("termination shock"), the defining risk.

Governance challenge

Intrinsically global, unilateral deployment by one nation alters all others' weather patterns. No international framework exists.

SRM technology

Marine Cloud Brightening (MCB)

Mechanism

Ships spray fine sea-salt aerosols into low marine clouds, increasing droplet density (Twomey effect), making clouds whiter and more reflective.

Scale and effect

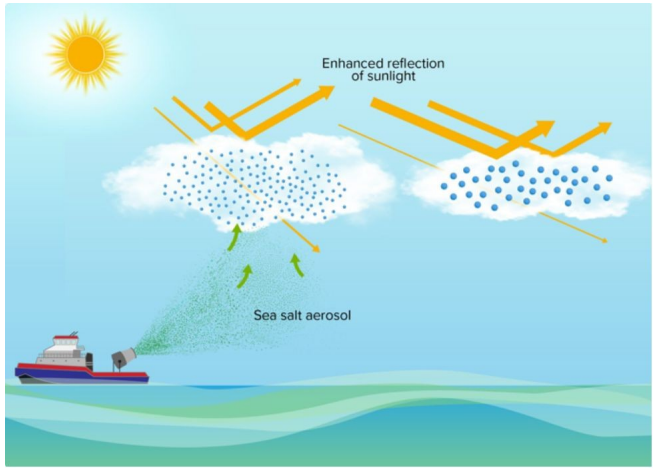
Regional to hemispheric. High uncertainty about downstream effects on regional precipitation patterns.

Reversibility

Highly reversible, effects dissipate within days of stopping. No termination shock equivalent. Expected lower risk profile than SAI.

Governance challenge

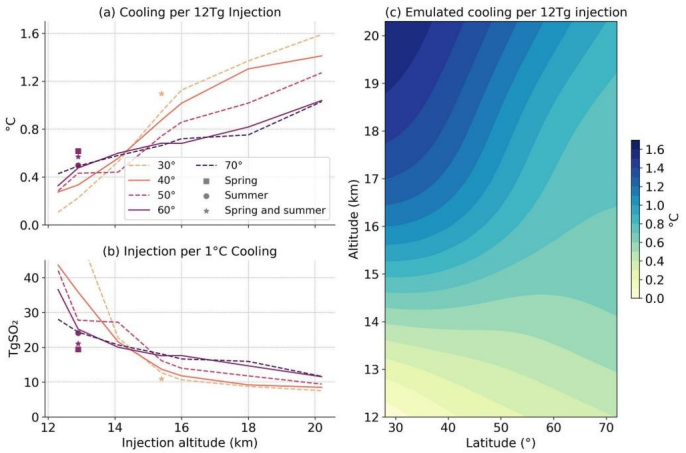
A single coastal nation could deploy unilaterally. Regional effects still cross borders, but governance is more tractable than for global SAI.



REF: Feingold et al "Physical science research needed to evaluate the viability and risks of marine cloud brightening"

The predicted cooling effect

Consensus across climate models predict that ~1–2°C of global mean cooling is achievable with continuous injection (REF: Geoengineering Model Intercomparison Project)



REF: Duffey et al. "Low-Altitude High-Latitude Stratospheric Aerosol Injection Is Feasible With Existing Aircraft"

Targeted cooling

Climate models consistently predict that SAI could be used to maintain global mean temperatures at specific targets, such as 1.5°C or 1.0°C above pre-industrial levels

Efficacy

Continuous injection of approximately 5 Tg S (roughly 10 Tg SO2) per year is projected to offset roughly half of the warming expected under high-emission scenarios.

How do we know?

Multiple independent climate models (from the US, UK, and Europe) converge on this ~1–2°C figure using the same 5 Tg S input. These models have a 50-year track record of predicting global mean warming in response to CO2 concentration increases with reasonable accuracy, although performance on atmospheric CO2 may not correlate to performance on stratospheric SO2.

Risks

Termination shock

1

SAI deployed

Temperatures stabilise or fall. CO2 continues rising in background.

2

SAI stops abruptly

Aerosol veil settles out within 1-2 years. Full CO2 forcing suddenly unmasked.

3

Rapid rebound

Temperatures rise at 2-4x background rate very rapidly. Ecosystems and societies have no time to adapt.

The lock-in problem

Once solar geoengineering is started at a scale sufficient to produce meaningful cooling, stopping becomes extremely dangerous, unless atmospheric CO2 has sufficiently also been reduced in parallel. This means SAI deployment likely creates a multi-generational commitment. Any geopolitical instability, war, or funding collapse that interrupts the programme could cause sudden, catastrophic warming.

REF: Jones et al. (2013), Nature Climate Change; Parker & Irvine (2018), ERL

Risks

Governance and deployment

There is currently no international governance framework for solar geoengineering. A UN Environment Assembly resolution on solar geoengineering governance failed to pass in 2024. The absence of rules does not prevent deployment.

Rogue state scenario

A nation facing existential climate risk, like low-lying islands, sub-Saharan drought zones, could plausibly decide to deploy solar geoengineering unilaterally. The technology is estimated to cost as little as $10 billion/year at scale, and technologically accessible to mid-size economies, though sustaining it against opposition from a major power is another matter (Horton et al., 2025). There is no treaty that prohibits it.

Regional winners and losers

Solar radiation modification cooling effects are not geographically uniform. Climate models consistently show differential impacts on regional precipitation, particularly the Asian and African monsoons. A deployment optimised for one region's climate could impair another's food security by altering rain patterns. There is no reason to expect winners and losers to agree to deployment.

Governance of research and deployment

Even governing outdoor experiments is contested. The SCoPEx stratospheric balloon experiment (Harvard, Kiruna, Sweden) was halted in 2021 after opposition from community groups, and abandoned in 2024. There is a large group of academics who have come out against any funding, research, experiments or deployment for the technology.

Normalising costs against carbon removal cost

To compare the feasibility of the potential response strategies, we can do a back of the envelope estimate of cost per ≈ 0.1C of warming. SAI is estimated to be 100x – 1000x cheaper than removal technologies.

The IPCC (AR6 WG1) state that global mean surface temperature is approximately linearly proportional to cumulative CO_2 emissions. They express this proportionality using the Transient Climate Response to cumulative Emissions (TCRE), which they give as 0.45C per 1000 GtCO2 (or 220 GTCO2e per 0.1C)

Technological removal cost (USD per tCO_2 removed)	Implied global cost to avoid ~0.1°C warming
$50	≈ $11 trillion
$100	≈ $22 trillion
$200	≈ $44 trillion
$1000	≈ $220 trillion

Global GDP, 2025 : $110 trillion

Limitations: These are **MASSIVELY UNCERTAIN**, global scale, order of magnitude estimates. They assume all CO2 removal occurs at the same cost; real world scenarios will deploy a mixture of carbon removal technologies, and learning curves may bring cost down.