Comparing stratospheric aerosol injection (SAI) and space-based sunshade (SBS) for solar radiation modification (SRM): Benefits, risks, costs, timing, governance

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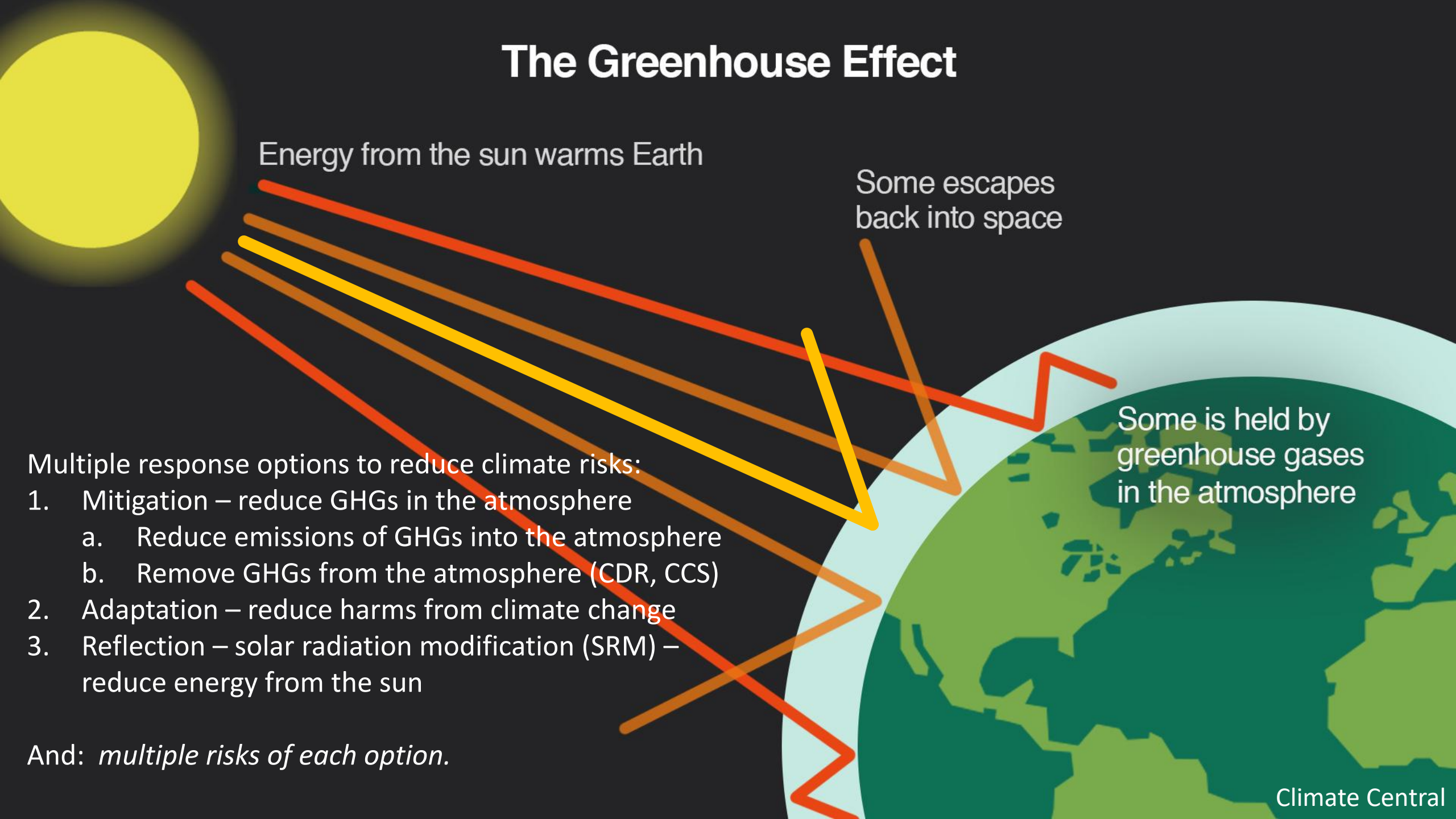
2026 RFF and Harvard SRM Social Science Research Workshop, Washington, DC, Sept. 10-11, 2026

Duke Center on Risk in Science & Society

Duke Space Initiative

The Greenhouse Effect

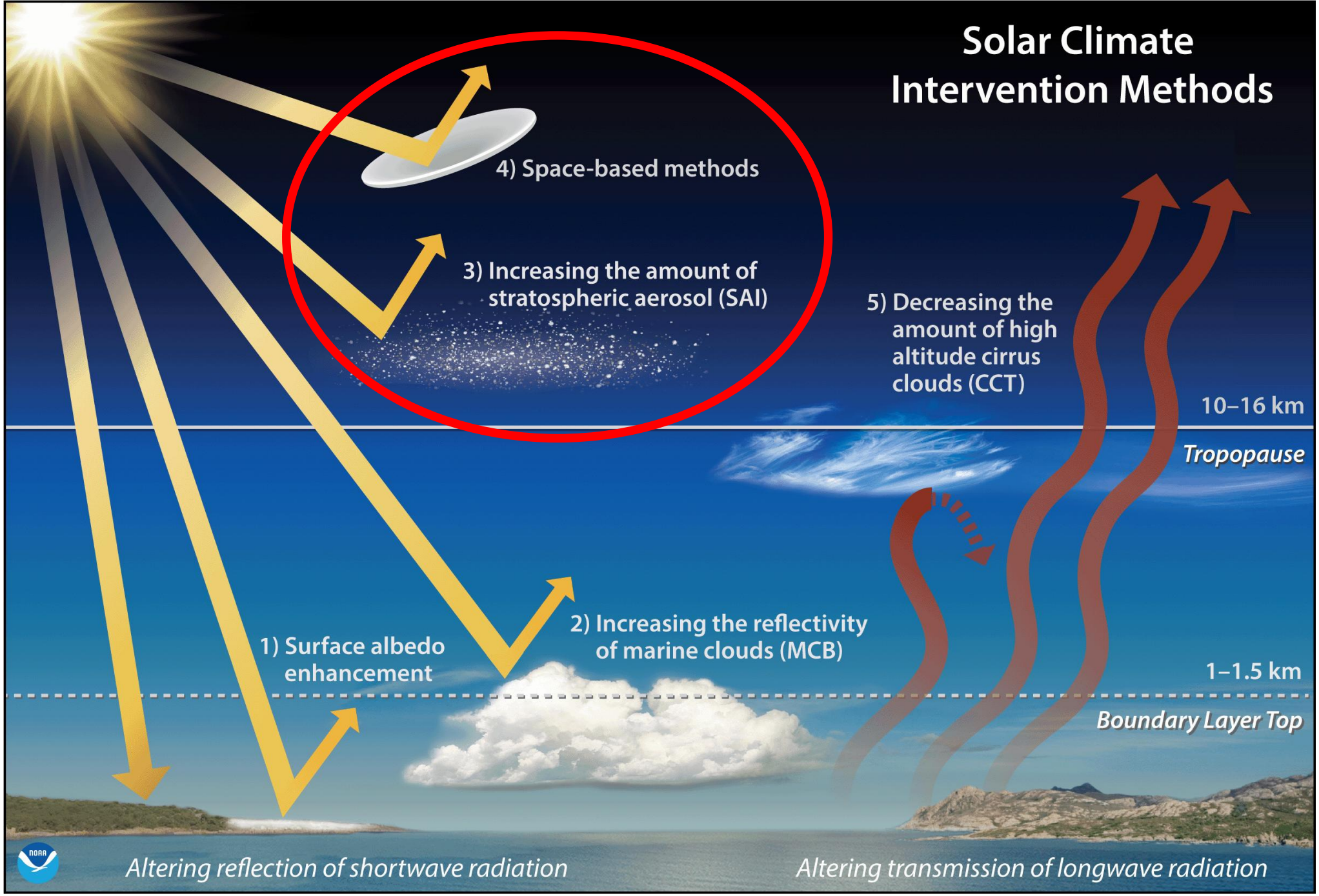


Multiple response options to reduce climate risks:

1. Mitigation – reduce GHGs in the atmosphere
   a. Reduce emissions of GHGs into the atmosphere
   b. Remove GHGs from the atmosphere (CDR, CCS)
2. Adaptation – reduce harms from climate change
3. Reflection – solar radiation modification (SRM) – reduce energy from the sun

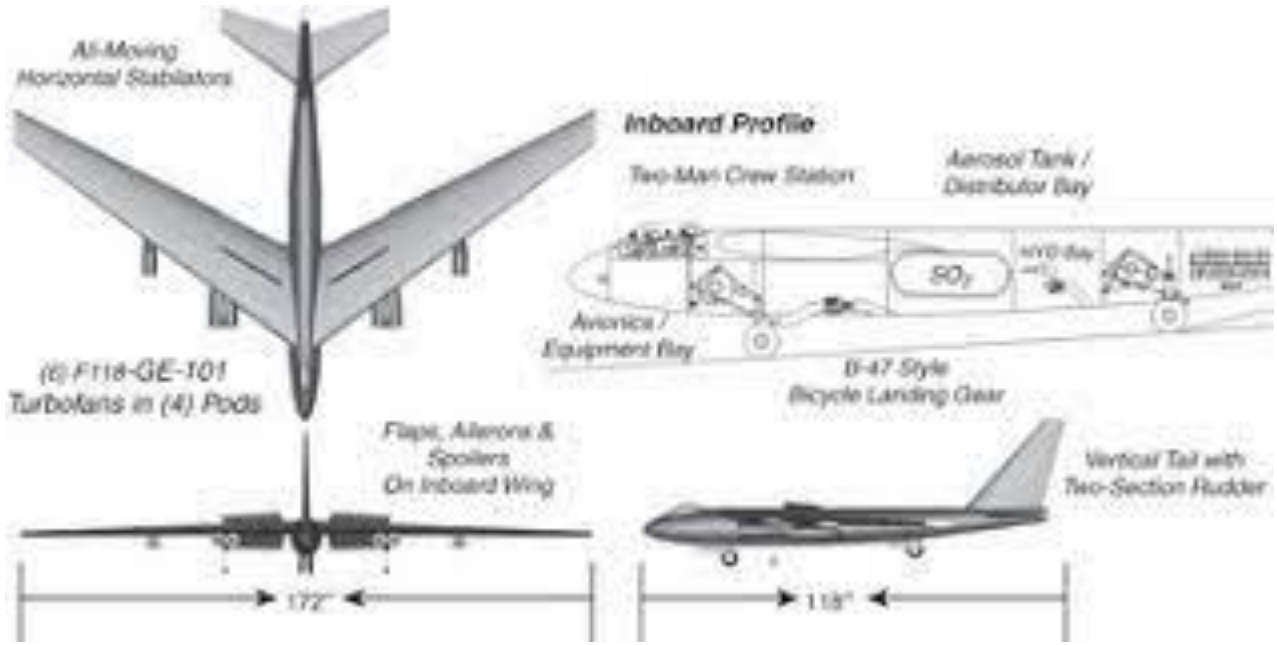
And: *multiple risks of each option.*

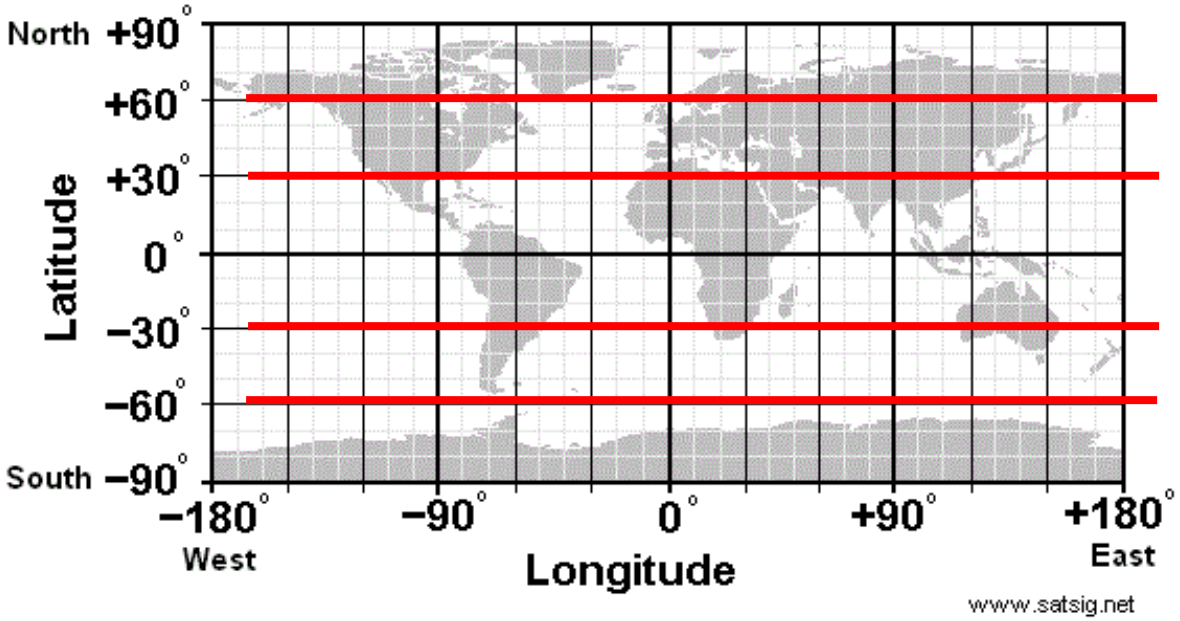
Climate Central

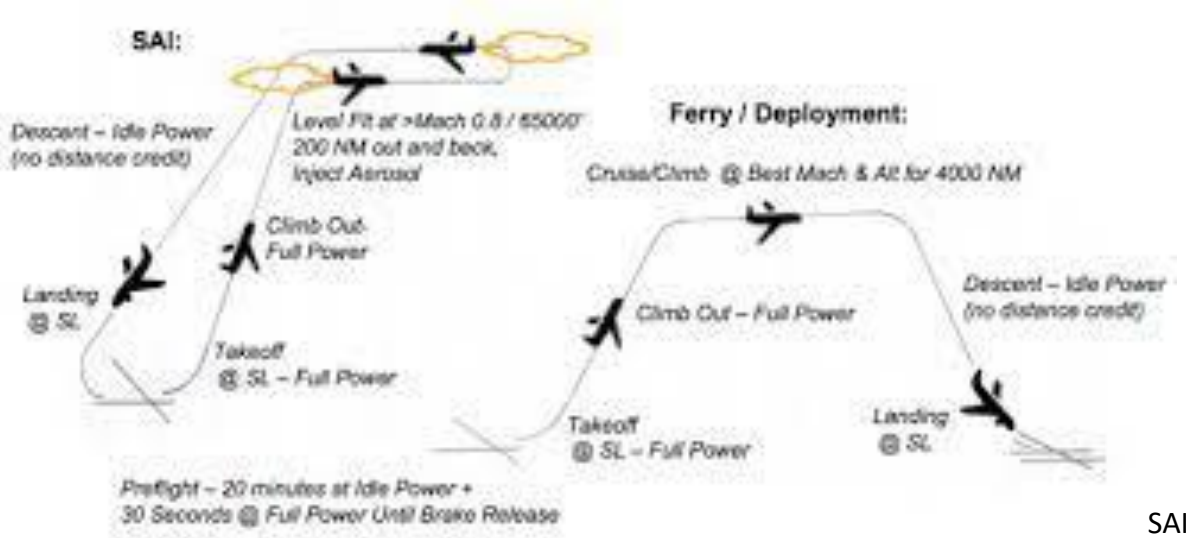


Chelsea Thompson, NOAA/CIRES - https://research.noaa.gov/News/Scientist-Profile/ArtMID/536/ArticleID/2758/Study-of-wildfire-plumes-provide-insights-into-methods-that-might-cool-the-planet

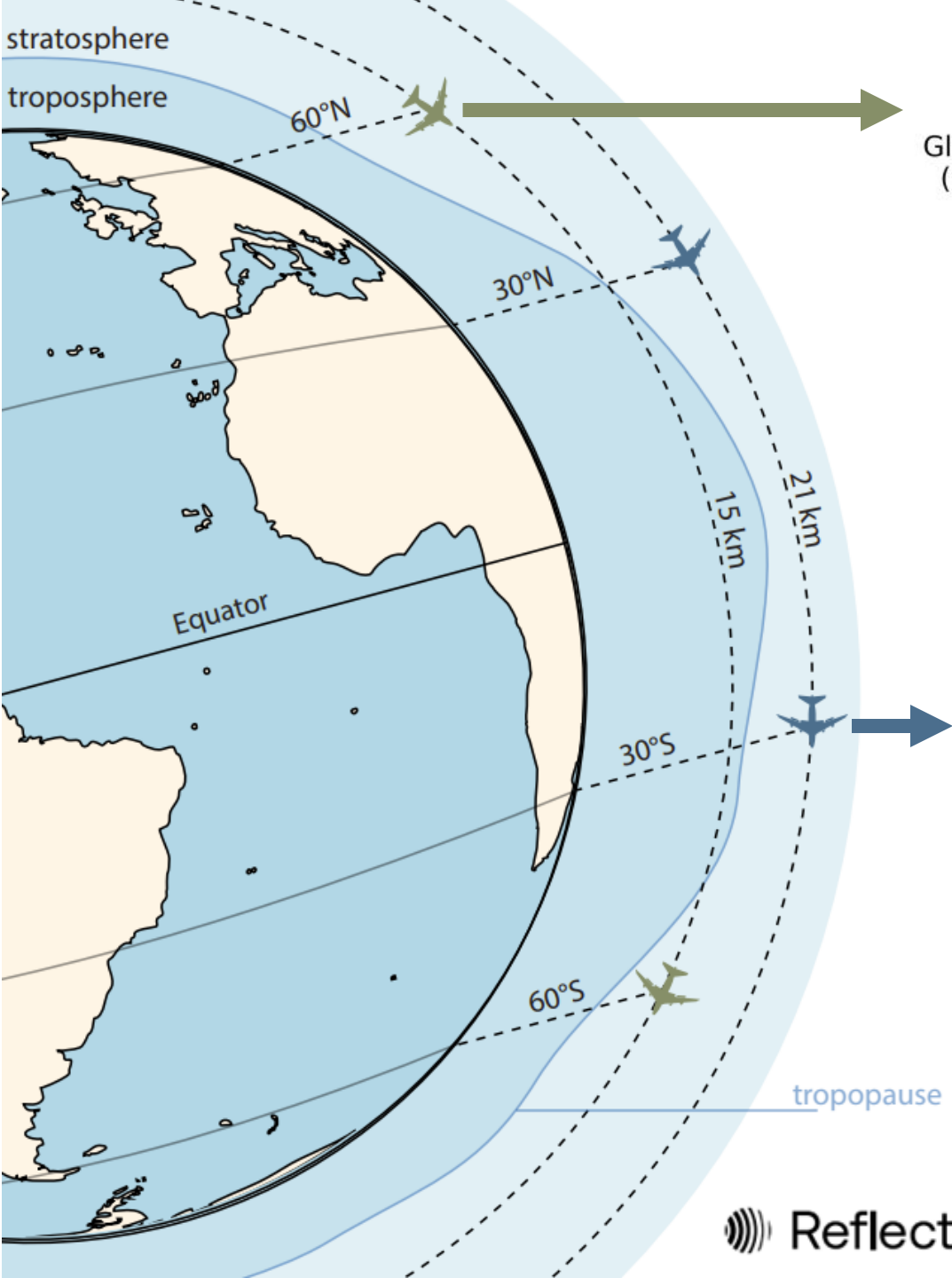
Stratospheric Aerosol Injection (SAI)

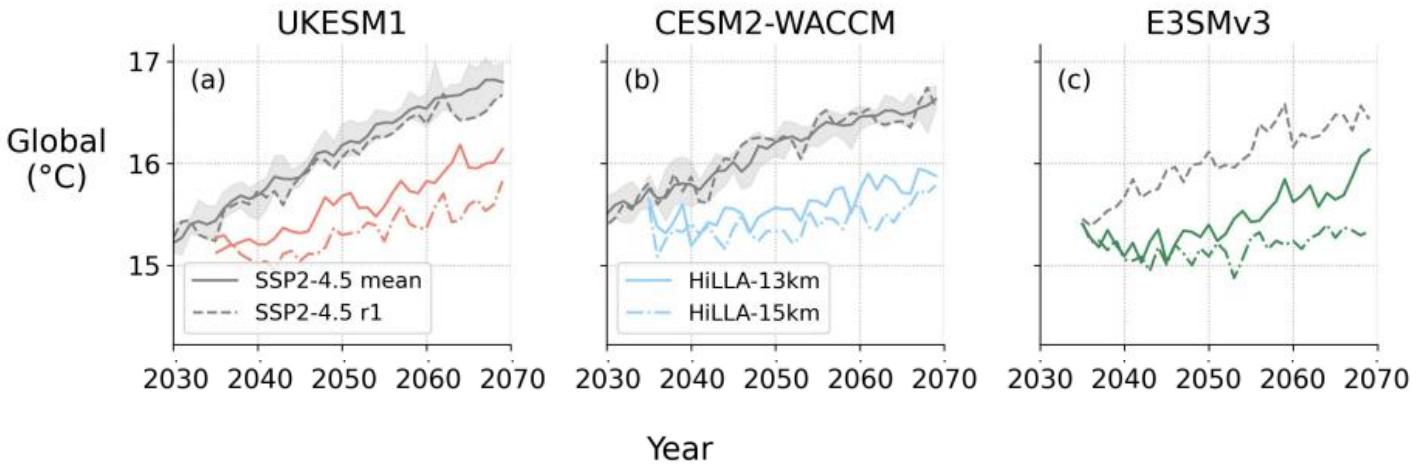




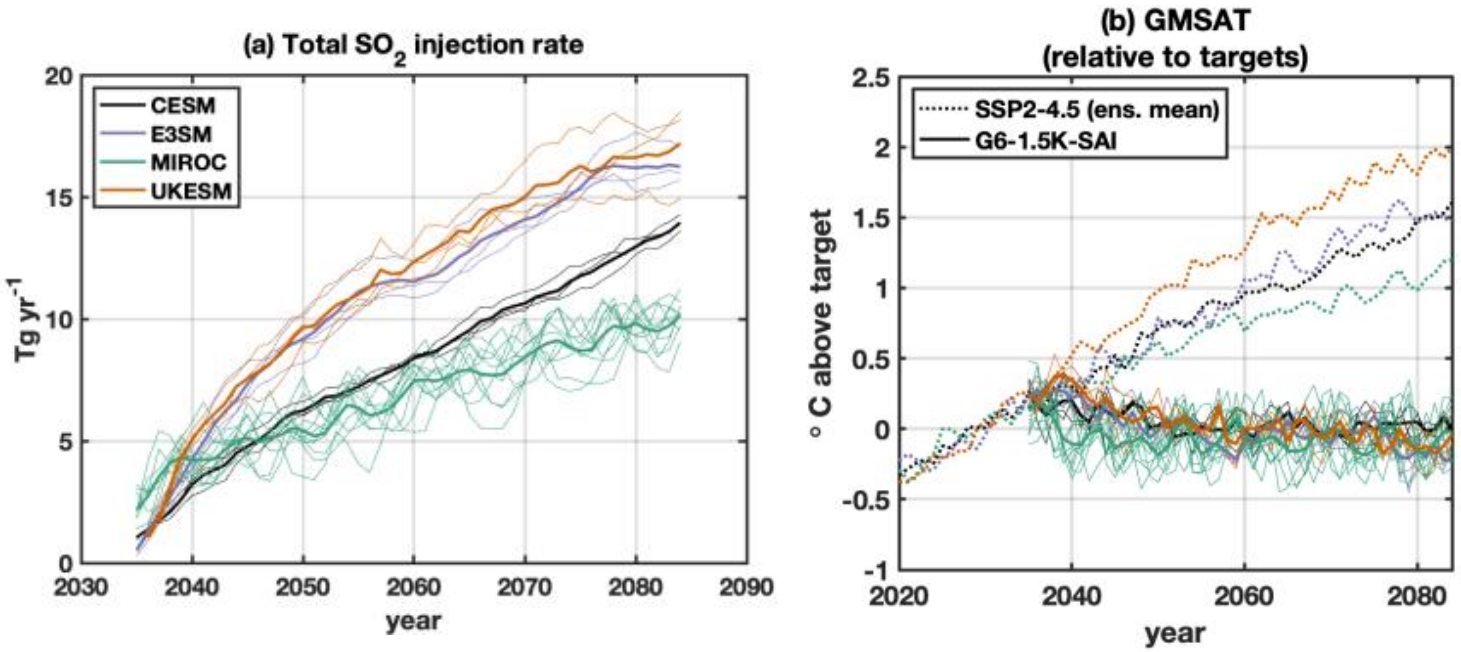


SAI lofter "SAIL" (above left) and mission profiles (below left) from Donald Bingaman and Christian Rice, reprinted in *Pandora's Toolbox: The Hopes and Hazards of Climate Intervention*, Wake Smith, 2022





Duffey, A., W. Lee, L. Wheeler, P. Irvine, B. Wagman, M. Henry, D. Visioni, M. Tsamados, and D. MacMartin. 2025. "The global climate response to High-Latitude Low-Altitude Stratospheric Aerosol Injection (HiLLA-SAI)." *EGUsphere 2025*: 1-41.

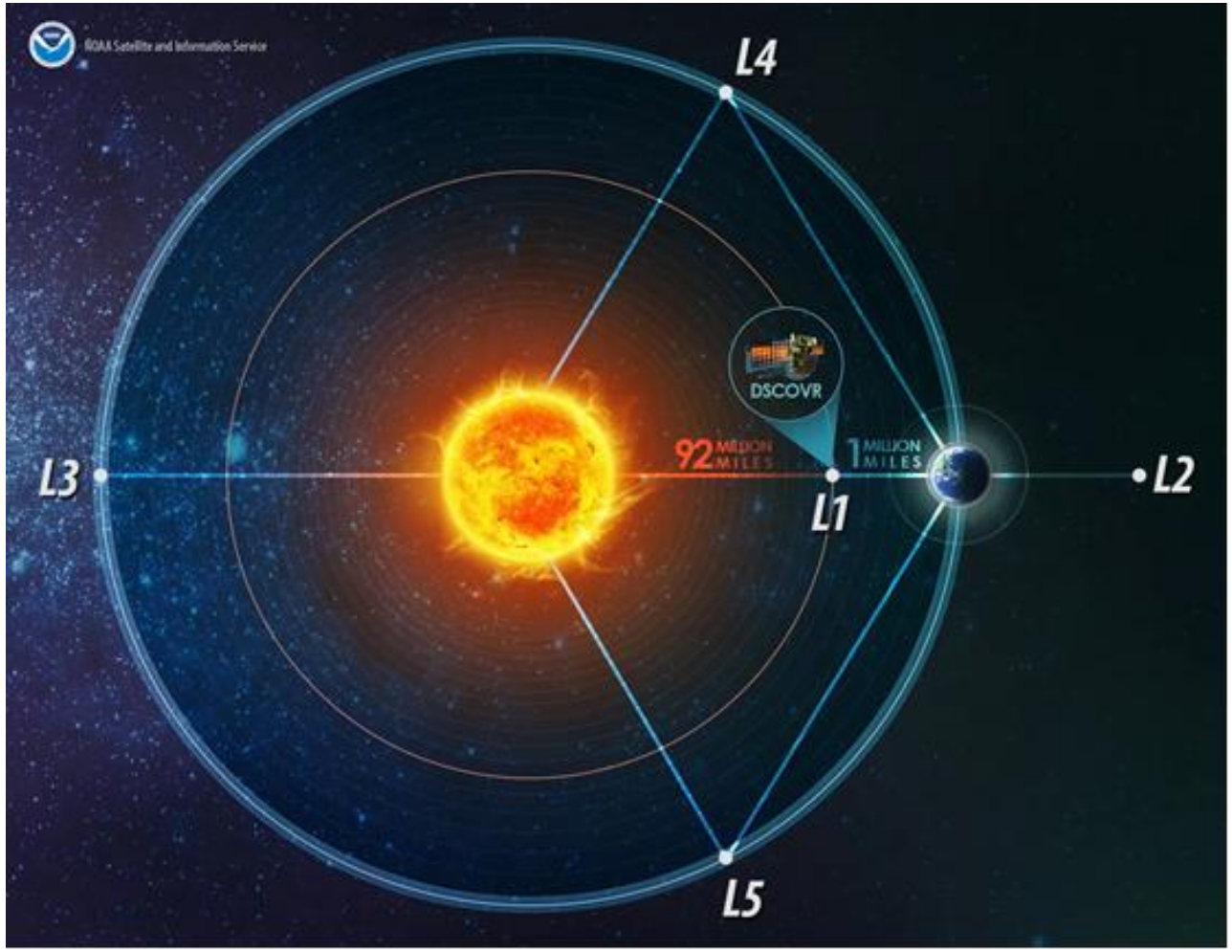


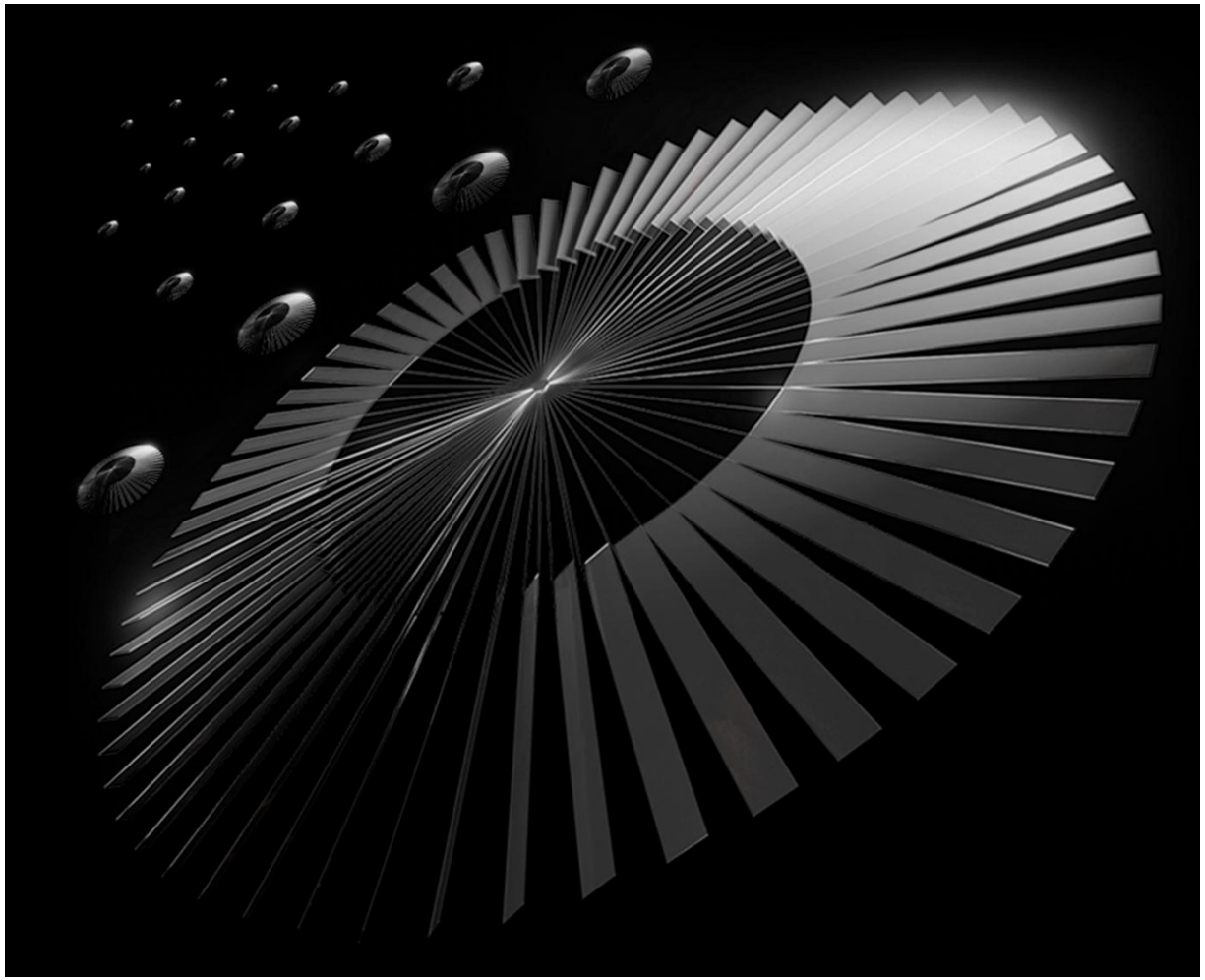
W. R. Lee, D. Visioni, B. M. Wagman, C. R. Wentland, B. Kravitz, S. Watanabe, et al. (2025) "G6-1.5K-SAI and G6sulfur: changes in impacts and uncertainty depending on stratospheric aerosol injection strategy in the Geoengineering Model Intercomparison Project," *EGUsphere 2025*: 1-33.

Reflective

Space-Based Sunshade (SBS)

(a.k.a. “planetary sunshade”)





https://www.nesdis.noaa.gov/news/points-of-lagrange-satellite-million-miles-home

https://planetarysunshade.org/engineering/

Space-Based planetary sunshade (SBS):

- Position a sunshade at/near Lagrange point L1, a stable orbit about 1% of the distance from the Earth toward the Sun
- Shading ~1% of solar energy would cool the Earth by ~1°C
- Construction may involve multiple rocket launches (from Earth, or from Moon?) and a long timeline (now–2080 ?)

Source: Planetary Sunshade Foundation, "State of Space-Based SRM" (October 2023)

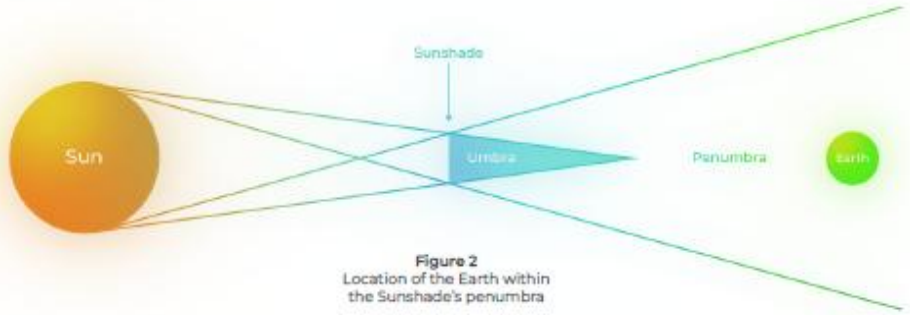


Figure 2
Location of the Earth within the Sunshade's penumbra

Due to the realities of gravitational physics, the most feasible location for a Planetary Sunshade is near the Sun-Earth Lagrange point 1 (L-1)[5] (see Figure 3). Lagrange points are equilibrium points where the gravity of two large bodies (in this case, the Sun and the Earth) and the centrifugal orbital forces balance. Objects located at L-1 remain on the line between the Earth and the Sun and require relatively minor station keeping to maintain their orbital location. Without orbital maintenance in the long term, objects will naturally drift away slowly from the shading position. The Sunshade's optimal location is about 2.4 million km from Earth, or about 5 times further away than our Moon's[6] orbit.

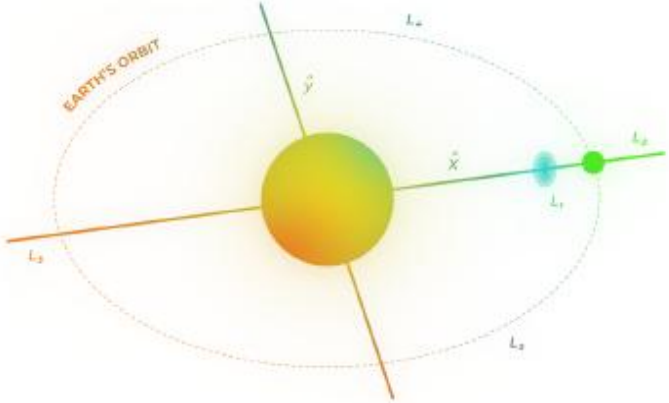


Figure 3
Planetary Sunshade location at Sun-Earth Lagrange point 1.[7]

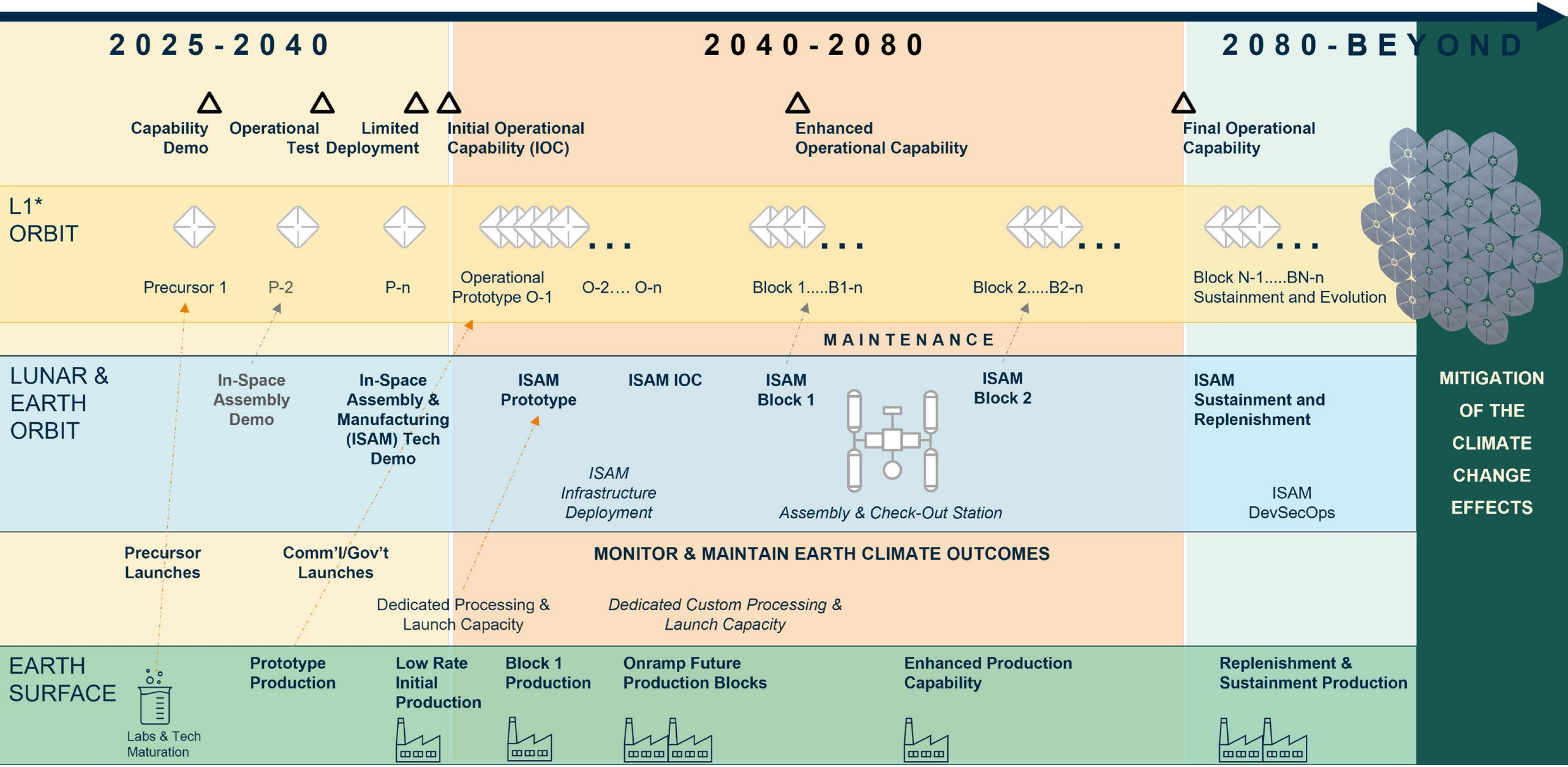
[5] Jehle, A., Scott, E., Centers, R. (2020) A Planetary Sunshade Built from Space Resources. AIAA ASCEND Conference, November 16-18, 2020, Virtual
[6] The length of the umbra of an object in sunlight near Earth is some 100 times its size. Elements of the Sunshade will be a few 10's meters to about a square mile in size. The umbra even of large elements would extend much less than a thousandth of the distance from the Sunshade to the Earth. It will not extend to the Moon or satellites.
[7] Sánchez, J. P., McInnes, C. R., & Marchis, F. (2015). Optimal Sunshade configurations for space-based geoengineering near the Sun-Earth L1 point. PLoS ONE, 10(8), 1-25.

Comparing SBS with SAI would investigate, e.g.:

- Climate benefits
- Cost, time
- Environmental risks: avoids aerosol injections of particles in atmosphere. But: rocket launches...
- Socio-political risks

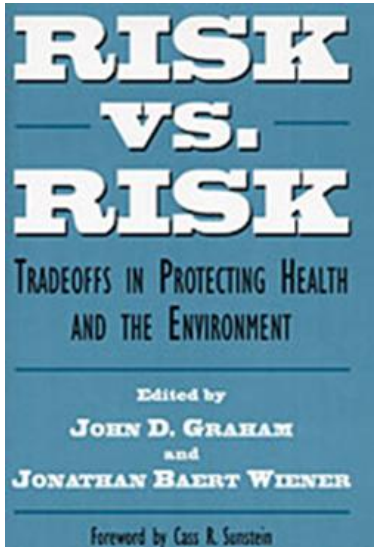
Governance of space-based planetary sunshade?

- Outer Space Treaty (1967)
- Artemis Accords (2020 -)
- Need a new regime?



"Roadmap toward a planetary sunshade for space-based solar geoengineering," C. L. Matonti, M. Coco, C. Cappelletti, B. Chesley, C. Fuglesang, G. Governale, et al., *Advances in Space Research* 2026, doi:/10.1016/j.asr.2026.04.007; https://www.sciencedirect.com/science/article/pii/S0273117726004503

Risk-Risk / Multi-Risk Framework

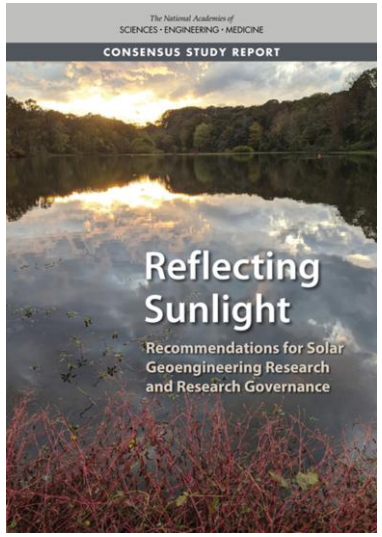


John D. Graham & Jonathan B. Wiener, eds., *Risk vs. Risk: Tradeoffs in Protecting Health and Environment* (Harvard Univ. Press, 1995):

Risk-Risk Analysis provides a framework to go beyond the typical narrow siloed focus on a target risk (due to bounded thinking, fragmented institutions, and 'omitted voice' of those affected).

In RRA, the **multiple risks – both target and ancillary –** of each policy option are **identified, weighed, and compared** to the multiple risks of other options –evenhandedly across impacts and affected groups – to inform policies that can **reduce overall risk**.

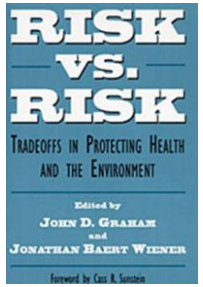
And RRA seeks **risk-superior** options to reduce multiple risks in concert.



US National Academies of Sciences, Engineering, and Medicine, *Reflecting Sunlight* (2021): 117-118:

For climate change, every policy option affects **multiple risks**. We need to **compare the risks of climate change and other impacts, under alternative sets of mitigation, adaption, and reflection policies**.

General framework for Risk-Risk / Multi-Risk Analysis



		Identifying Impacts	
		favorable	unfavorable
Risks	Target risk	A. Benefits: reduction in target risk	C. Costs and counterproductive effects on target risk
	Ancillary risks (side effects)	B. Co-benefits: favorable side effects on non-target risks	D. Countervailing risks: unfavorable side effects on non-target risks

Multi-Risk Framework for SAI (stratospheric aerosol injection)

Source:
T. Felgenhauer, G. Bala, M.E. Borsuk, I. Camilloni, J.B. Wiener, and J. Xu, "Practical Paths to Risk-Risk Analysis of Solar Radiation Modification," *Oxford Open Climate Change* (2025).

Table 1. Identification of the potential change in important risks from an SAI deployment aiming to limit global temperature increase to 1.5°C above pre-industrial levels in comparison to a non-SAI BAU scenario, approximated by SSP2-4.5.

	Benefits	Harms
Impacts of SAI on the target risk of climate change	*(a) Reduction in climate risks* • Reduced frequency of climate-related extreme events such as heat waves, droughts, floods, and wildfires [51] • Slowed polar [52] and glacial ice loss • Slowed sea level rise [53] • Reduction in hurricane intensity [51] • Reduced risk of surpassing tipping points [5]	*(b) Increase in climate risks* • Poorly designed deployment could have adverse impacts on regional precipitation [54–58] • Excessive cooling, if the SAI turns out to be more effective and/or sustained than expected, yielding harms that outweigh benefits [59–61]
Impacts of SAI on ancillary, non-climate change risks	*(c) Co-benefits* • Enhanced vegetation productivity in some regions (from increased diffused sunlight) [62] • Reduced tropospheric ozone and the associated benefits to air pollution and crop yields [63] • Enhanced land and ocean carbon sinks (from cooling) and slight reduction in atmospheric CO_2 [64]	*(d) Countervailing risks* Biophysical: • Changes in surface ultraviolet exposure, both from stratospheric and tropospheric ozone changes (due to increased surface area density of aerosols and stratospheric warming and associated stratospheric water increase [65–67]) as well as scattering by sulfate aerosols) [68, 69] • Increased acid deposition [70] Socio-political: • International tension or conflict (e.g. from non-cooperative unilateral or multilateral deployments and/or inadequate governance) [31, 32, 71] • "termination shock," depending on several factors [46]
	(e) Possible positive or negative impacts • Effects on global inequality in climate or non-climate impacts (decreasing or increasing) • Effects on GHG emissions mitigation (stimulation vs. displacement) [27–30] • Interactions with volcanic eruptions [72, 73] • Other unknown positive and negative effects of slowed global warming and SAI deployment	

The use of SAI to help address climate change would have a wide range of implications, and not all potential impacts may be shown here, including both extremely low probability risks as well as other potential reasons for concern [35].

Multi-Risk Framework for Comparing SAI with SBS

		IDENTIFYING IMPACTS	
		Favorable	Unfavorable
RISKS	Target risk	**Benefits: reduction in target risk** **SAI** • Could slow, halt, or even reverse warming • Fewer climate extremes (heat waves, droughts, floods, wildfires); slower sea-level rise & ice loss **SBS** • Same benefits – with more evenly distributed global shade • Effective, and adjustable, global cooling	**Costs & counterproductive effects on target risk** **SAI** • Poorly designed deployment could harm regional precipitation • Excessive cooling if more effective/sustained than expected **SBS** • Harmful climate effects less uncertain, more evenly distributed shade • Higher cost & longer deployment time (may deter hasty unilateral use?)
	Ancillary risks (side effects)	**Co-benefits: favorable side effects on non-target risks** **SAI** • Enhanced vegetation productivity (more diffuse light) • Reduced tropospheric ozone → air-quality & crop benefits • Enhanced carbon sinks; slight CO_2 reduction **SBS** • Co-development of space commerce, Moon industrialization & related tech — though may be more likely to ride the space-race boom than to drive it? • Possible overlap/synergy with solar-array technology • Early warning of solar storms (CMEs) — possible added protection of Earth from CMEs, or added vulnerability of SBS to CMEs (termination risk)?	**Countervailing risks: unfavorable side effects on non-target risks** **SAI** • **Environmental:** ozone depletion, UV/surface changes, acid deposition • **Socio-political:** international tension/conflict, moral hazard/mitigation deterrence, termination shock, incompetent/malevolent deployment; governance challenges beyond existing law **SBS** • **Environmental:** avoids aerosols in atmosphere. But, rocket launches (noise, pollution, debris, re-entry risk). Moon-based launches could help Earth environment, but raise Moon industrialization risks • **Socio-political**: monopoly / non-representative corporate/government control; moral hazard/mitigation deterrence (possibly greater than SAI – higher status and visibility); termination shock (may be more reliable, but harder to restart, than SAI); incompetent/malevolent deployment; governance challenges beyond existing law

Comparing launches/flights and costs of SAI vs. SBS

SAI
(Smith & Wagner 2018; Smith 2020)

- ~4,000 flights/yr in year 1, linearly increasing to ~60,000 flights/yr in year 15
- Average early costs: $2.25 - $18 billion/yr
- Through year 2100: $250 billion - $2.5 trillion all-in

vs.

SBS – launching everything from Earth:
(Matonti et al. 2024)

- ~10^5 to 10^6 Starship launches, + ~ 10^6 boosters and ~ 10^6 tankers
  - Extreme ultralight .55 Mt designs, if possible, could need <10k launches over ten years (Borgue & Hein 2023)
- All-in costs ~$6 trillion over ~40 years

SBS – maximizing manufacturing on the Moon:

- ~10^2 – 10^5 Starship launches to the Moon for setup (depending on how good lunar manufacturing is for advanced goods, e.g. chips, or how sophisticated the sunshade)
- All-in costs $23 billion - $10 trillion (Maheswaren 2018; Angel & Worden 2006)

Potential Socio-Political Risks of SAI vs. SBS

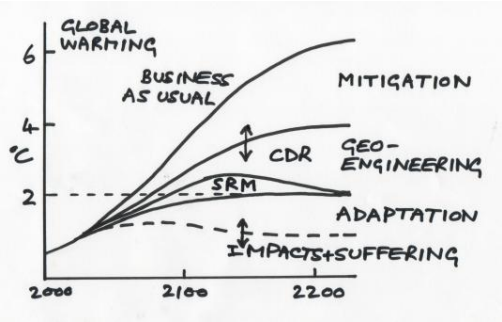
Socio-political risk	Stratospheric Aerosol Injection (SAI)	Space-Based Sunshade (SBS)
"Moral hazard" – emissions mitigation displacement	Prospective: unclear; studies vary Deployed: residual side effects, regional climate effects, and unaddressed ocean acidification may encourage mitigation	Prospective: unclear Deployed: less due to longer timeline? more due to perceived greater efficacy in reducing climate risk? (but not ocean acidification)
International conflict	Low cost may invite unilateral deployment, by a state or even a non-state actor; others might seek to block or attack Prestige motivations for SAI ? Great power competition or cooperation? Misperceptions, disputes re attribution?	High cost may deter unilateral deployment Requires strong global cooperation? Prestige motivations stronger for SBS ? Great powers / rivals could block? Great power cooperation on joint SBS – e.g. bipolar solar hegemony?
Termination shock	Easier to restart if stopped? May depend on cause of interruption/failure (e.g. supply chain, or adversarial attack)	More reliable in routine operation, but more vulnerable to low-p system failure? CMEs? Harder/more costly to restart if stopped?
Incompetent deployment	Possible, but pressure from other actors to correct quickly?	Less likely, if very long timeline and high cost promote more careful design, testing, deployment, supervision?
Malevolent deployment	Possible, but very difficult to weaponize, and other actors would counter	Possible to weaponize once deployed? Only if a single power or alliance has control?

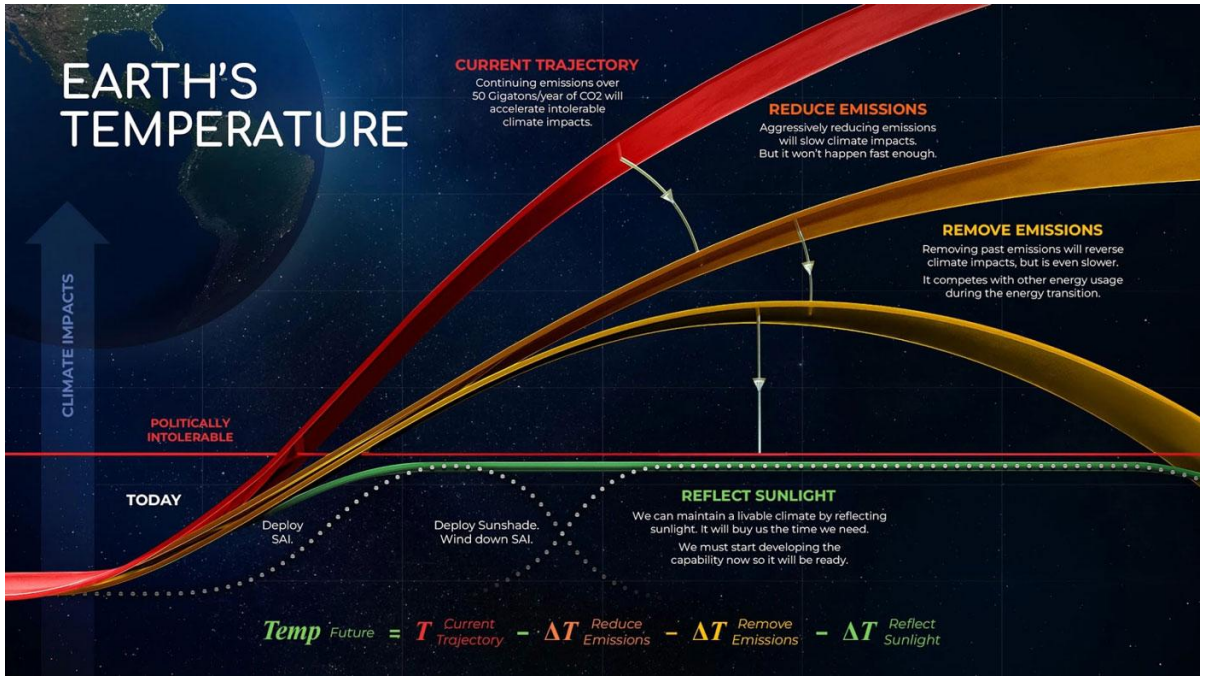
Potential Futures

Innumerable potential futures exist from now to 2100, for both SRM and climate change. Here are some ones that might anchor our thinking:

Solar Geoengineering Non-Use Agreement

No SRM ever: Climate change is addressed (or not) with existing approaches (mitigation, adaptation, and CDR).
Only SAI SRM: SAI starts, ramps up, ramps down, and halts; no SBS ever.
Only SBS SRM: SBS is built over many decades and is still in existence in 2100.
Technological handoff: SAI starts, ramps up, ramps down, and halts. As SAI peaks, work begins on an SBS while SAI starts to taper down.





https://planetarysunshade.org/climate-science/

Many technology milestones on the path to SBS also present novel governance challenges, complicating the overall risk analysis. For example:

Increased rocket launches on Earth

- Environmental effects from launches and rocket / infrastructure production

Moon base(s)

- Competition for scarce/chokepoint lunar resources or regions

Lunar industrialization (including AI-driven robotics)

- AI risks
- Environmental impacts on the Moon
- Potential concentration of economic power

Lunar mass driver

- Potential weaponization, e.g. against Earth

Space-based sunshade ★

Dyson swarm (solar-collecting megaconstellation)

- Distribution of energy resources across people/planets
- Reflection of heat to planets

Our publications on SRM include:

Duke Center on Risk in SCIENCE & SOCIETY

Duke SPACE INITIATIVE

- "Comparing SAI with SBS for SRM" (in progress) (Wiener, Felgenhauer, Garg, Hamilton, Scolnic)
- "Multi-risk Governance of SRM" (Wiener, Felgenhauer and Borsuk), *Eur. J. Risk Regulation* 16: 1246-1262 (2025).
- "Practical Paths to Risk-Risk Analysis of Solar Radiation Modification (SRM)" (Felgenhauer, Bala, Borsuk, Camilloni, Wiener and Xu), *Oxford Open Climate Change* 5(1): kgaf012 (2025).
- "The Evolving International Climate Change Regime: Mitigation, Adaptation, Reflection" (Wiener and Felgenhauer), *Texas A&M Law Review* 11: 481-485 (2024).
- "Improving Risk Governance Strategies via Learning: A Comparative Analysis of Solar Radiation Modification and Gene Drives" (Grieger, Wiener and Kuzma), *Environment Systems and Decisions* 44: 1054-1067 (2024).
- "Solar Radiation Modification: A Risk-Risk Analysis" (Felgenhauer, Bala, Borsuk, Brune, Camilloni, Wiener and Xu), report for Carnegie Climate Governance Initiative (C2G) (2022).
- "Social Science Research to Inform Solar Geoengineering" (Aldy, Felgenhauer, Pizer, Borsuk, …, Wiener, et al.), *Science* 374: 815-818 (12 November 2021).
- "Emerging Risk Governance for Stratospheric Aerosol Injection as a Climate Management Technology" (Grieger, Felgenhauer, Renn, Borsuk and Wiener), *Environmental Systems and Decisions* 39: 371-382 (2019).