Geoengineering the Earth's Climate: The World's Largest Control Problem

Impacts and risks associated with climate change will continue to exist, even with aggressive reductions in CO_2 emissions. *Is it possible to intentionally intervene in the climate system to reduce risk?*

The climate can be "engineered" in two ways: by removing CO_2 from the atmosphere (slow and expensive) or by blocking some sunlight—this could be fast and cheap.

Solar geoengineering or *solar radiation management* refers to any large-scale intentional technique that reflects some incoming sunlight back to space, cooling the planet. This constitutes a control problem.

Feedback to Manage Uncertainty

A common question in geoengineering is: *"How can we engineer a system that we don't understand?"* The answer, of course, is with feedback.

Feedback design requires a dynamic model describing global mean temperature response to radiative forcing (defined as the difference between the radiant energy received by the earth at the upper atmosphere and the energy radiated back into space).

Simple dynamic models have been developed that are feasible for use in feedback control. These models show a good match, for control purposes, with complex climate models such as the HADCM3L coupled atmosphere-ocean general circulation model (AOGCM).

How Might the Planet Be Cooled?

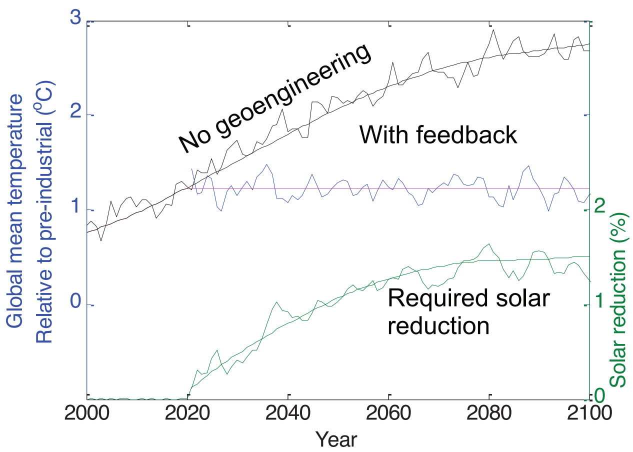
No solar geoengineering experiments have been conducted or are currently planned; however, we can learn from nature about possible "actuation mechanisms" that would act to cool the planet. These include creating a layer of stratospheric sulfate aerosols (as have resulted from volcanic eruptions; see figure below) or brightening of marine stratocumulus clouds (as in "ship tracks"—more reflective clouds caused by ship exhaust).

2009 Sarychev volcanic eruption as seen from the International Space Station (Source: NASA)

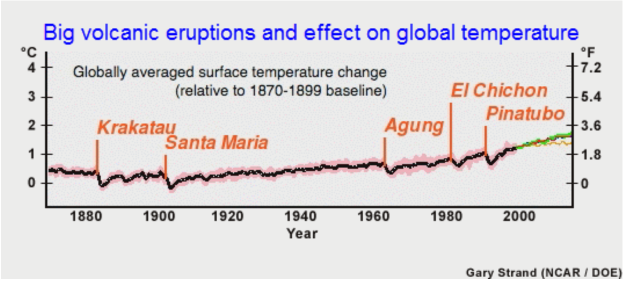
Risks of Using Solar Geoengineering

- May lead to delay in reducing CO_2 emissions, thus requiring geoengineering for centuries
- Possible "side effects" such as ozone loss, whiter skies, and unknown unknowns
- Will not compensate climate changes precisely, leading to regional differences
- Uncertainty: the need to design for a system that is not fully understood
- Must get it right the first time; experimentation is not possible

Control theory can help address these (last three items)



Simulations with the HADCM3L AOGCM demonstrate adjusting solar reduction using feedback of the global mean temperature to maintain a target level. A simple PI controller was used, with feedback gains designed using a reduced-order dynamic model. The resulting model predictions are shown as smooth lines and match the full climate model (the lines that include variability).



Major volcanic eruptions in recent history and their effect on global temperature

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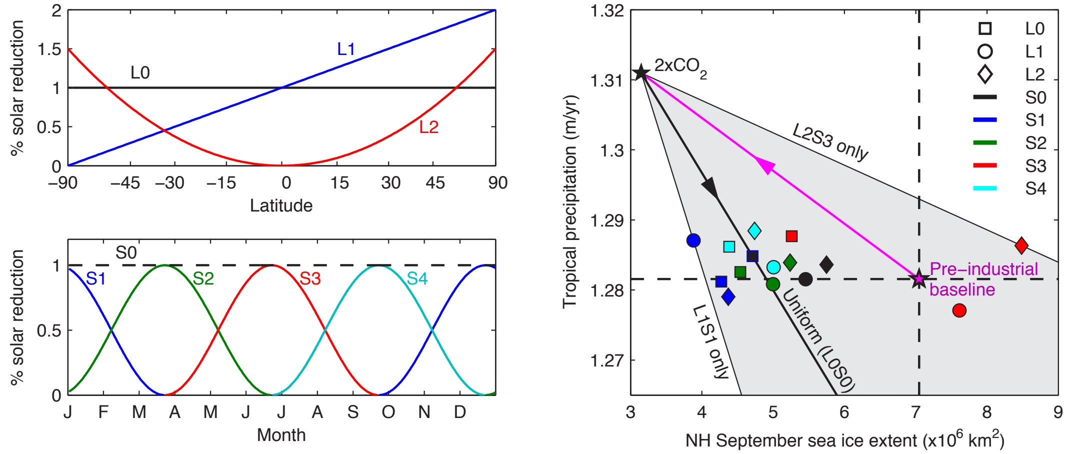
Optimization to Minimize Impacts

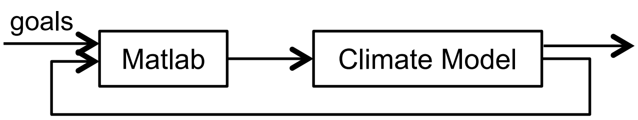
Compensation of climate change with solar geoengineering is not perfect, so some regions might benefit from more geoengineering than other regions, leading to the question: *"Who gets to set the thermostat?"* However, we can vary the distribution of solar reduction in space and time and we can choose distributions to maximize benefits, such as restoration of northern hemisphere (NH) sea ice. See the figure below for a simulation example.



The example above considers 15 "basis functions" (shown at left), with solar reduction uniform or peaking in each season and spatial reduction constant or varying with latitude. The right panel shows how two specific climate impacts of a doubling of CO_2 concentration relative to the pre-industrial baseline can be ameliorated by solar geoengineering: a uniform solar reduction cannot perfectly compensate for increased CO_2, but varying the distribution of solar reduction can influence multiple variables—any climate in the shaded region can be chosen by a linear combination of the basis functions. (Of course, we care about more than these two variables; we can't independently change the climate everywhere with only 15 degrees of freedom.)

More Opportunities for Control!

Control theory and techniques can be widely useful in climate science. Wrapping an external feedback loop can be used to:



Explore human/climate interactions:

- Geoengineering—how to manage multiple goals despite deep uncertainty, high background variability (poor signal-to-noise ratios), and the need to "get it right" the first time without prior experimentation
- Determine optimal emission pathways to achieve climate goals with learning about uncertainty

Explore natural climate behavior:

- Example: permafrost thaw releases methane, causing warming, causing more methane release, and so on
- Understand climate variability, e.g., El Niño or meridional overturning dynamics: use system-identification tools to evaluate subsystem process dynamics from data and in different models

Explore climate model behavior:

- Can we use feedback to automate and accelerate model tuning?
- Can we use feedback to artificially alter time constants to accelerate model convergence?
- Compare different greenhouse gases: e.g., how much CH_4 is equivalent to how much CO_2?

For more information: D.G. MacMartin et al., Dynamics of the coupled human-climate system resulting from closed-loop control of solar geoengineering, Climate Dynamics, 2013; D.G. MacMartin et al., Management of tradeoffs in geoengineering through optimal choice of non-uniform radiative forcing, Nature Climate Change, vol. 3, pp. 365-368, 2013; B. Kravitz et al., Explicit feedback and the management of uncertainty in meeting climate objectives with solar geoengineering, Environmental Research Letters, vol. 9, no. 4, 2014.