The Science and Technology of Solar Geoengineering: A Compact Summary

A background briefing for the workshop on Governance of the Deployment of Solar Geoengineering convened by the Harvard Project on Climate Agreements

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This compact point-form summary assumes familiarity with climate science and its policy context. We have tried to keep to physical science and technology and avoid claims and assumptions about the social science, public policy, or politics. This is our summary judgment of the current state of knowledge. We do not address important questions such as: What is unknown? And, how could research reduce uncertainties?

Some definitions:

- *Radiative Forcing* (RF) is the most relevant quantitative global measure of the human drivers of climate change. There is a sharp distinction between climate *forcing* caused by aerosols or greenhouse gases (GHGs) from the climate *response* measured by changes in climatological and other environmental quantities.
- *Solar Geoengineering* (SG) is the deliberate large-scale alteration of earth's radiative balance with the goal of reducing some of the risks of accumulating greenhouse gases.
    - Technically plausible methods include:
        - **Stratospheric Aerosols**: adding aerosols to the stratosphere where they reflect some (~1%) of incoming sunlight back to space.
        - **Marine Cloud Brightening**: adding cloud condensation nuclei (a specific class of aerosols) such as sea salt to specific kinds of low-lying clouds over the ocean with the goal of increasing the reflectivity or lifetime of these clouds.
        - **Cirrus Thinning**: adding ice nuclei (another class of aerosols) to high-altitude cirrus clouds with the goal of reducing the density of such clouds[i].
        - Other methods include space-based reflectors, tropospheric aerosols, and increasing the reflectivity for crops or other land cover.
    - Many methods of SG mirror ways in which human actions or natural processes alter RF. Tropospheric aerosols from combustion and other sources currently have a negative (cooling) RF that offsets a significant fraction of the positive RF from GHGs. Likewise, aerosol pollution from shipping sometimes brightens marine clouds and aircraft emissions alter cirrus clouds. Some volcanic eruptions produce a pulse of stratospheric aerosol.
- Solar geoengineering partially decouples cumulative carbon emissions from global-mean temperature.
    - With SG, the 1.5 °C target could in theory be achieved for very large cumulative CO_2 emissions, though even with SG, net emissions (including removals) must eventually be zero to achieve a stable climate.
    - The climate in a 1.5 °C world achieved with SG and emissions reductions differs from the climate in a 1.5 °C world achieved by emissions reductions alone.

- If SG is used to maintain a fixed net RF as GHGs increase, then differences from pre-industrial climate—and thus climate impacts—will grow with cumulative emissions.

- Reducing uncertainties about solar geoengineering requires climate science and engineering:
  - *The engineering problem*: Proposing and developing the specific methods of SG designed to achieve some specific objective. Many objectives are possible, and their impacts could be very different, e.g. limit global warming to 1.5 °C with a globally uniform aerosol layer or by only cooling one hemisphere[ii].
  - *The scientific problem*: Predicting the climate's response to a specific deployment of SG is a problem that is closely related to the problem of predicting response to other anthropogenic influences such as aerosol pollution.
    - The scientific challenge of predicting the climate's response to a specific deployment of SG can, in turn, be divided into two (mostly) independent problems:
      - Predicting the RF that arises from some well-specified intervention, and;
      - Predicting the climate response to that RF.
- Specifics of **Stratospheric Aerosols**[iii]:
  - There is high confidence that RF, sufficient to offset half the RF from a doubling of CO_2 concentrations (~2 Wm^{-2}), could be achieved with stratospheric aerosols.
  - Techno-economic assessments suggesting that stratospheric aerosols could be delivered with aircraft at a cost of less than $10B per year for 2 Wm^{-2}.
  - By choosing where to release aerosols, a fairly uniform global aerosol layer could be created, or the aerosol layer could be thicker at high latitudes or in one hemisphere or the other. The circulation in the stratosphere strongly limits what can be achieved; it is not possible to limit cooling to one country. The roughly 1-2 year lifetime of stratospheric aerosols constrain how rapidly this pattern of cooling could be adjusted.
  - The direct health risks arising from increased particulate matter and decreased stratospheric ozone from stratospheric aerosols are small—one or two orders of magnitude less than climate impacts/benefits. If, for example, stratospheric sulfate aerosol injection was adjusted to produce the same RF as is produced by tropospheric sulfate aerosol pollution, the mortality from the stratospheric sulfates would be roughly 1,000-fold smalleriv.
- Specifics of **Marine Cloud Brightening** and **Cirrus Thinning**:
  - There is much lower confidence that a substantial RF (~2 Wm^{-2}) could be achieved with marine cloud brightening or cirrus thinning. The magnitude, and even sign, of the effect is uncertain in both cases, and both are applicable over a limited domain of susceptible clouds so may not be scalable to achieve a substantial RF.
  - For both marine cloud brightening and cirrus thinning, the spatial pattern of RF could be adjusted on timescale of days, a capability that may allow some form of weather modification.
  - Marine cloud brightening is most effective in a specific kind of marine boundary layer cloud that covers ~10% of the earth's surface, so the RF produced is inherently non-uniform.
  - Engineering estimates of the cost and technical feasibility of delivery are much less certain than for stratospheric aerosols.

    - Cirrus cloud thinning acts primarily by increases outgoing thermal radiation so the nature of its RF is more similar to GHGs than most other SG methods, however unlike GHGs, its RF would be patchy.
- Climate response to radiative forcing from solar geoengineering:
    - SG cannot eliminate all climate change from GHGs even if the net RF is reduced to zero.
        - This is a consequence of the fact that climate variables respond differently to the RF from SG and GHGs. For example, if SG RF is adjusted to restore global-average precipitation to pre-industrial conditions, the global-average temperature will be significantly above pre-industrial.
    - Strong evidence shows that if SG is spatially uniform and adjusted to offset roughly half the RF from GHGs, then the change in important climate variables would be reduced in most locations and increased in only a small percentage of the land surface[v].
        - Non-uniform or strongly patchy RF—as might be produced by marine cloud brightening—produces more unevenness in the climate response.
    - Around half of the long-run climate response to a change in RF is realized within a decade, which means that rapidly scaling up or ending SG deployment would produce sudden changes in climate[vi].
    - The uncertainty in climate predictions grows with total RF, and so it may be that uncertainty in predicting the impacts of SG and GHGs is less than predicting the climate change from the same amount of GHGs alone.
        - Reducing uncertainties in the climate response to RF from GHGs will also improve our understanding of the climate response to RF from SG.
    - Much of the uncertainty in the impacts of climate change, e.g. on ecosystems, arises from climate conditions moving away from pre-industrial conditions. As solar geoengineering would generally reduce the magnitude of change in most variables in most places, systems will remain closer to these observed bounds.

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[i] Low clouds tend to cool the climate so increasing them has a cooling effect while high clouds do the opposite, hence reducing them will also tend to cool.
[ii] See Kravitz et al. (2016) for a discussion of geoengineering as a design problem, DOI:10.5194/esd-7-469-2016
[iii] See Irvine et al. (2016) for a review of stratospheric aerosol geoengineering, DOI:10.1002/wcc.423
[iv] See Eastham et al. (2018) for an analysis of the health impacts of stratospheric aerosols, DOI:10.1088/1748-9326/aaad2e
[v] Our quantitative analysis demonstrating this result is currently under review but Keith and Irvine (2016) reviews the literature to present an argument why this is likely, DOI:10.1002/2016EF000465
[vi] See Parker and Irvine (2018) for a discussion of the risks of a so-called “termination shock” arising from a sudden cessation of large-scale SG deployment, DOI:10.1002/2017EF000735