

Counteracting climate change via solar radiation management

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Background on SRM

Since the pre-industrial period, increase in atmospheric carbon dioxide (CO₂) and other greenhouse gases (GHGs) has exerted a positive radiative forcing on the climate system by trapping longwave radiation¹. Solar radiation management (SRM) schemes aim to offset the warming influence from GHGs by reducing the amount of solar radiation absorbed by the Earth. This can be achieved in two ways: (1) reducing the amount of solar radiation reaching the Earth and (2) increasing the reflectivity of the planet. Radiation reaching the earth can be reduced by space-based sunshades²⁻⁵ and the reflectivity of the planet can be increased by increasing the albedo of clouds in the atmosphere^{6,7} or the reflectivity of the land surface⁸ or ocean surface⁹. Reflectivity could be also increased by artificially injecting sulphate aerosols into the stratosphere^{10,11}.

Most SRM schemes are intentional. Since they operate on large spatial scales, the SRM schemes could result in large-scale modification to the global climate and hence they are also known as 'geoengineering' proposals¹². In the broader context of moderation of climate change, geoengineering refers to two distinct categories of climate remediation techniques¹³: (1) the SRM proposals and (2) the carbon dioxide removal (CDR) methods which would accelerate the removal of atmospheric CO₂ and enhance its storage in the land, ocean and geological reservoirs. In this note, we restrict our discussion to SRM proposals.

It has been estimated that a doubling of atmospheric CO₂ causes a positive radiative forcing of approximately 3.5 Wm⁻² (ref. 1). The amount of solar radiation reduction needed to offset this forcing can be estimated from the radiative balance of the Earth system: since the amount of solar absorption by the planet is about 235 Wm⁻², for the space-based techniques, a deflection of about 1.5% reduction of incoming radiation is required. For atmosphere and surface-based schemes, an offset of 3.5 Wm⁻² radiative forcing requires a reduction in planetary albedo of about 1%, or alternatively, a reduction in surface albedo of

about 2% (ref. 13). In this note, I briefly discuss the major scientific considerations for SRM, unmitigated climate effects and unintended side effects. Only the physical science aspects of SRM are considered here with an important caveat that other concerns such as governance, ethical, economical and political issues need to be considered and addressed before any field research or actual implementation.

Scientific considerations

SRM can rapidly cool the Earth

The main scientific consideration for SRM in counteracting anthropogenic climate change is the rapidity with which these schemes can act on the climate system: SRM schemes could cool the Earth rapidly to pre-industrial levels within one or two decades. Insight into the potential to cool the Earth can be gained from the observed cooling following large volcanic eruptions such as Mt Pinatubo in 1991 (ref. 14), which cooled the Earth by about 0.5 K within a year following the eruption. More detailed recent studies show that the climate system responds with a <5-year relaxation timescale for instantaneous changes in forcing to pre-industrial levels¹⁵. The short decadal timescale for rapid cooling is dictated by the thermal inertia of the surface mixed layer ocean which comes to equilibrium within 15–20 years for any imposed climate perturbation. On longer timescales, feedbacks with deep ocean and heat storage in the deep ocean do become important and it is possible that long-term climate change could be substantially different from the short-term change. However, in practice, the time taken for the equilibration of mixed-layer oceans is a reasonable indicator of the timescale for climate change. The first modelling study on the transient (as opposed to equilibrium) climate response to sunlight reduction suggests that the climate system responds quickly (<5-years of relaxation timescale) to artificially reduced solar radiation¹⁶; hence, there may be little cost to delaying the deployment of SRM strategies until such time as 'dangerous' climate change is imminent.

SRM can reduce the magnitude of climate change significantly

Modelling studies¹⁷⁻²⁰ have shown that relative to the climate with elevated CO₂ concentration, a geoengineered climate with low solar irradiance and high atmospheric CO₂ level is more similar to the 'natural' climate with normal solar irradiance and low atmospheric CO₂ level. These studies have essentially shown that the residual climate change in the geoengineered world, both globally and regionally, is much smaller than in a non-geoengineered world with higher CO₂ concentration. It may be also possible to identify a level of SRM capable of meeting multiple targets, such as maintaining a stable mass balance of the Greenland ice sheet and cooling global climate, but without reducing global precipitation below pre-industrial levels or exposing significant fractions of the Earth to 'novel' climate conditions²¹.

SRM would weaken the global water cycle

The reduced solar radiation, by offsetting the positive CO₂ forcing, could in principle lead to a zero global-mean surface temperature change. However, a zero change in global-mean surface temperature in the high CO₂ concentration and low solar radiation Earth would inevitably cause a reduction in global-mean precipitation²². This is caused by the different vertical heating profiles of CO₂ and solar forcing: CO₂ forcing heats the atmosphere, but solar forcing primarily heats the surface. While the precipitation response per degree surface temperature change is the same for solar and CO₂ forcing, it has been established that in the absence of surface warming, enhanced atmospheric CO₂ suppresses precipitation by stabilizing the atmosphere, while the solar forcing has a much smaller effect on precipitation²²⁻²⁴. Therefore, SRM schemes, if implemented to offset global-mean surface warming, by offsetting only temperature-related precipitation change, would cause a weakening of the global water cycle^{18,20,22}. Alternatively, if the goal of SRM is to counteract

changes in global-mean precipitation, a residual surface warming will remain. Clearly, SRM would be an optimization problem²⁵ and it is important to consider the impacts on all components of the climate system rather than focusing only on surface temperature.

SRM may need to be maintained for multiple centuries

It is now widely recognized that the atmospheric lifetime of anthropogenic CO₂ is extremely long. While more than half of the emitted CO₂ is absorbed by natural carbon sinks on land and in the surface ocean, additional permanent removal requires transport of carbon to the deep ocean, which occurs slowly over many centuries. More than two-thirds of the peak atmospheric CO₂ will likely remain in the atmosphere after several centuries and on the order of one-third of the peak atmospheric CO₂ may still be present after 10,000 years²⁶. Therefore, SRM, if implemented, may need to be maintained for several centuries until atmospheric CO₂ returns to the desirable levels.

Failure of SRM can lead to catastrophic climate change

SRM schemes, if implemented at large scales, could also subject the planet to the problem of 'termination effect'. The termination effect refers to the fact that a sudden halt or failure of the SRM schemes could lead to a rapid warming. The timescale that is involved in cooling the system rapidly also governs the termination problem. The failure of the SRM schemes could subject the Earth to extremely rapid warming, with the rate of warming being many times that of the current warming¹⁶. Whereas a non-geoengineered world would warm slowly with the slowly increasing CO₂, the SRM-failed scenario instantaneously imposes a large climate forcing at the point of SRM failure and the climate system responds to this on a timescale of 10–20 years (the timescale of the mixed layer ocean), with larger warming rates. Furthermore, compared to a climate with higher temperature and high CO₂ level, much more carbon would be stored in the oceans and land in a climate with low solar irradiance, low temperature and high CO₂. In the case of a halt or failure of the SRM schemes, a sudden warming

would cause the carbon stored in the land and ocean reservoir to be released into the atmosphere, triggering a further warming that is much greater and faster than the climate in the absence of SRM geoengineering¹⁶.

Unmitigated climate effects

SRM would not mitigate CO₂-fertilization effect

While SRM techniques may counter the radiative effects of CO₂, they do not remove any direct effects of CO₂ on natural ecosystems. On land, elevated CO₂ stimulates uptake by terrestrial vegetation and hence enhances vegetation and soil carbon stocks through CO₂-fertilization effect. Modelling studies have shown that SRM would tend to limit changes in vegetation distribution caused by radiatively induced climate warming, but would not prevent fertilization-induced changes in terrestrial plant productivity or carbon stocks²⁷.

SRM would not mitigate ocean acidification

In the ocean, acidification caused by elevated CO₂ which may be detrimental to marine ecosystems, is not prevented by SRM. However, due to the strong coupling between climate and the carbon cycle, SRM could marginally affect the carbon cycle through indirect means. For instance, modelling studies have shown that SRM methods could indirectly affect ocean chemistry²⁸ by re-distributing carbon emissions among the atmosphere, land and ocean reservoirs with enhanced carbon stocks over land simulated for an SRM case.

SRM schemes do not mitigate CO₂-physiological effect

In addition to trapping longwave radiation, increasing atmospheric CO₂ affects the climate system by its effect on plant stomata. This effect, referred to as CO₂-physiological forcing, enhances the CO₂-radiative warming by about 10% at the global scale and can account for up to 30% of the total warming at regional scales^{29,30}. More importantly, the CO₂-physiological forcing has significant implications on the global hydrological

cycle since it reduces plant transpiration and could potentially lead to increase in run-off^{29,31,32}. The SRM schemes do not counteract the effect of CO₂-physiological forcing, since they only act on the radiative budget of the planet.

Most SRM schemes do not mitigate CO₂-induced stratospheric cooling

Idealized modelling studies have shown that uniform reduction in incoming solar radiation (space-based schemes) could actually increase the cooling in the stratosphere^{17,33}, which could aggravate changes to stratospheric chemistry and ozone depletion. The non-mitigation of stratospheric cooling for marine cloud-albedo enhancement schemes has also been demonstrated by modelling studies³⁴.

Unintended side effects

SRM is imperfect

SRM schemes have been often characterized as imperfect because they act on effects of climate change rather than the root cause of climate change¹³. One issue common to all SRM schemes is that it may not be feasible to simultaneously restore all climatic fields (e.g. temperature and precipitation) to the natural state, even in terms of global-mean values; and it may not be possible to simultaneously restore climate change in all the regions, even for a single climate field. For instance, modelling studies have shown that the residual temperature changes are much smaller than the change in the system without the SRM schemes, but all models show large residual changes in precipitation. Some studies have shown reduction in Asian summer monsoon rainfall³⁵ for stratospheric aerosol injections.

SRM may result in altered climates

The moderation of global-mean climate does not necessarily lead to a moderation of climate in all the regions. For space-based SRM schemes, the forcing could be applied uniformly, but due to the different spatial patterns between GHG and solar forcing, the resulting climate response would vary over regions. Cooling and drying of the tropics and warming in high latitudes have been simulated for geoengineered simulations in model-

ling studies^{21,33}. SRM could be successful in lowering the global-mean surface temperature, but would result in significant change in regional climate³⁶. For example, both tropical and Arctic SO₂ injection could disrupt the Asian and African summer monsoons³⁵. Using a large ensemble of modelling experiments, it has been found that it may not be possible to stabilize the climate in all the regions simultaneously by modifying stratospheric aerosols³⁷.

For the cloud-albedo enhancement scheme and schemes involving surface-albedo change, the compensating solar forcing is applied non-uniformly, and thus the climate response is expected to be heterogeneous. For instance, precipitation and run-off over land could be enhanced for marine cloud-albedo enhancement schemes³⁴, and conversely, severe drying of continents has been simulated for land-albedo enhancement schemes³⁸. For the latter schemes, significant residual cooling of NH and warming of SH have been also simulated.

Changes in climate variability and other climatic aspects resulting from reduced solar forcing are also examined by a few modelling studies. Compared to the natural climate, a uniform reduction in solar radiation may lead to reduced El Niño Southern Oscillation (ENSO) vari-

ability and increased North Atlantic overturning²⁰. Simulations have also shown that large reduction in solar radiation could cause changes in ENSO and related climate teleconnection patterns³⁹.

Stratospheric aerosol injection could cause ozone depletion

Sulphate aerosol injection into the stratosphere could have significant effect on stratosphere chemistry and ozone. An injection of stratospheric sulphate aerosols large enough to offset the warming from a doubling of CO₂ would cause a 30–70 year delay in the expected recovery of the Antarctic ozone hole^{40,41}. Sulphate aerosol injection accelerates the hydroxyl-catalysed ozone destruction cycles and causes a significant depletion of the ozone layer⁴².

Stratospheric aerosol injection can alter ecosystem productivity

Enhanced stratospheric aerosols are likely to increase the amount of diffuse solar insolation at the surface at the expense of direct light¹⁰. Recent theoretical and observational studies have demonstrated that photosynthesis is more effi-

cient under diffuse light conditions^{43–45}. Therefore, stratospheric aerosol injection has the potential to enhance the terrestrial carbon sink. However, reduction in photosynthetically active radiation (PAR) due to SRM methods could cause a drop in land uptake of carbon. Sufficient information is lacking to ascertain whether the net effect of such SRM schemes would be to enhance the carbon sink due to enhanced diffuse light, or to reduce it due to a reduction in overall PAR. Reduced direct sunlight could also reduce the potential of energy generation by solar power plants, and affect surface-based optical astronomy⁴⁶.

Summary

SRM schemes aim to counteract GHG warming by reducing the solar absorption by the climate system, either globally or regionally. Some of the proposed SRM methods, the major scientific considerations, unmitigated climate effects and unintended side effects of SRM are schematically summarized in Figure 1. There are many other issues such as governance, ethical, societal, economical, technological, risks and uncertainty¹³, which are not discussed in this note.

Compared to the climate with high GHG concentration and no SRM geoengineering, the climate with high GHG concentration and SRM geoengineering would be more similar to the climate with ‘natural’ GHG concentration. However, with continued emissions of anthropogenic CO₂ and other GHGs, it might not be possible for the SRM schemes to restore different fields of the climate system to the pristine state simultaneously, even for the global-mean values. Furthermore, for any climate field, it might not be possible for the SRM schemes to restore its value at all regions to the pristine state simultaneously.

Therefore, on both global and regional scales there would be a trade-off between climate fields such as surface temperature, precipitation, sea ice and monsoon. What we might want to seek is a geoengineering approach and/or a combination of different SRM schemes that would yield optimal solution to these trade-offs. Steps have been taken in this exploration^{21,25,47}. Furthermore, to have a robust assessment of climate impact from SRM methods, a standard modelling experiment protocol with the same SRM forcing

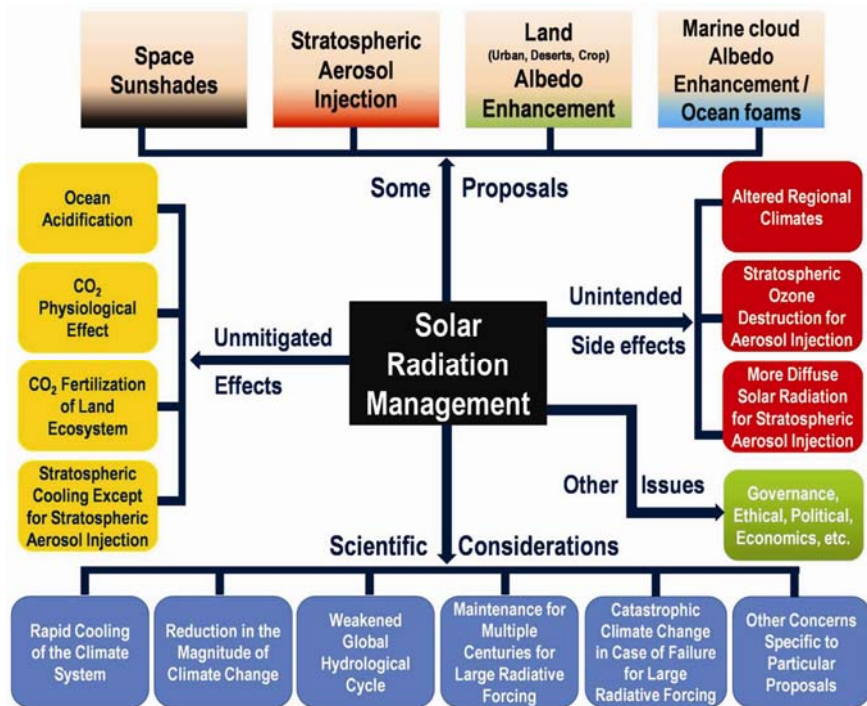


Figure 1. Schematic diagram for solar radiation management (SRM) proposals.

applied to multiple climate models is needed. This effort has been initiated for the modelling of climate effects from stratospheric aerosol injections⁴⁸. Finally, but not the least important, the possibility of SRM geoengineering is by no means an excuse of continued fossil-fuel emissions. A combined emission mitigation and geoengineering strategy is what we might want to seek to avoid dangerous climate change and reduce our dependence on fossil-fuel emissions⁴⁹.

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Corporate education in natural sciences: a professional approach for universities

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The joint education panel of the Indian Academy of Sciences, the Indian National Science Academy and the National Academy of Sciences, India has pointed out that the enormous potential for India to become a leading knowledge power can be realized only if our younger generation has opportunities for all-round good education and training, especially

in science and technology¹. Though the society around our universities has changed and evolved under the selective pressures of a liberalized economy, the intellectual environment of the university has probably declined². We have produced more unemployable graduates, as we treated universities more as a place where students get credentialed and

teachers educate without much concern for societal problems/issues or for the economic future of students.

The Yashpal Committee of 2009 on renovation and rejuvenation of the higher education system in India has given several suggestions³. The position paper of the science academies¹ emphasizes the need for making higher education more