

Solar Radiation Management



Figure 1: Marine stratocumulous clouds increase ocean albedo and reflect incoming solar radiation (ASR Marine Low Cloud Workshop, 2009).

Table of Contents

Table of Contents	2
Introduction	3
Strategies	5
Aerosol Injection	5
Marine Cloud Brightening	7
Surface Albedo Enhancement	9
Space-Based Technologies	10
Concerns and Risks of SRM	10
Environmental Risks	11
Environmental Concerns of Aerosol Injection	11
Environmental Concerns of Marine Cloud Brightening	11
Environmental Concerns of Surface Albedo Enhancement	11
Environmental Concerns of Space-Based Technologies	12
Termination Shock	12
Governance Risks	13
Ethical Risks	13
Glossary	15
Supplements	16
References	17

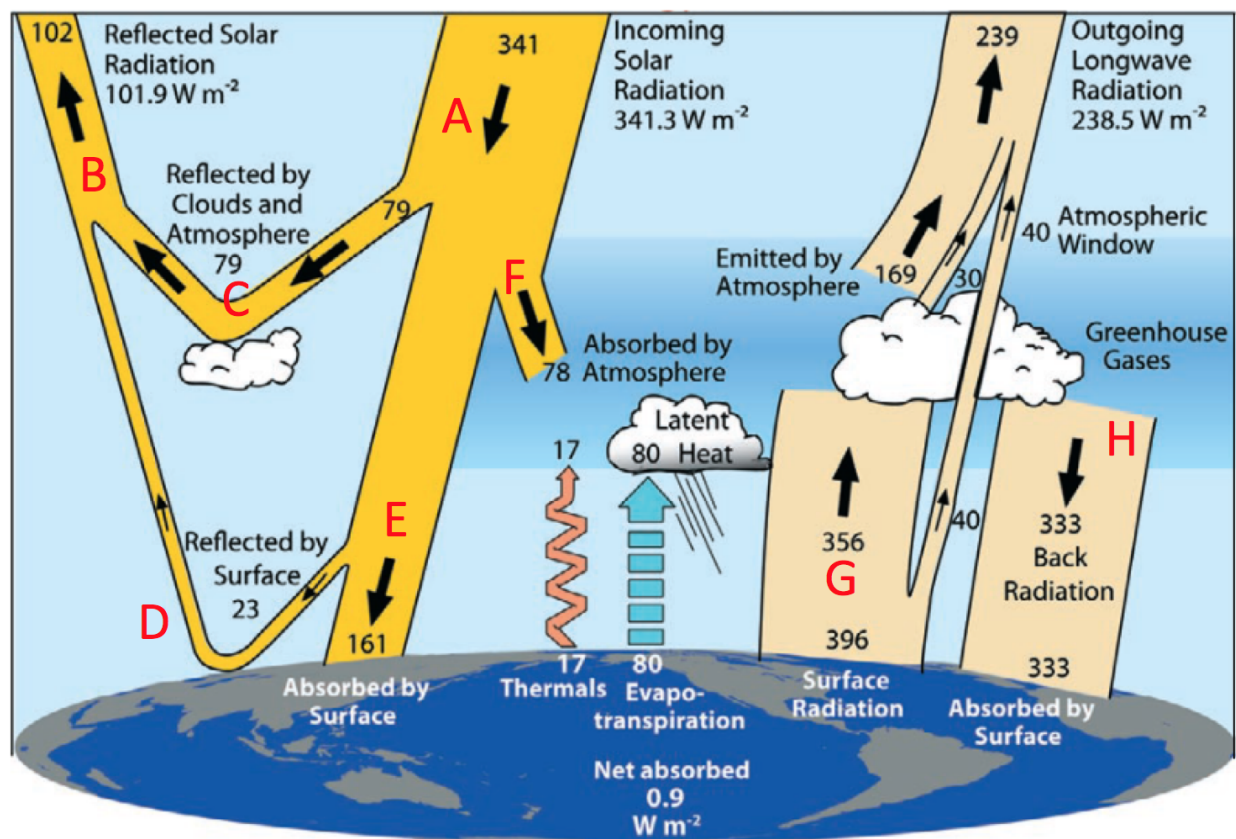
Introduction

Solar Radiation Management (SRM), also known as albedo modification or sunlight reflection modification, is the intentional manipulation of the earth's solar energy budget in order to mitigate warming from climate change. SRM strategies aim to alter the earth's albedo, increasing its reflectivity and reducing the net energy input to the earth system (i.e. heat) from the sun.

SRM addresses global warming through its interactions with incoming solar radiation. Most incoming [shortwave radiation](#) (incoming high-energy light from sun) entering the climate system is absorbed as heat by the earth's surface and then re-emitted as outgoing longwave (infrared) radiation. The longwave radiation is trapped and re-radiated by greenhouse gases in a process known as the greenhouse effect (Fig. 2 G & H). Anthropogenic greenhouse gas emissions are strengthening this effect and driving climate change. SRM increases the albedo of the atmosphere and surface (Fig. 2 C & D) to reduce their net absorption (Fig. 2 E). The higher the albedo of a surface, the more shortwave radiation it reflects. A reduction of incoming shortwave radiation by $3.7\text{W}/\text{m}^2$ is required to counteract the rise in GMST that would occur as a result of a doubling of pre-industrial atmospheric CO_2 concentrations (Shepherd, 2009). This value serves as a reference for comparing the reflectance capacity of various SRM techniques based on the fraction of the radiation balance they can achieve.

Major forms of SRM include stratospheric aerosol injection, marine cloud brightening, and surface albedo enhancement. There are several environmental risks associated with these techniques, most notably termination shock, as well as potential governmental and ethical concerns.

Earth's Energy Balance



Source: Trenberth et al. 2009

Figure 2: Global mean annual solar energy budget for the March 2000 to May 2004 period, measured in watts per square meter (W/ m^2). The broad arrows indicate the schematic flow of energy in proportion to their magnitude. Relevant to discussion: **A**: total incoming solar shortwave radiation. **B**: total incoming shortwave radiation reflected out of the atmosphere. **C**: Shortwave radiation reflected by clouds and atmospheric aerosols. **D**: shortwave radiation reflected by the surface. **E**: shortwave radiation absorbed as heat by the surface. **F**: shortwave radiation absorbed by the atmosphere. **G**: outgoing longwave radiation from the surface **H**: back radiation of longwave radiation by greenhouse gases. Note, this image only covers the fluxes most relevant to SRM (Trenberth, K. et al., 2009).

Strategies

Aerosol Injection

Though controversial, the injection of sulfate aerosols into the stratosphere is one of the most discussed and researched SRM strategies (Robock, 2008). If introduced into the stratosphere, teragrams of aerosolized sulfate could reflect enough incoming shortwave solar radiation to neutralize the average GMST rise resulting from a doubling of atmospheric CO₂ from pre-industrial concentrations (Shepherd, 2009). Regular reintroduction of aerosols would be necessary to sustain this effect, as they fall out of the stratosphere within roughly two years of injection (Gertner, 2017). This intervention, though ongoing, would be relatively cost effective - according to one estimate, implementation would cost under one billion dollars per year (Gertner, 2017).

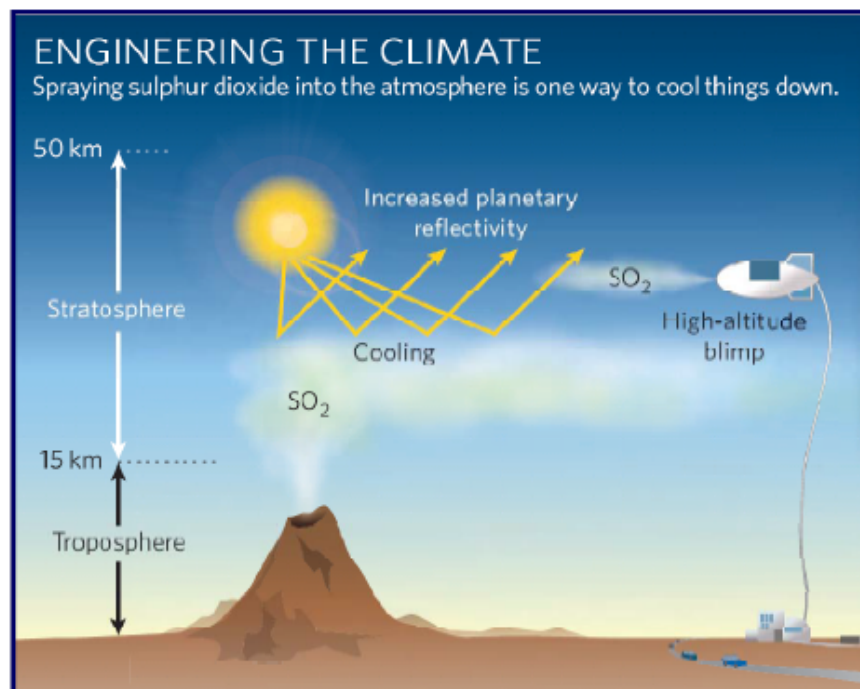


Figure 3: Sulfate aerosols are one candidate for stratospheric aerosol injection. Some large volcanic eruptions can introduce sulfur aerosols into the atmosphere naturally - the same process could be replicated by humans to reflect a percentage of incoming shortwave radiation (Morton, 2007).

Experimentation with aerosol injection has so far been limited. However, potential consequences of injection can be understood through the study of climate in the aftermath of volcanic eruptions. Volcanoes release a large amount of particulate matter into the atmosphere, including sulfur aerosols similar to those under consideration for use in geoengineering

schemes. Eruptions tend to lead to periods of cooling for the earth; the 1991 eruption of Mount Pinatubo in the Philippines cooled the earth by about 0.5° C for roughly two years (Pope et al., 2012).

Several small-scale trials will investigate the effects of injection using various aerosols. [The Scopex project](#) plans to inject a small amount of calcium carbonate and ice particles (alternative potential aerosols) into the atmosphere and will measure local changes in incoming radiation (Gertner, 2017).

Experiments involving real-world injection of aerosols into the stratosphere are complicated because the impacts of aerosol injection are unpredictable and no satisfactory method for equal representation and protection of stakeholders exists. Climate modelling partially circumvents this difficulty. The Geoengineering Model Intercomparison Project (GeoMIP) runs identical climate intervention scenarios in different earth-systems models, and compares the results to inform conclusions about the efficacy and consequences of SRM via aerosol injection. The four experiments (G1, G2, G3, and G4) run in GeoMIP simulate different SRM scenarios with varying degrees of complexity. The G1 experiment quadruples CO₂ from pre-industrial levels and decreases solar radiation such that top-of-atmosphere (TOA) radiation is unchanged. The G2 experiment increases CO₂ by 1% per year, and decreases incoming radiation gradually so that TOA radiation is unchanged. G3 simulates the CO₂ increases predicted by RCP 4.5 from 2020 to 2070 and introduces enough sulfur aerosols to keep TOA radiation at 2020 levels. G4 injects five teragrams of sulfur aerosols into the atmosphere every year from 2020 to 2070 in the RCP 4.5 scenario. The GeoMIP project indicates that while SRM would stabilize or reduce GMST, it would also change global precipitation patterns. Areas of inconsistency between the models (including bioproductivity and sea-ice loss), suggest that some impacts of SRM are still unpredictable (Kravitz et al, 2013a). These models also show a latitudinal bias in that the tropics would experience greater cooling relative to the poles, indicating that SRM may not stabilize ice sheets (see Fig. 4).

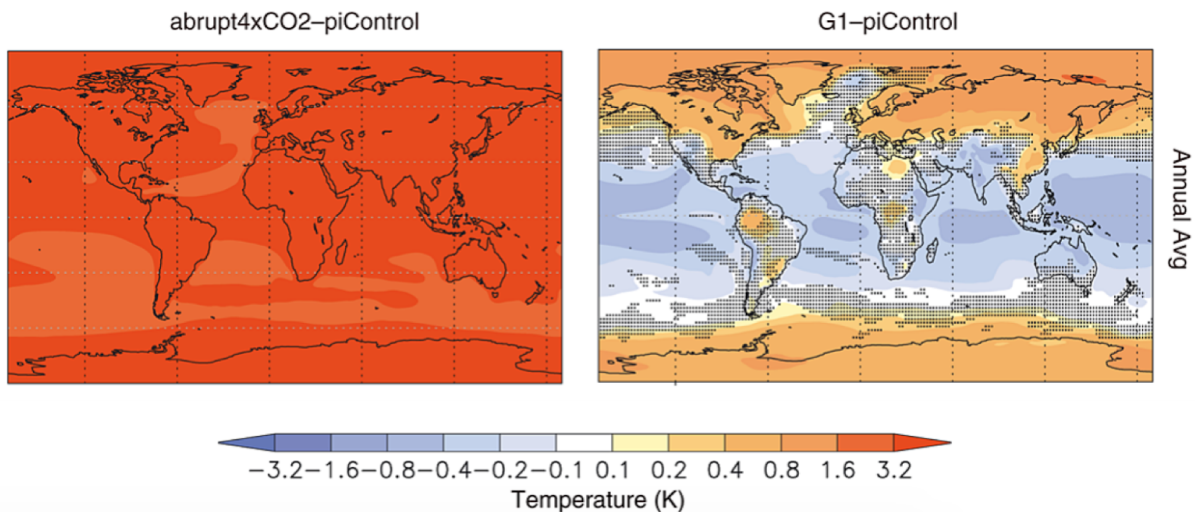


Figure 4: Temperature anomaly results from GeoMIP for G1 control (temperature anomaly from 4x preindustrial CO₂ without solar dimming, left) and G1 (4x preindustrial CO₂ balanced by solar dimming, right). Stippling indicates regions where fewer than 75% of the models included in the GeoMIP analysis agree on the sign of temperature change (Kravitz et al., 2013a).

Marine Cloud Brightening

Marine Cloud Brightening (MCB) reflects shortwave radiation by enhancing the albedo of clouds (Stevenson et al., 2012). This is accomplished by injecting particles into the troposphere, which intensifies cloud formation (Stevenson et al., 2012). Larger clouds reflect more incoming radiation (Stevenson et al., 2012).

The physical mechanisms of MCB are based on the Twomey effect. The Twomey effect occurs after particle injection into the troposphere. An increase in the number of cloud condensation nuclei (CCN) (particles onto which water droplets condense to form clouds) increases the number of droplets in clouds, which in turn increases the albedo of clouds (Hudson, 1993; Stevenson et al., 2012). MCB aims to increase the number of CCN in marine stratocumulus clouds, which are especially sensitive to changes in aerosol concentration and will become more reflective than other clouds if MCB is implemented. Sea salt is the most popular particle for MCB techniques; accordingly, its potential effects are the focus of many MCB research efforts (Latham et al., 2012; Maalick, Korhonen, Kokkola, Kühn, & Romakkaniemi, 2014). Injection of aerosols like sea salt into the troposphere could be performed by airplanes, balloons or ships, but currently airplanes are the most supported option (Latham et al., 2012) (Jones et al., 2010). Unlike stratospheric aerosols, tropospheric aerosols used in MCB have lifetimes on the scale of days (Wood & Ackerman, 2013).

Experiments related to MCB, though limited, involve examination of sea salt sprays and pollution. Increased albedo has been observed in marine stratocumulus clouds as a result of commercial shipping (Wood & Ackerman, 2013). Although a large local albedo change occurs as a result of this brightening, the overall cooling effect is uncertain given the small scales of these shipping tracks (Wood & Ackerman, 2013). Several proposed MCB field tests would implement salt spray technologies and ship tracks and examine their environmental effects, but they have received little attention (Wood & Ackerman, 2013).

MCB has also been tested through computer modelling. Relevant GeoMIP projects for MCB include *G1ocean-albedo*, *G4cdnc*, and *G4seasalt* (Kravitz et al, 2013a). *G1ocean-albedo* models the increase in ocean albedo needed to offset a quadrupling of atmospheric CO₂ concentration (Kravitz, 2013b). *G4cdnc* models increasing CCN in marine stratocumulus clouds to offset RCP 4.5, a predicted warming model developed in the IPCC report (Kravitz, 2013b). *G4seasalt* models how much sea salt spray must be added to the regions between 30° S and 30° N to combat an increase in effective radiative forcing of 2 W/m² based on an RCP4.5 model of warming (Kravitz, 2013b). The results of these methods show changes in precipitation

patterns, increased land/sea temperature contrasts, and localized effects (Kravitz, 2013b). For example, the below results for *G4seasalt* and *G1ocean-albedo* show that while overall radiative forcing decreases, most of the decrease occurs over tropical oceans. Precipitation is predicted to increase around the tropics but decrease elsewhere (Kravitz, 2013b).

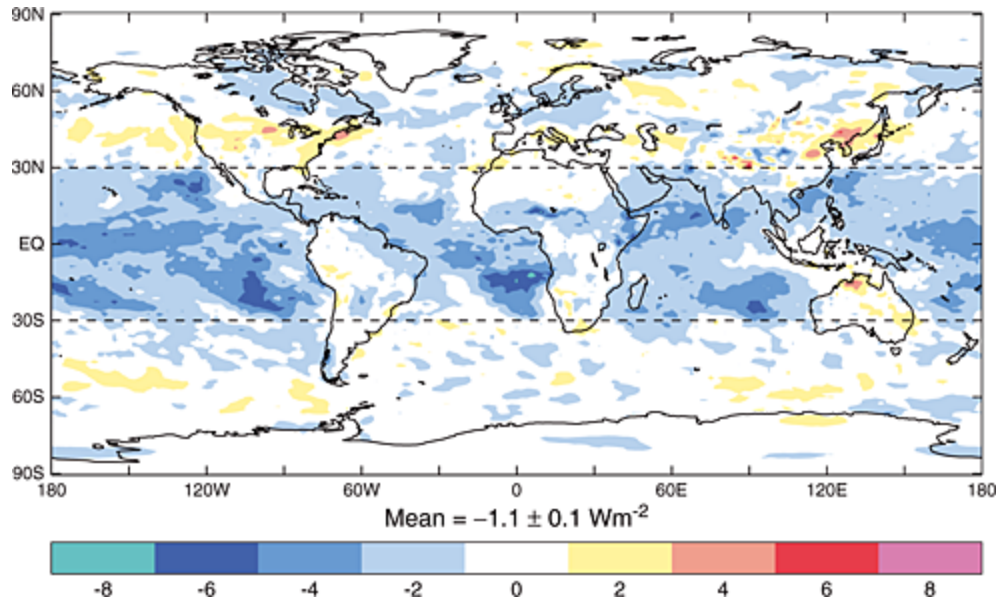


Figure 5. Changes in radiative forcing modeled by GeoMIP project *G4seasalt*. The results show the localized effects of MCB - cooling effects are concentrated over oceans, especially tropical latitude oceans (Alterskjær et al, 2013).

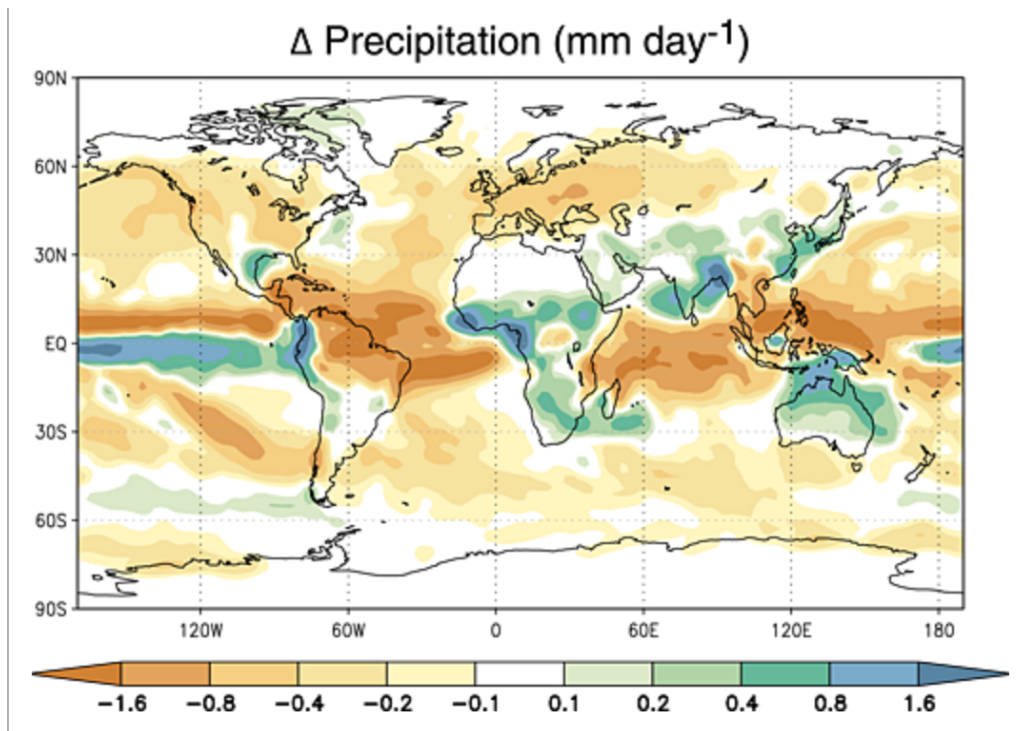


Figure 6. Precipitation changes as a result of MCB modeled in the GeoMIP project *G1ocean-albedo*. The largest increase in precipitation occurs over tropical latitude oceans and the largest decrease in precipitation occurs over tropical latitude continental areas (Alterskjær et. al, 2013).

MCB is capable of inducing the 3.7W/m^2 negative forcing of incoming shortwave radiation required to neutralize the average GMST rise that would occur as a result of a doubling of atmospheric CO_2 (Shepherd, 2009). Thus, MCB can be effective at combating anthropogenic climate change as a standalone strategy (Kravitz, 2013b).

Overall, the effects and costs of MCB are not fully understood due to the lack of research on the topic. The [US National Academies](#) however estimates MCB to cost five billion US dollars annually for a large deployment program (reducing radiative forcing by 5W/m^2) (Committee on Geoengineering Climate, 2012).

Surface Albedo Enhancement

Several SRM strategies aim to enhance the albedo of various surfaces on the earth. These region-specific methods include Cool Roof technologies, Reflective Sheeting, Grassland Management, and Seafoam Rafts.

Cool Roof technologies propose to paint roofs and roads a white or pale color to increase their albedo (Akbari, Menon, & Rosenfeld, 2009; Lenton & Vaughan, 2009; Akbari, Matthews, & Seto, 2012). Models show that this strategy produces 0.01 to 0.019W/m^2 of globally averaged negative forcing, which is insignificant compared to the total required offset of 3.7W/m^2 (Shepherd, 2009; Akbari, Menon, & Rosenfeld, 2009; Lenton & Vaughan, 2009; Irvine, Ridgwell, & Lunt, 2011; Akbari, Matthews, & Seto, 2012). This strategy is limited by the small surface area of roads and rooftops relative to the entire surface area of the earth, and thus more effectively controls local temperatures than GMST (Shepherd, 2009; Lenton & Vaughan, 2009; Akbari, Matthews, & Seto, 2012).

Reflective Sheeting is a proposition to cover $67,000\text{mi}^2$ ($170,000\text{km}^2$) of desert, an area slightly larger than Washington State, with reflective plastic sheets. This could yield a global negative radiative forcing of 2.75W/m^2 , which would contribute significantly towards meeting the total negative forcing needed to counteract a doubling of atmospheric CO_2 (Shepherd, 2009).

Grassland and Crop Management strategies rely on the cultivation of plants with higher albedo. This is thought to increase grassland albedo from 0.17 to 0.21 , equivalent to an average global negative forcing of about 0.56W/m^2 (although the exact potential change in radiative forcing is uncertain). Values of 0.51 and 0.59W/m^2 have also been estimated (Hamway, 2007; Shepherd, 2009; Lenton & Vaughan, 2009; Irvine, Ridgwell, & Lunt, 2011). Similarly, the management of crops and the selection of higher albedo varieties for agricultural use estimates an increase in farmland albedo by 0.08 . This would result in a negative radiative forcing of 0.35W/m^2 (Lenton & Vaughan, 2009). Consequent cooling could reduce heat stress on a local scale. Selection of high albedo plants has also been proposed for the tundra biome to prevent local warming and subsequent melting of carbon-rich permafrost (Zimov, 2005).

Seafoam Rafts are a recent proposition to raise ocean albedo by increasing the extent and longevity of seafoam (Evans, Stride, Edirisinghe, Andrews, & Simons, 2010). Researchers in the United Kingdom have developed biodegradable foams with an albedo of 0.5-0.55 that are stable in laboratory conditions that simulate still ocean water (Aziz, Hailes, Ward, & Evans, 2014). The GeoMIP G4Foam experiment simulated an increase in ocean albedo from near-zero to 0.15 by raising the albedo of three gyres in the southern hemisphere within the GeoMIP models and model ensembles, which generated an average global negative forcing of 1.5W/m^2 (Gabriel, Robock, Xia, Zambri, & Kravitz, 2017).

There are currently no available estimates of the expenses associated with the various Surface Albedo Enhancement techniques that have been proposed.

Space-Based Technologies

Space-based techniques propose to reduce the amount of incoming solar radiation by placing sun-shields in space to reflect radiation before it arrives at Earth (Shepherd et al., 2009). The two prominent groups of space-based technology proposals are Near-Earth Reflectors and L1 Reflectors. Near-Earth Reflectors are reflective satellites placed in a near-Earth orbit. Due to the proximity of these satellites' orbit to the earth, many are required to achieve a globally uniform reduction of incoming solar radiation. In 1992, the US National Academy of Sciences proposed that a swarm of 50,000 mirrors with an area of 100m^2 could be placed in random orbits around the earth in a Near-Earth Reflection scheme (Shepherd et al., 2009). Another proposal involves placing a ring of lightweight electrodynamically tethered satellites 2000-4500km above the equator (Pearson et al., 2006).

L1 Reflectors are technologies that propose to achieve a globally uniform reduction of incoming solar radiation by placing a reflector at the L1 point, the position approximately 1.5 million miles away from the Earth in the direction of the sun where the gravitational pull of the two bodies is equal (Shepherd et al, 2009). This strategy offers the advantage of requiring approximately 100 times less material to accomplish the same negative radiative forcing as a Near-Earth Reflection method, due to the large distance between the L1 Reflector and Earth (Shepherd et al., 2009). The reflector required to achieve this forcing would need an area of 3 million km^2 (Shepherd et al., 2009). Implementation of either space mirror strategy is unrealistic due to resource requirements and deployment logistics (Shepherd et al., 2009).

Concerns and Risks of SRM

The potential consequences of SRM strategies can be broadly divided into environmental risks, governmental risks, and ethical risks. The magnitude and nature of these risks vary for each

SRM technique, although all particle injection based SRM techniques pose the risk of termination shock.

Environmental Risks

Though some environmental consequences of sulfate injection and MCB are known, the exact effects of these strategies are unclear in part due to a lack of empirical observations on the topic (Robock, 2016). There are general concerns regarding disruptions to the [hydrologic cycle](#) and increased incidence of extreme droughts and floods (Robock, 2016a). Moreover, SRM would not address other negative effects of climate change, including high levels of carbon in the atmosphere and ocean acidification (Robock, 2016).

Please look at chat if you have not yet

Environmental Concerns of Aerosol Injection

Studies show that aerosol injection could deplete the ozone layer, which would increase incoming radiation (Anderson, Wilmouth, Smith, & Sayres, 2012; Robock, 2016a). Models also show that aerosol injection will overcool tropical regions and undercool polar regions. (Tilmes et al., 2013; Kravitz et al., 2013a; Xia, 2014). Additionally, aerosol particles could sink into the troposphere, where they would react with oxygen in the atmosphere to form sulfuric acid and create higher concentrations of acid rain (Crutzen, 2006).

Aerosol injection could also have an aesthetic cost, as it would decrease visibility, obstructing star gazing, satellite monitoring, and mountain viewing. (Alterskjær et al., 2013; Robock, 2016a).

Environmental Concerns of Marine Cloud Brightening

MCB is projected to have uneven effects on the planet that will alter existing precipitation patterns. MCB slightly intensifies precipitation and latent heat flux over continents, which could affect agriculture and vulnerable communities. In some MCB models, global mean precipitation is reduced 1.6% but regionally, rainfall decreases over South America and increases over Sub-Saharan Africa and Australia (Jones, 2009). MCB's impacts on precipitation lead to changes in Net Primary Productivity (NPP). NPP typically increases in areas with increased precipitation and decreases in areas with reduced precipitation, which can lead to decreases in agricultural productivity (Jones et al., 2009; Lathan et al., 2012). Furthermore, changes in precipitation and NPP affect existing ecosystems and carbon sinks - reductions in rainfall stunt the growth of rainforests in South America and reduce the carbon sink of the rainforest (Jones, 2009).

Environmental Concerns of Surface Albedo Enhancement

Regional application of surface albedo enhancement would alter temperature and lead to changes in the hydrologic cycle (Shepherd, 2009). The Reflective Sheeting scheme would

physically cover thousands of square miles of land, destroying pre-existing ecosystems (Shepherd, 2009). There remains uncertainty as to Foam Rafts will affect the hydrological cycle. The G4Foam experiment simulated Foam Rafts by raising ocean albedo in 3 gyres to 0.15 (Gabriel, Robock, Xia, Zambri, & Kravitz, 2017). The models used did not incorporate the changes to the properties of the ocean surface that the foam would cause. Therefore, they did not account for alterations to the hydrological cycle that would likely result from changes to air-sea exchange caused by the foam's effect on ocean surface properties. Similarly, Grassland and Crop Management strategies have the potential to facilitate the introduction and spread of invasive species (Shepherd et al., 2009). Cool Roof Technologies entail comparatively few environmental risks, however their small reflectance potential makes them an unrealistic alternative (Shepherd et al., 2009).

Environmental Concerns of Space-Based Technologies

The GeoMIP G1 experiment simulated the conditions that Near-Earth Reflectors or L1 Reflectors would ideally induce. Thus, Space-Based technologies are thought to cause cooling at low latitudes and heating at higher latitudes relative to the current GMST (Kravitz et al., 2013a).

Termination Shock

Perhaps the largest risk associated with SRM is termination shock, the sudden change in climate that would occur if SRM abruptly stopped. In this scenario, the effects of climate change previously avoided by SRM would occur within a span of 10 to 15 years, at a drastic pace allowing little time for adaptation (Jones et al., 2013).

According to some GeoMIP simulations, if SRM were implemented for 50 years and then stopped without any change in CO₂ emissions, temperature would rapidly rise to meet the projected non-SRM temperature within 15 years, rather than the slow adjustment expected in a business as usual scenario (BAU) (Jones et al., 2013). Additionally, Arctic and Antarctic sea ice would melt more rapidly, and precipitation would increase more rapidly than in BAU (Jones et al., 2013).

Figure 5: The lines indicate different climate models, part of the G2 GeoMIP experiment, each predicting a sharp increase in temperature and change in precipitation due to termination shock if SRM were to be abruptly stopped after 50 years of implementation (Kravitz et al., 2013a).

These rapid changes pose large risks because they leave little time for humans and ecosystems to adapt. In a non-SRM scenario, changes occur more slowly, allowing a greater chance for adjustment. Thus, reserve funding or alternative plans would be necessary if SRM could not monetarily or otherwise be sustained.

There are, however, several possible ways to avert termination shock. If CO₂ is removed from the atmosphere, less and less SRM will be necessary to prevent climate change, and it could eventually be tapered off (Reynolds, Parker, & Irvine, 2016). In this case, SRM would act as a temporary solution until carbon dioxide removal could be implemented at a large scale. More experiments in the GeoMIP style are needed to see if SRM could be gradually decreased, slowing the adjustment back to a non-SRM climate (Keith & MacMartin, 2015).

Governance Risks

Technical consequences may be much less complex than addressing governance and ethical issues (Shepherd, 2009). Currently, no international governance mechanism exists for SRM geoengineering.

Implementation of SRM technologies will have internationally-felt environmental side effects with effects spanning decades. Conflict of interest could make agreement on the topic of SRM difficult. Moreover, rich and stable countries have the greatest means to implement SRM and thus to determine environmental effects experienced by other countries (National Research Council, 2015). The current lack of governmental regulation leaves loopholes for individual persons, companies, universities or countries with the economic resources to venture into SRM (Robock, 2008). In addition, governments could weaponize SRM (Robock, 2008), potentially resulting in wide-ranging, unintended consequences.

Events such as global war or pandemic would make continuing SRM difficult or impossible in the short or long term, increasing the risk of termination shock (Baum, Maher, & Haqq-Misra, 2013).

Ethical Risks

Implementation of SRM may be used to justify continued use of greenhouse gas-producing fuels or to excuse failures to mitigate greenhouse gas emissions, the root cause of climate change (Robock, 2016a). Addressing the symptoms of climate change while not addressing the causes constitutes a moral hazard.

In general, people with less socioeconomic power are more vulnerable to the impacts of climate change and to the differential impacts of SRM. Furthermore, smaller and less stable countries will likely have less input on implementing SRM (Mach & Mastrandrea, 2014). Precipitation patterns are likely to change, and incidences of floods and droughts will increase, both of which will disproportionately affect disenfranchised people.

Glossary

GeoMIP: Geoengineering Model Intercomparison Project

GMST: Global Mean Surface Temperature

IPCC: International Panel for Climate Change

MCB: Marine Cloud Brightening

RCP: Representative Concentration Pathway

SRM: Solar Radiation Management

UNEP: United Nations Environment Programme

WMO: World Meteorological Institute

Moral Hazard: Moral hazard refers to the risk that those insulated from the negative consequences of an action will not factor those consequences into their decision making processes.

Supplements

Table 1: Benefits and risks/concerns of stratospheric aerosol injection as based on Robock, 2016a meant to summarize consequences of aerosol injection given in “Concerns and Risks”.

Benefits	Risks and Concerns
Reduce temperature of surface air, mitigating some effects of climate change on frequency and intensity of floods, droughts, hurricanes	Disrupts hydrological cycle, causing more intense, less frequent rains
Diffusion of incoming radiation could increase plant productivity	Depletes the ozone layer
Could reduce temperatures long enough for other longer-term methods, especially CDR, to take effect or develop technologies to scale	Ocean acidification continuation
	Ice sheet melting may continue, leading to sea level rise
	Solar electricity generation less productive
	Solar passive heating less productive
	Negatively impacts satellite remote sensing due to decreases in visibility
	Negatively impacts stargazing, both amateur and scientific
	Rapid warming when stopped (see Termination Shock)
	How and who decides the ideal temperature? Which governments? How are corporations involved or not involved?
	Concern about continuation of project during major disruptions such as pandemic, war, etc.
	Is the technology precise enough to be militarized?
	Possible reduction in societal motivation to mitigate or adapt if implemented (sense that something is already being done)

References

- Akbari, H., Matthews, H. D., & Seto, D. (2012). The long-term effect of increasing the albedo of urban areas. *Environmental Research Letters*, 7(2), 024004. Retrieved from <http://iopscience.iop.org/article/10.1088/1748-9326/7/2/024004/meta>
- Akbari, H., Menon, S., & Rosenfeld, A. (2009). Global cooling: increasing world-wide urban albedos to offset CO₂. *Climatic change*, 94(3), 275-286. Retrieved from <https://link.springer.com/article/10.1007/s10584-008-9515-9>
- Alterskjær, K., Kristjánsson, J. E., Boucher, O., Muri, H., Niemeier, U., Schmidt, H., ... & Timmreck, C. (2013). Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models. *Journal of Geophysical Research: Atmospheres*, 118(21). <http://dx.doi.org/10.1002/2013JD020432>
- Anderson, J. G., Wilmoth, D. M., Smith, J. B., & Sayres, D. S. (2012). UV dosage levels in summer: Increased risk of ozone loss from convectively injected water vapor. *Science*, 1222978. doi: 10.1126/science.1222978
- ASR Marine Low Clouds Workshop Held. (2016, February 29). Retrieved December 07, 2017, from <https://www.arm.gov/news/events/post/36451>
- Aziz, A., Hailes, H. C., Ward, J. M., & Evans, J. R. (2014). Long-term stabilization of reflective foams in sea water. *RSC Advances*, 4(95), 53028-53036. doi:10.1039/C4RA08714C
- Baum, S. D., Maher, T. M., & Haqq-Misra, J. (2013). Double catastrophe: intermittent stratospheric geoengineering induced by societal collapse. *Environment Systems & Decisions*, 33(1), 168-180. <https://doi.org/10.1007/s10669-012-9429-y>
- Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts; Board on Atmospheric Sciences and Climate; Ocean Studies Board; Division on Earth and Life Studies; National Research Council (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. National Academies Press.
- Crutzen, P. J. (2006). Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma?. *Climatic change*, 77(3), 211-220. <https://doi.org/10.1007/s10584-006-9101-y>
- Evans, J., Stride, E., Edirisinghe, M., Andrews, D., & Simons, R. (2010). Can oceanic foams limit global warming? *Climate Research*, 42(2), 155-160. Retrieved from <http://www.jstor.org/stable/24870330>
- Gabriel, C. J., Robock, A., Xia, L., Zambri, B., & Kravitz, B. (2017). The G4Foam Experiment: global climate impacts of regional ocean albedo modification. *Atmospheric Chemistry and Physics*, 17(1), 595. <https://doi.org/10.5194/acp-17-595-2017>
- Gertner, J. (2017). Is it o.k. to tinker with the environment to fight climate change? *New York Times*. Retrieved from https://www.nytimes.com/2017/04/18/magazine/is-it-ok-to-engineer-the-environment-to-fight-climate-change.html?_r=0
- Hamwey, R. M. (2007). Active amplification of the terrestrial albedo to mitigate climate change: an exploratory study. *Mitigation and Adaptation Strategies for Global Change*, 12(4), 419-439. doi.org/10.1007/s11027-005-9024-3
- Hudson, J. G. (1993). Cloud condensation nuclei. *Journal of Applied Meteorology*, 32(4), 596-607. [https://doi.org/10.1175/1520-0450\(1993\)032<0596:CCN>2.0.CO;2](https://doi.org/10.1175/1520-0450(1993)032<0596:CCN>2.0.CO;2)
- Irvine, P. J., Ridgwell, A., & Lunt, D. J. (2011). Climatic effects of surface albedo geoengineering. *Journal of Geophysical Research: Atmospheres*, 116(D24). <http://onlinelibrary.wiley.com/doi/10.1029/2011JD016281/abstract>
- Jones, A., Haywood, J. M., Alterskjær, K., Boucher, O., Cole, J. N., Curry, C. L., ... & Moore, J. C. (2013). The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, 118(17), 9743-9752. dx.doi.org/10.1002/jgrd.50762
- Jones, A., Haywood, J., & Boucher, O. (2009). Climate impacts of geoengineering marine stratocumulus clouds. *Journal of Geophysical Research: Atmospheres (1984–2012)*, 114(D10).

- Jones, A., Haywood, J. and Boucher, O. (2011). A comparison of the climate impacts of geoengineering by stratospheric SO₂ injection and by brightening of marine stratocumulus cloud. *Atmospheric Science Letters*, 12, 176–183. doi:10.1002/asl.291.
- Keith, D.W., & MacMartin, D. G. (2015). A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change*, 5(3), 201-206. doi:10.1038/nclimate2493
- Kravitz, B., Forster, P. M., Jones, A., Robock, A., Alterskjær, K., Boucher, O., ... & Niemeier, U. (2013b). Sea spray geoengineering experiments in the geoengineering model intercomparison project (GeoMIP): Experimental design and preliminary results. *Journal of Geophysical Research: Atmospheres*, 118(19). doi:10.1002/jgrd.50856.
- Kravitz, B., Robock, A., Forster, P. M., Haywood, J. M., Lawrence, M. G., & Schmidt, H., ... (2013c). An overview of the geoengineering model intercomparison project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, 118. <https://doi.org/10.1002/2013JD020569>
- Latham, J., Bower, K., Choullarton, T., Coe, H., Connolly, P., Cooper, G., ... Wood, R. (2012). Marine cloud brightening. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 370(1974), 4217–4262. <http://doi.org/10.1098/rsta.2012.0086>.
- Latham, J., Parkes, B., Gadian, A., & Salter, S. (2012). Weakening of hurricanes via marine cloud brightening (MCB). *Atmospheric Science Letters*, 13(4), 231-237.
- Lenton, T. M., & Vaughan, N. E. (2009). The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics*, 9(15), 5539-5561. doi:10.5194/acpd-9-2559-2009.
- Maalick, Z., Korhonen, H., Kokkola, H., Kühn, T., & Romakkaniemi, S. (2014). Modelling artificial sea salt emission in large eddy simulations. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 372(2031), 20140051. <http://doi.org/10.1098/rsta.2014.0051>
- Mach, K., & Mastrandrea, M. (2014). *Climate change 2014: impacts, adaptation, and vulnerability* (Vol. 1). C. B. Field, & V. R. Barros (Eds.). Cambridge and New York: Cambridge University Press. Retrieved from http://ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf
- Morton, O. (2007). Climate change: Is this what it takes to save the world?. *Nature*, 447(7141), 132-136. Retrieved November 15, 2017, from <https://www.nature.com/articles/447132a>
- National Research Council. (2015). Climate intervention: reflecting sunlight to cool earth. <https://doi.org/10.17226/18988>.
- Pearson J, Oldson J & Levin E (2006). Earth rings for planetary environment control. *Acta Astronautica* 58, 44–57.
- Pope, F. D., Braesicke, P., Grainger, R. G., Kalberer, M., Watson, I. M., Davidson, P. J., & Cox, R. A. (2012). Stratospheric aerosol particles and solar-radiation management. *Nature Climate Change*, 2(10), 713-719. doi:10.1038/nclimate1528. <https://www.nature.com/articles/nclimate1528>
- Reynolds, J. L., Parker, A. & Irvine, P. (2016). Five solar geoengineering tropes that have outstayed their welcome. *Earth's Future*, 4: 562–568. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1002/2016EF000416/abstract>
- Robock, A. (2008). 20 reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists*, 64(2), 14-18. <https://doi.org/10.2968/064002006>
- Robock, A. (2016a, July). Smoke and mirrors are not the solution to global warming. *Royal Society of Chemistry Environmental Chemistry Group Bulletin*, 19-21. Retrieved from <http://climate.envsci.rutgers.edu/pdf/RoyalSocChemBulletinRobock.pdf>.
- Robock, A. (2016b). Albedo enhancement by stratospheric sulfur injections: More research needed. *Earth's Future*, 4(12), 644-648. Retrieved from onlinelibrary.wiley.com/doi/10.1002/2016EF000407/epdf.
- Shepherd, J. G. (2009). Geoengineering the climate: science, governance and uncertainty. *Royal Society*. Retrieved from https://royalsociety.org/~media/Royal_Society_Content/policy/publications/2009/8693.pdf
- Stevenson, H. W., Wang, Q., Wood, R., Ormond, B., Parkes, B., Rasch, P., ... & Leslie, B. (2012). Marine cloud brightening. Retrieved from <https://pdfs.semanticscholar.org/9e5b/4f8a93069e45f8f525f9370156cfe06ebb8e.pdf>
- Stevenson, S., Otto-Bliesner, B., Fasullo, J., & Brady, E. (2016). “El Niño Like” hydroclimate responses to last millennium volcanic eruptions. *Journal of Climate*, 29, 2907–2921. <https://doi.org/10.1175/JCLI-D-15-0239.1>

- Tilmes, S., Fasullo, J., Lamarque, J. F., Marsh, D. R., Mills, M., Alterskjær, K., ... & Cole, J. N. (2013). The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, 118(19).
<http://dx.doi.org/10.1002/jgrd.50868>
- Trenberth, K. et al. (2009). Earth's Global Energy Budget. *Bulletin of American Meteorological Society*. Volume 90, No. 3. pp. 311-324.<https://doi.org/10.1175/2008BAMS2634.1>
- Wood, R. & Ackerman, T.P. Climatic Change (2013) 121: 459. <https://doi.org/10.1007/s10584-013-0932-z>
- Xia, L., Robock, A., Cole, J., Curry, C. L., Ji, D., Jones, A., ... & Singh, B. (2014). Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, 119(14), 8695-8711. doi:10.1002/2013JD020630
- Zimov, S. A. (2005). Pleistocene park: return of the mammoth's ecosystem. *Science*, 308(5723), 796-798. doi:10.1126/science.1113442