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Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts

Peter J. Irvine[1], David W. Keith[1], John Moore[2,3]

[1]Harvard John A. Paulson School of Engineering and Applied Sciences, Cambridge, Massachusetts, USA
[2]Joint Center for Global Change Studies, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China
[3]Arctic Centre, University of Lapland, Rovaniemi 96101, Finland

Correspondence to: peter_irvine@g.harvard.edu

Abstract. Stratospheric aerosol geoengineering, a form of solar geoengineering, is a proposal to add a reflective layer of aerosol to the stratosphere to reduce net radiative forcing and so to reduce the risks of climate change. Solar geoengineering could reduce temperatures and so slow melt, but the efficacy of solar geoengineering at offsetting changes to the cryosphere is uncertain. For example, shortwave forcing acts more strongly on the surface than longwave forcing so solar geoengineering would reduce surface melt more effectively but would also suppress the global hydrological cycle potentially reducing accumulation on glaciers. Regardless of how effective solar geoengineering would prove to be at offsetting surface mass balance changes, slow-acting changes below the surface of the ocean and ice-sheets may strongly limit its potential to reduce the retreat of marine glaciers and can't be evaluated without high-quality process model studies. Here we review the literature on solar geoengineering and the cryosphere and identify the key uncertainties that research could address. Solar geoengineering is a contentious emerging issue in climate policy and it is critical that the potential, limits and risks of these proposals are made clear for policy makers.

1 Future Sea-level rise and the potential of solar geoengineering

How far sea-levels would rise under some scenario of future climate change depends mainly on global temperature rise, and uncertainties in projections rise rapidly as warming increases more than 2°C above pre-industrial (Jevrejeva et al., 2016; Kopp et al., 2014). Most of this uncertainty is due to a lack of agreement on how the large ice sheets will respond (Bamber and Aspinall, 2013; Oppenheimer et al., 2016). For example, two recent estimates of Antarctica's contribution (DeConto and Pollard, 2016; Ritz et al., 2015), both of which were published in Nature, estimated best guesses of 10 cm and about 1 m respectively.

A rapid transition towards a carbon-free economy will reduce additional temperature increases but the temperature response to cumulative emissions—and thus the impact on sea level—will remain for millennia without measures beyond emissions cuts. Two broad categories of measures might reduce long-term commitments to global sea level rise: solar geoengineering and carbon removal. Solar geoengineering, which describes a set of proposals to increase Earth's albedo, offers this potential. Solar geoengineering is not a substitute for emissions cuts, but it could offer an independent means of reducing the growth in radiative forcing and thus the impacts of climate change and so be a complement to emissions cuts. The two responses may be synergistic: carbon removal can reduce the long-term driver of climate change, while solar geoengineering might temporarily reduce the net radiative forcing. Our focus is on assessing solar geoengineering impact on sea level rise because existing research is quite limited because it's effects may not be the same as would be achieved with the same temperature change achieved by reduction in carbon burden through carbon removal.

The human, environmental and financial costs of sea level rise are substantial. The rapidly rising concentration of population and infrastructure in coastal cities mean costs of flooding without adaptation measures are projected at $50 trillion per year by 2100, while coastal protection would cost $15-70 billion per year (Hinkel et al., 2014). One important consideration is that sea level rise is not globally uniform, due to a combination of local factors: glacial isostatic adjustment and ground water extraction resulting in local vertical land movement, the self-gravitational influence of mass loss from the large ice sheets and changes in ocean dynamics and rates of volume expansion of warming sea water. Taking all these together Jevrejeva et al. (2016) find that the 80-90% of global coastlines will experience sea level rises about twice as large as the global ocean average.

Whilst some, including one of us (David Keith), have been working on solar geoengineering for decades, more than ten times as many articles have been published on the topic since 2007 than before. Whilst many proposals for solar geoengineering have been made, work now focuses on a few of the more likely candidates. Marine Cloud Brightening, a proposal to increase the albedo of marine strato-cumulus by releasing sea-salt aerosols from ships (Latham, 1990); Cirrus Cloud Thinning, a proposal to suppress cirrus cloud persistence, and hence reduce their warming effect, by releasing ice nuclei to encourage the formation of larger, shorter-lived ice crystals (Mitchell and Finnegan, 2009); and Stratospheric Aerosol Geoengineering, a proposal to release aerosol particles into the stratosphere to create a persistent reflective aerosol layer (Budyko, 1977). Of these proposals stratospheric aerosol geoengineering is the most likely to be technically achievable. Multiple, independent feasibility assessments of the proposal conclude that a substantial cooling could be achieved with a few Terragrams of material released per year and that lifting a Terragram to the lower stratosphere (~20km) could be achieved at a cost in the range of order a billion US dollars per Terragram (McClellan et al., 2012; Moriyama et al., 2016). The clouds and aerosols chapter of the last IPCC report concluded that "there is medium confidence that stratospheric aerosol [geoengineering] is scalable to counter the RF from increasing GHGs at least up to approximately 4 W m-2" (Boucher et al., 2013). For this reason, here we focus on stratospheric aerosol injection and unless otherwise stated, solar geoengineering will heretofore refer to stratospheric aerosol geoengineering only.

The tens of climate model studies of solar geoengineering prior to 2015 were summarized in the last IPCC report (Boucher et al., 2013): "Models consistently suggest that [solar geoengineering] would generally reduce climate differences compared to

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Discussion started: 26 January 2018

a world with elevated GHG concentrations and no [solar geoengineering]; however, there would also be residual regional differences in climate (e.g., temperature and rainfall) when compared to a climate without elevated GHGs." This reduction in the magnitude of many climate trends means that solar geoengineering may offer a means to reduce the risks of climate change (Keith and Irvine, 2016).

Beyond its effect on climate (which will be discussed in more depth below), stratospheric aerosol injection would have a number of side-effects. Simulations of stratospheric sulphate aerosol injection (the most commonly analyzed scenario of stratospheric aerosol geoengineering) consistently show that it would lower ozone concentrations, delaying the recovery of the ozone hole by a number of decades (Pitari et al., 2014; Tilmes et al., 2012). As well as scattering light back to space the stratospheric aerosol cloud would also scatter light downwards shifting the balance of direct to diffuse light (Kravitz et al., 2012). The aerosols would also absorb radiation, warming the stratosphere affecting stratospheric chemistry and dynamics (Tilmes et al., 2009). The magnitude of these side-effects will depend on the properties of the injected aerosols, and alternatives to sulphate particles may have substantially reduced side-effects (Keith et al., 2016).

In its seminal 2009 report (Shepherd et al., 2009), the United Kingdom's Royal Society predicted that the social and political challenges posed by solar geoengineering would be far greater than the technical ones. Its potentially low cost could mean that individual nations or very wealthy individuals could have the resources to deploy solar geoengineering (Weitzman, 2014). The global impacts of any large-scale deployment could be the source of international tension and poses a serious challenge for international governance (Victor, 2008).

Technical analyses and climate model simulations suggest solar geoengineering may offer a means of reducing the risks of climate change but it would also introduce new risks, both physical and socio-political. A robust understanding of the potential and limits of solar geoengineering as a means to reduce climate risks is a necessary, but not sufficient, basis for a much broader discussion of this idea. This study aims to highlight the key questions around the sea-level rise response to solar geoengineering that only the sea-level and cryosphere community will be able to resolve. In section 2, we provide a brief review of studies into the sea-level rise response to solar geoengineering noting the methodological shortcomings and gaps in the literature. In section 3, we evaluate how different the effects of solar geoengineering and a reduction in GHG forcing could be at reducing sea-level, discussing its potential effects on surface mass balance and on ocean-driven melt and discharge. In section 4, we discuss the ways in which solar geoengineering could be tailored to increase its efficacy at reducing sea-level and note some of the trade-offs involved in such decisions. In section 5, we look at long-run projections of sea-level and argue that it is critical to introduce solar geoengineering into such analyses. In section 6, we summarize the article and make a number of recommendations for research.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-279
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Discussion started: 26 January 2018

2 Critical review of existing literature on solar geoengineering and sea-level rise

As solar geoengineering would reduce temperatures across the world it is clear that to first order it would reduce both the thermal expansion of the oceans and the melting of land ice. Wigley (2006), Moore et al. (2010) and Irvine et al. (2012) illustrate this using simple models of the sea-level rise response to a range of solar geoengineering scenarios. Moore et al. (2010) used a semi-empirical model relating radiative forcing to sea level calibrated by tide gauge data from the past 200 years to evaluate a range of different forms of solar geoengineering. Wigley (2006) and Irvine et al. (2012) adapted the simple models used in the Intergovernmental Panel on Climate Change third and fourth assessment reports, respectively, to evaluate a range of different levels of cooling from solar geoengineering. Moore et al. (2015) used the relationship observed between sea surface temperatures and Atlantic hurricanes to evaluate the effects of solar geoengineering on storm surges along the East coast of North America.

In addition to these studies with models of reduced complexity there have been a few studies employing glacier and ice sheet models. Irvine et al. (2009) conducted a study of the response of the Greenland Ice Sheet to a range of idealized and fixed scenarios of solar geoengineering deployment using the GLIMMER ice dynamics model driven by temperature and precipitation anomalies from a climate model and found that solar geoengineering could slow and even prevent the collapse of the ice sheet. Applegate and Keller (2015) used a simplified ice dynamics model driven by an Earth system model of intermediate complexity to evaluate the response of the Greenland Ice Sheet to scenarios of future GHG emissions and solar geoengineering deployment. They found that whilst solar geoengineering could slow or halt melting, there is strong hysteresis and restoring temperatures would not lead to a rapid recovery of the ice sheet. Zhao et al. (2017) evaluate the response of the 94,000 High Mountain Asia glaciers using an empirical model based on each glacier's median elevation sensitivity to changes in only temperature and precipitation. Under scenarios where solar geoengineering halts regional temperature increases, 30% of present-day glaciated area will still be lost this century due to the glaciers being out of balance with present day climate.
These studies illustrate that if solar geoengineering were deployed it could reduce the rate of sea-level rise substantially compared with greenhouse forcing alone. However, all studies to date have employed simplified global models. Thus these studies miss out on some of the fundamental differences between scenarios of climate change with and without solar geoengineering.

Whilst increasing the planetary albedo would undoubtedly cool the climate, the effects of a reduction in incoming light differ substantially from the heat-trapping effects of greenhouse gas forcing. GHG forcing acts more-or-less uniformly, whereas solar forcing acts only when the sun is up. Offsetting the GHG forcing with solar forcing would therefore produce seasonal, diurnal and latitudinal differences in radiative forcing.

Furthermore, solar forcing acts primarily on the surface whereas GHG forcing acts most strongly on the middle troposphere where infrared radiation escapes to space. As a result solar forcing reduces the intensity of the hydrological cycle more strongly than does a reduction in GHG forcing that produces the same top-of-the-atmosphere radiative forcing. Bala et al. (2008) evaluated the sensitivity of the global hydrological cycle, finding a 2.4 $\%K^{-1}$ change in global mean precipitation for solar forcing and only a 1.5 $\%K^{-1}$ for CO_2 forcing. They note that insolation changes result in relatively larger changes in net radiative fluxes at the surface than CO_2 forcing resulting in larger changes in sensible and latent heat fluxes.

Beyond this fundamental difference in the climate response to solar forcing, some stratospheric aerosols, particularly sulfuric acid the most important single proposal, have significant near infrared absorption bands that would result in a warming of the stratosphere. This warming would have dynamic implications, for example McCusker et al. (2015) find significant changes in circulation in the Antarctic stratosphere which propagates down to affect surface winds and the mixing of waters around Antarctica.

These differences between greenhouse gas and shortwave forcing matter for making predictions of the surface mass balance of glaciers and ice-sheets: Melting of ice peaks during the day in summer when it is most sensitive to changes in surface energy balance; Changes in snowfall amount and seasonality would affect glacier mass balance; And, solar geoengineering would alter atmospheric and oceanic circulation patterns which can affect the upwelling of warm waters around ice shelves weakening them. In the following sections we will identify how solar geoengineering could affect these factors and identify the most pressing uncertainties.

3 How effective could stratospheric aerosol geoengineering be at reducing surface mass losses?

Virtually all Earth System Models simulations and also glacier dynamics models have, to date, only included crude parametrization of surface mass balance. Essentially using a "degree-day" factor to characterize the amount of melt per degree above freezing at the glacier surface. Degree day factors are determined empirically and vary due to surface albedo, meaning that a weathered ice surface such as the Greenland ice margin are rather dark and have high degree-day factors, while pristine snow cover has a low factor.

Fundamentally the surface melt rate depends on the availability of energy at the surface; this means that sensible, latent and radiative fluxes all matter. Whilst a warmer climate will be one with more energy available for melt, a look at some case studies reveal that changes in insolation can have outsized impacts which will likely be under-estimated by degree-day approaches. Increased summer insolation at high-latitudes during the Eemian interglacial period (115-130 kyr BP) raised temperatures but also directly affected surface melt. Van de Berg et al. (2011) made an attempt to separate the contributions of elevated temperatures and increased solar forcing and suggested that 45% of the change in surface mass balance could be attributed to the changed solar forcing alone.

Volcanic eruptions provide a more contemporary analogy to the potential effects of solar geoengineering on surface melt. Fettweis et al. (2007) simulated the surface mass balance of Greenland between 1979 and 2006 and find maxima for surface mass balance in 1983 and 1992, the years after the El Chichon and Pinatubo eruptions, respectively. Hanna et al. (2008) combine observations and modeling to evaluate the surface mass balance of Greenland over a longer period finding that the years following El Chichon and Pinatubo have the third lowest and the lowest runoff, and the third and sixth greatest surface mass balance, respectively between 1958 and 2006.

Hofer et al. (2017) found that the substantial reduction in cloud cover over Greenland in the past two decades is the likeliest cause for the accelerated mass loss from the ice-sheet over this period. To arrive at this result they simply calculated how much melt would result from the change in downward surface shortwave energy received over the melt season as a result of the change in cloud cover, and compared this against the other contributions to melt and accumulation. They find that the ~10% reduction in summer cloud cover over Greenland in the past two decades led to a ~4000 Gt loss of mass making it the dominant driver of surface mass balance change in this period.

These examples suggest that solar geoengineering would be more effective at changing surface melt than achieving the same reduction in temperature with a reduction in GHG forcing. An implication of this is that degree-day factors determined for one set of radiation conditions are not likely to predict behavior if there is a significant change in the amount of incoming radiation. However, the effects of these changes in radiation will not be felt evenly. The effect will be greatest for glaciers and ice sheets that are presently in negative mass balance and have the greatest amount of incoming solar radiation, that is glaciers at low latitudes such as in High Mountain Asia. Greenland is also in net negative mass balance and so also susceptible. Greenland's mass balance is expected to become increasingly negative as surface melt, which presently accounts for about half of mass loss, will rapidly rise with warming temperatures (Fettweis, 2007; Fettweis et al., 2013). In Antarctica, the picture is very different as the ice sheet is cold enough that little melt occurs outside of the Antarctic Peninsula today and melt won't become a significant factor in Antarctica's mass balance unless temperatures rise very substantially (Morris and Vaughan, 2003).

Accumulation would also be affected by solar geoengineering which would reduce the intensity of the hydrological cycle more than achieving the same reduction in temperature with a reduction in GHG forcing. This may offset, to some extent, the reduced melt on glaciers around the world. This effect will be most significant on the Antarctic Ice sheet where there is very little melt and accumulation is expected to rise with temperatures as the water-carrying capacity of air increases (Frieler et al., 2015). In contrast to mountain glaciers and the Greenland Ice Sheet, the surface mass balance contribution of Antarctica to future sea-level rise is projected to remain negative for the foreseeable future. Ligtenberg et al. (2013) predict an increase of Antarctic surface mass balance of 98 Gt year^{-1} K^{-1} using the RACMO2 model and Lenaerts et al. (2016) predict an increase of 70 Gt year^{-1} K^{-1} using the CESM model. As solar geoengineering would lower temperatures and reduce the global intensity of the hydrological cycle it would reduce, and perhaps even reverse, the negative contribution of Antarctic Surface Mass Balance to

The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-279
Manuscript under review for journal The Cryosphere
Discussion started: 26 January 2018

sea-level rise. Outside of Antarctica changes in melt have been the dominant driver of recent mass loss so it seems likely that changes in accumulation will be of secondary importance to changes in melt (Fettweis et al., 2013; Zhao et al., 2017).

4 Ocean-driven melt, discharge and the stability of West Antarctica

Global warming and solar geoengineering will also affect the rate of discharge of marine-terminating glaciers. The warming of the atmosphere will alter the flow of glaciers and hence the rate of calving in a number of ways: warmer ice is less viscous (though this is a slow process and negligible for the ice sheets on centennial time scales) and increased melt-water may better lubricate the bed of glaciers. However, in Antarctica where sub-ice shelf melt and calving are the dominant drivers of mass loss, increased mass loss from grounded ice is due to the weakened buttressing effect of the thinned and retreating from ice shelves. Fürst et al. (2016) show that ice shelves in the West Antarctic Amundsen and Bellingshausen seas are extremely sensitive to calving, meaning that even small amount of increased calving will trigger dynamical responses in the feeding ice streams raising sea level. Furthermore, West Antarctica's geography makes its ice sheet especially vulnerable to such changes. Much of the ice sheet rests on bed-rock below sea-level, and which gets deeper further from the coast making many glaciers susceptible to "marine-ice sheet instability" (Mercer, 1978). In fact, observations suggest that recent increases in the temperature of water around Antarctica may have already triggered a process that will lead to the collapse of the Pine island and Thwaites glaciers (Favier et al., 2014; Joughin et al., 2014).

A recent study (DeConto and Pollard, 2016), has added to fears around the fate of the Antarctic ice sheet. They suggest that the same processes that led to the break-up of Antarctic Peninsula ice-shelves could destabilize the much larger southern ice-shelves in the future (Liu et al., 2015). In the Antarctic Peninsula, surface melt filled crevasses in the ice-shelves with water that led to a "hydro-fracturing" and dramatic collapse of the ice-shelves. Furthermore, they suggest that once large ice shelves begin to retreat, the large unstable ice cliffs formed could promote further rapid retreat. Together these processes combined to produce a substantially greater Antarctic contribution to sea-level rise than earlier studies which did not account for these highly uncertain processes (DeConto and Pollard, 2016). Properly accounting for these calving loss mechanisms is extremely challenging for continuum ice sheet models, for this reason, as well as West Antarctica's inherent vulnerability, uncertainties in the contribution of Antarctica to future sea level rise dominates total sea level uncertainty for warmings above 2°C (Jevrejeva et al., 2016).

Stratospheric aerosol geoengineering could lower surface air temperatures reducing surface melt, and so could limit the potential hydro-fracturing-driven collapse of Antarctic ice-shelves projected in the study of Deconto and Pollard (2016). Deconto and Pollard's study provides support for this view as they find that the dramatic Antarctic sea-level rise they predict is driven primarily by atmospheric warming rather than oceanic forcing. In a simulation where the ice sheet sees only the changes in ocean temperature (corrected to adjust for a cold bias) and no change in atmospheric temperatures the sea-level rise contribtution of Antarctica is slashed from over 12m by 2500 to 0.75m by 2500 (compare their figure 4b with extended data figure 6a).

However, these are the results of a single model and most models project that current and future melting of the Antarctic ice-shelves will be dominated by ocean-driven basal melting. The water mass responsible for this melt is not the surface waters around Antarctica, but rather the deeper circumpolar waters (~500 m) that surround Antarctica. These deeper waters are able to penetrate the ice shelf cavities, reaching the grounding line where the ice starts to float and where pressure requires the ice to have the lowest melting point temperature. The fate of the ice-shelves is thus likely to be determined by the degree to which this circumpolar deep water is able to penetrate into the deep ice shelf cavities rather than by surface melt (Liu et al., 2015; Pritchard et al., 2012).

A recent study of the effects of stratospheric sulphate aerosol geoengineering found that it would warm the stratosphere, changing both atmospheric and oceanic circulation patterns (McCusker et al., 2015). They simulated a greater mixing of the relatively warm circumpolar deep water with the colder waters under the continent's ice-shelves relative to achieving a similar reduction in temperature with a reduction in GHG forcing. If this result proves robust then it suggests that the cooling effects of stratospheric aerosol geoengineering may be offset to some extent by dynamical changes and so it may have a limited ability to reduce shelf basal melt rates and so to stabilize the West Antarctic ice Sheet.

5 Sea-level rise engineering?

Solar geoengineering covers a variety of proposed technologies, each of which could be implemented in a range of ways. Solar geoengineering could thus be tailored to some extent to achieve particular objectives (MacMartin et al., 2013). As Kravitz et al. (2016) point out; this means that solar geoengineering is a design problem.

For example, the latitude and season of stratospheric aerosol injection could be chosen and thus some control over the zonal and seasonal distributions of the resultant aerosol cloud is possible (Dai et al., under review; Niemeier et al., 2011). Furthermore, Sulphate aerosols, the most frequently discussed option, are only one possible aerosol and others could be used. Sulphate aerosols absorb quite a lot of radiation as well as scattering light, leading to changes in atmospheric and, consequently, ocean circulation changes. Alternative aerosols which absorb less radiation, such as alumina, diamond, or calcium carbonate could be released instead which may reduce these circulation changes (Dykema et al., 2016). Stratospheric aerosols provide a surface area for ozone-destroying reactions to occur on (Pitari et al., 2014), but calcium carbonate, for example, may be able to boost ozone concentrations by neutralizing the acidic species behind these reactions (Keith et al., 2016).

Other methods of solar geoengineering may also be deployed instead of, or in combination with, stratospheric aerosol geoengineering. An interesting example is the idea to seed cirrus clouds with ice nuclei to dissipate them, allowing more

The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-279
Manuscript under review for journal The Cryosphere
Discussion started: 26 January 2018

thermal radiation to escape to space (Mitchell and Finnegan, 2009). This would produce a cooling effect with less of a reduction of the hydrological cycle than is the case for stratospheric aerosol geoengineering (Cao et al., 2017).

It will be instructive to ask the question, if solar geoengineering were deployed with the goal of stabilizing glaciers and ice-sheets how effective could it be? Concentrating the cooling effect in the summer and at high latitudes would increase the effectiveness of solar geoengineering at limiting surface mass balance changes. There may also be ways to tailor solar geoengineering to limit the mixing of relatively warm waters onto the Antarctic shelves. However, we want to stress that it won't be possible to isolate the effects of solar geoengineering to glaciated regions alone (Robock et al., 2008). Moreover, changes to the cryosphere are but one of many aspects of global change that would need to be considered when defining an objective for solar geoengineering.

6 Conclusion and recommendations for future research

In this study we've reviewed the literature on the effects of solar geoengineering on sea-level rise and highlighted a number of gaps in the literature and shortcomings in the approaches used to date. We've also highlighted important differences between a reduction in GHG forcing and solar geoengineering that will affect the surface mass balance of glaciers and ocean-driven melt of ice-shelves and so the discharge rate of marine glaciers. We will conclude by framing a number of overarching questions which we believe should guide future research into this topic as well as making a number of specific recommendations.

6.1 Would solar geoengineering be more or less effective at reducing sea-level rise than achieving the same reduction in temperature with a reduction in GHG forcing?

Scenarios with equivalent global radiative forcing with and without solar geoengineering will have similar global-mean temperature responses but will be importantly different in a number of other respects. Changes to the surface energy budget, the hydrological cycle, and to circulation patterns will affect both the surface mass balance and ocean-driven losses of ice-sheets. An evaluation of such equivalent scenarios will provide valuable information on the potential efficacy of solar geoengineering.

As we've shown above there are good reasons to believe that solar geoengineering will be more effective at reducing surface mass balance losses than achieving the same reduction in temperature with a reduction in GHG forcing due to the fact that solar forcing has a larger effect on the surface energy budget and acts most strongly during the summer melt season. However, the magnitude of this difference is not certain. To resolve this uncertainty we recommend:

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Manuscript under review for journal The Cryosphere
Discussion started: 26 January 2018

- That detailed surface mass balance simulations with full energy-moisture balance representations be conducted for scenarios with equivalent radiative forcing achieved through reductions in GHG forcing and with solar geoengineering.
- A reanalysis of relevant paleo-climate analogues, observed local trends in cloudiness, and the records of the effects of large volcanic eruptions be conducted to provide an empirical grounding for estimates of the relative efficacy of solar and GHG forcing.
- An evaluation of the discrepancy between the simple degree-day formulations for surface melt used in most ice-sheet models and full energy-moisture balance formulations for surface melt when applied to scenarios of solar geoengineering. The results of this evaluation should be used to develop and apply corrections to appropriately represent solar geoengineering in such degree-day schemes.

Changes to ocean-driven melt and the calving of ice-sheets are harder to predict than changes in surface mass balance so the relative efficacy of solar geoengineering at reducing these changes is much less certain. Stratospheric sulphate aerosol geoengineering would warm the stratosphere, changing stratospheric and tropospheric winds with effects that would propagate down to affect the mixing of these deep waters around Antarctica. The effect of such changes on ocean circulation is uncertain and whether it would be offset by the general cooling of surface waters and reduced surface melt on ice-shelves and increased sea ice extent is also unclear. To help resolve these uncertainties we recommend:

- High-resolution coupled climate model simulations are run to evaluate the effects of the heating from stratospheric aerosols on the southern ocean and the mixing of deep circumpolar water around Antarctica.
- Detailed, coupled ocean-ice models, of the type being evaluated under the Marine Ice Sheet Model Intercomparison Projects experiments (Asay-Davis et al., 2016), should simulate the effects of stratospheric aerosol geoengineering on the stability of ice-shelves and the evolution of the grounding line. Simulating the coupled ocean-ice interactions at the grounding line and below ice-shelves requires high spatial and temporal resolution and will be incredibly computationally demanding. This probably means that the coupled ice-ocean model be limited in regional scope and duration of simulation. The boundary conditions for such simulations could be derived from global coupled climate model simulations such as the ones described above.
- That the processes responsible for driving calving be better understood and described. The susceptibility of low altitude Antarctic ice shelves to surface melt and hydro-fracturing should then be evaluated in models with improved representation of ice shelf fracturing and the weakening of their buttressing force (Benn et al., 2017). If the kind of hydro-fracturing induced break-up of ice-shelves that DeConto and Pollard (2016) project is realistic then an evaluation of the potential for solar geoengineering to prevent such an outcome should be a high priority.

How solar geoengineering is deployed would be a choice and it could be tailored to better achieve certain outcomes. The results of the studies recommended above would be useful in clarifying how to tailor solar geoengineering to more effectively reduce sea-level rise. We recommend that simple metrics be developed that capture the important factors determining the efficacy of solar geoengineering at reducing sea-level rise. The trade-offs between tailoring solar geoengineering to better reduce sea-level rise and tailoring it to promote other objectives could then be evaluated in idealized climate model studies using these and other metrics.

6.2 What are the limits to solar geoengineering's potential to reduce or reverse sea-level rise?

Clark et al. (2016) stressed in a recent perspective piece in Nature Climate Change that it's important to look beyond the 21st century to understand the implications of 21st Century emissions policies. CO_2 emitted to the atmosphere has an incredibly long half-life and the warming effect of our emissions could have multi-millennial climate and sea-level rise implications as a result. However, Clark et al. (2016) do not evaluate the potential of solar geoengineering or carbon dioxide removal geoengineering, which both have the potential to fundamentally change this long-term outlook. Our focus is on solar geoengineering and we make a number of recommendations to help answer some unresolved questions about its potential to reduce or even reverse sea-level rise.

Solar geoengineering could be deployed to not just reduce sea-level rise but to halt or even reverse it (Irvine et al., 2012). However, there is considerable inertia and hysteresis in aspects of the response of glaciers and ice-sheets to these driving forces that will limit the extent to which sea-level rise could be reduced and will shape how much cooling would be required to halt it (Applegate and Keller, 2015). Understanding what it would take to halt sea-level rise using solar geoengineering will provide valuable information on the limits of solar geoengineering in this regard. To address this we recommend:

- Idealized studies of the response of the oceans, glaciers and the Greenland and Antarctic ice-sheets to upper-end scenarios of solar geoengineering deployment which return temperatures to pre-industrial levels or below. In particular, we recommend idealized studies to evaluate what level of solar geoengineering cooling would be needed to: 1) halt the retreat of marine-terminating glaciers that are subject to marine ice sheet instability, and 2) preserve glaciers in regions where they provide irreplaceable water supplies in summers and drought years.
- The results of such idealized studies should be complemented by analysis of the ice-sheet response to paleo-climate events with a sudden cooling to see what constraints these events can provide on future behavior.
- Multi-century scenarios including solar geoengineering are developed to provide boundary conditions for long-run sea-level rise simulations. These could build on the successors to the Representative Concentration Pathways and the work of the Geoengineering Model Intercomparison Project (Kravitz et al., 2015, p.6). Such scenarios could explore the different effects of solar geoengineering to slow, halt or reverse temperature change.

It will be important to understand the potential efficacy and the limits of solar geoengineering as a means of reducing sea-level rise but it is only one of many issues that must be considered when discussing solar geoengineering. Sea-level rise is one of the key risks of climate change but there are others. There are likely good reasons not to deploy solar geoengineering with the objective of halting or reversing sea-level rise as this could require a substantial reduction in global temperatures which could result in potentially harmful shifts in regional climate and significant non-climatic side-effects. Furthermore, whilst an understanding of the potential physical consequences of climate change and solar geoengineering is necessary for a discussion of the potential use of solar geoengineering, it is not sufficient. Whether and how to deploy solar geoengineering is a question that demands a nuanced discussion encompassing not only the physical consequences of deployment but also a careful consideration and negotiation of the complex socio-political issues it raises. A good understanding of the potential and limits of solar geoengineering to reduce sea-level rise will be an important part of the foundation of this much broader discussion which we invite you to get involved in.

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