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Interactive comment on "Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts" *by* Peter J. Irvine et al.

Peter J. Irvine et al.

p.j.irvine@gmail.com

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A combined pdf with responses to both reviewers is attached. A - Author responses, R - Reviewer comments

A - We submitted this article to The Cryosphere as a brief communication after communicating to the editors that our article that was someway between a commentary and a technical review of the sea-level rise response to solar geoengineering. In such articles novelty is not the central goal. However, in responding to the reviewer comments we have added some novel analysis of the surface mass balance response to solar geoengineering. With the revisions recommended by the reviewers we believe this article makes a useful contribution to the discussion on the sea-level rise response to solar geoengineering.

Reviewer 1

R - This article reviews the links between solar engineering and the surface mass balance of glaciers and ice sheets. Given the potential importance of the topic I am rather reluctant to report this article to be a rather awkward read. It pokes out in many directions, but not sufficiently far enough in any one to be truly novel. Perhaps this opinion reflects that I am well-read on the general topic, and personally feel that this qualitative discussion on cryospheric implications fall short of The Cryosphere community's consistent ability to deliver quantitative assessments on just about every other front. Personal opinion aside, this article objectively resurveys many of the same well-trodden roads of Irvine et al. [2017; Earth Future], Keith and Irvine [2016; Earth Future] and Irvine et al. [2012; Nature Climate Change] – clear disambiguation of a novel core is paramount.

A - We thank the reviewer for their suggestions and have made several major changes to address the concerns raised and to improve the manuscript: - We've added a quantitative analysis of the factors driving surface mass balance changes for the GeoMIP climate model ensemble. - We've restructured the main section of the paper. Sections 3 and 4 from the original paper are now sub-sections of a broader section which frames the issues we address more clearly and also briefly addresses thermosteric sea-level rise. - We've removed the "sea level rise engineering" section - We've rewritten the recommendations for research.

R - P6L15 – "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." – A fundamental assertion of this article is that SW reduction is more effective in modulating melt than a LW reduction, but there is a huge body of literature to suggest that melt is LW-dominated. To review Ohmura (2001; J.

Applied Meteorology) – under cloudless-sky conditions, 90% of atmospheric emission is derived from the first 1 km of atmosphere – which is why air temperature index can perform remarkably well as a melt proxy. I am not sure that LW modification by GHG drawdown can be ignored entirely.

A - Ohmura (2001) explains the surprisingly robust physical basis for the surface air temperature driven approaches to surface melt used in many models, highlighting the fact that surface air temperature is strongly correlated with lower atmospheric temperature and hence downwelling longwave (LW) radiation. Against a backdrop of elevated GHGs Solar geoengineering would cool the surface and lower atmosphere and so there will be a significant reduction in downwelling longwave (LW) radiation compared to a case with elevated GHGs and no solar geoengineering. The examples we highlight suggest that all-else-equal offsetting GHG forcing by a reduction in incoming sunlight would produce a greater reduction in melt than an equivalent reduction in CO2 forcing.

A - We note the insights of the Ohmura (2001) paper at the start of the surface mass balance section, changing the tone to be less critical of positive degree-day models of surface melt. The new quantitative analysis of the GeoMIP results, which we add at roughly the point the reviewer refers to, describes the changes in surface energy budget that bears out our intuition that solar geoengineering would be more effective at changing the surface energy budget than an equivalent reduction in GHG forcing.

R - P6L20 – "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." My understanding is that the stratosphere is several km lower polar areas than at mid latitudes, so the majority of solar geoengineering proposals have advocating for injection aerosols into the polar regions. If this is indeed the case, I am not sure why low latitudes would benefit more from injected aerosols than high latitudes.

A - The optical depth of the aerosol cloud will determine the fraction of light that it

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Discussion paper

scatters and hence the reduction in sunlight that reaches the surface below. Simply injecting aerosols into the equatorial stratosphere can produce a fairly evenly distributed global aerosol cloud with effects similar to a reduction in incoming sunlight (Niemeier et al. 2013, 10.1002/2013JD020445) though fine-tuning can produce a much more even cloud (Kravitz et al. 2018, 10.1002/2017JD026874). This means that all regions should experience a similar fractional change in incoming sunlight. The fact that the aerosol layer is at a lower altitude at high latitudes should not affect this.

A - We have edited this section to make clear that a fractional change in incoming sunlight at the ice surface will have a greater effect in sunnier places, i.e. lower latitude regions.

R - P2L29 – Scalable to 4W/m2. The potential magnitude of SW modification is never compared with characteristic magnitude for SMB components. Fausto (2016; GRL) presents a straightforward radiation balance associated with extreme melt events in Greenland. The article would benefit from a simple thought experiment, whereby a plausible magnitude of SW RF suppression is applied to a summer melt season. The Fausto2016 values, for example have daily mean incoming SW around 100W/m2, with several instances of daily mean sensible heat flux exceed 50 W/m2. Without the authors saying what range of SW modification scenario they deem feasible, it is tough to gauge how that will ultimately effect melt.

A - The significance of this quoted figure was perhaps not clear so we have added a note in the text that 4Wm-2 is roughly equal to the forcing from a doubling of CO2. We believe the new quantitative surface mass balance analysis of the GeoMIP ensemble addresses the reviewer's concern here.

R - Bioalbedo – If 4 W/m2 decreased incoming SW on a total incoming radiation of 150 W/m2 daily mean is being proposed, that is something like a 2.7% decrease in incident radiation. Emerging mechanisms are highlighting much larger changes in melt season albedo. For example, bioalbedo feedback (darkening of the glacier surface due to snow algae) can lower melt season albedo by 13% (or five times as much as the plausible SG mentioned in passing). This sort of contextualization of solar geoengineering is critical but absent from this paper. In jest, one could ask if cryospheric experts would better combat climate change by finding a “cure” for snow algae.

A - We thank the reviewer for highlighting this omission, the darkening of snow by pollution and by snow algae is an important factor to consider. Snow surfaces with a lower albedo would exhibit a greater sensitivity to changes in incoming sunlight than brighter snow surfaces. This suggests that our quantitive results which focus on the responses over the entire ice-sheet may be underestimating the efficacy of solar geoengineering to reduce melt. We’ve added some text to explain how the response over darkened snow differs from that over fresh snow and clean ice.

R - P3L10 – This discussion of the multifaceted effects of aerosol injection seems somewhat cursory/inferior to the tabulated pros and cons of Robock et al. (2009; GRL). I would also note a general absence of comparison with that study, which, for example, yields very different costs estimates of placing 1 Tg S in the stratosphere, and is generally much, much, more negative about the side-effects of geoengineering than presents here.

A - We didn’t believe that a full discussion of the pros and cons of solar geoengineering would be appropriate in a short-format article focused on the cryosphere response, and so included only a brief description of the major side-effects. In introducing the side-effects of stratospheric aerosol geoengineering, we now point the reader to a more up-to-date review of the full effects (Irvine et al. 2016, Wiley Interdisciplinary Reviews). We do not agree with the reviewer’s assessment that we have underplayed the side-effects of stratospheric aerosol geoengineering, we believe the text adequately described most of these side-effects. For the shift from direct to diffuse light we’ve added a brief note on the implications of this shift for plant productivity and concentrating solar power. In terms of the costs of deployment, we refer to more recent estimates than that of Robock et al. (2009) and note that in personal communications Alan Robock agrees with the newer estimates of the costs (personal communication between David Keith and Alan Robock).

R - Section 5 – This section seems mislabeled as "sea-level rise engineering". One would expect that discussion to move towards how many mm sea-level equivalent may be associated with each geoengineered W/m2, instead this is rather a rehash candidate aerosols with the only tangential brush with sea level being discussion of seasonality of SMB modification.

A - We have removed this section.

R - Section 5 – This section is introduced as highlighting why it is "critical to introduce solar geoengineering into such analyses [of future sea level rise]" (P3 L30) – but does seems to miss that mark. Pointing to an IPCC/EGU/EGU community statement on the value of solar geoengineering may serve to anchor the "critical" assertion, but my sense is that international reports generally do not advocate for the inclusion of solar geoengineering as "critical" (i.e. https://eos.org/agu-news/revised-agu-position-statement-addressesclimate-intervention) Perhaps an analogy is a small group of permafrost researchers saying the potential for an Arctic methane bomb is vastly more important than judged by the IPCC. OK, but why? Expand.

A - The description of the section in this paper that appeared on page 3 was from an earlier draft and did not reflect the structure of the piece we submitted. We no longer make this specific claim.

R - P6L33 – "As solar geoengineering would lower temperatures and reduce the intensity of the hydrological cycle it would reduce, perhaps even reverse, the negative contribution of Antarctic Surface Mass Balance to sea-level rise." May I highlight his sentence a microcosm of the paper? Unabashed praise for the promise of solar geoengineering with no apparent source for this tremendously speculative statement, and also glazes over/ignores a good deal of cryospheric research that highlights East Antarctic's SMB (the majority of the continent) is net positive, meaning it already draws down sea level today.

A - Our text here was perhaps not as clear as it could have been. We were indeed referring to the net positive SMB of Antarctica today (which is a net negative contribution to SLR, as we noted) and suggesting that solar geoengineering could potentially offset or even reverse that. We make the same claim in the revised surface mass balance section:

A - “These results suggest that the negative contribution to sea-level rise of the positive surface mass balance response of Antarctica to global warming would decline roughly in line with temperatures if solar geoengineering were deployed though more work is needed to explore this issue.”

R - P7L20 – This discussion of ice dynamics should more clearly articulate the concept of committed mass loss. I suspect a quantitative assessment of solar geoengineering SMB buffering potential would find that committed loss from Antarctica is substantially larger. It may also be disingenuous to say that SW engineering could counter some of the ice dynamics trends now underway. The major mass loss contributors like Thwaites Glacier do not have ice shelves (i.e. Joughin et al., 2014; Science). The physical basis of committed mass loss purports that once it is triggered, it is only the density difference between ice and water, along with the gradient in bedrock slope, that determines when retreat will stop.

A - We accept the reviewer’s criticism on this point, we perhaps overstated the potential of solar geoengineering in this regard. We have completely rewritten the section (now section 3.3) and end with a more complete discussion of ice dynamics changes that stresses the committed mass loss.

R - P11L9 – “Solar geoengineering could be deployed to not just reduce sea-level rise but to halt or even reverse it (Irvine et al. 2012).” This sentence is quite problematic. Irvine et al. (2012) only discuss the potential to stop sea-level rise, not reverse it as is being implied by this (self) citation. Keith and Irvine (2016) previous characterize the same study (Irvine et al., 2012) as demonstrating feasibility of solar geoengineering to limit sea-level rise "...by around a quarter". Highlighting these differences in self-characterization of previous studies makes me uneasy, as it seems the current manuscript could be used as a vehicle for expanding, without new foundation, the implications of earlier studies. Here, I caution the editors that it is difficult for me, or perhaps any reader, to comfortably separate conjecture from fact.

A - The reviewer is right that we make two different statements about the potential of solar geoengineering to change sea-level rise based on the results of a single paper. However, both are appropriate as they refer to different scenarios of solar geoengineering deployment. Irvine et al. (2012) analyzed solar geoengineering scenarios built off the RCP 8.5 emissions scenario with reductions in radiative forcing at 2100 ranging from 2.75 to 9.5 Wm 2, i.e. ranging from scenarios that reduce the warming by around a third (and sea-level rise by around a quarter) to scenarios that reduce temperatures below the pre-industrial mean (reversing recent sea-level rise in these simulations). However, in the revising the text we no longer make this specific claim.

R - Summary: I might summarize this article as 60% non-cryosphere, which I am familiar with from previous studies, and 40% cryosphere, which I feel is not robust or up-to-date with the present literature. An idealized surface energy budget with and without solar geoengineering modification seem like a minimum requirement to highlight precisely why solar geoengineering is "critical" for the cryospheric community to consider. I get the slight sense that the Brief Communication format here being used more like a popular opinion piece than a substantive review of the subject.

A - We have revised the paper substantially based on the reviewer's suggestions and hope that these changes address the concerns raised.

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2017-279/tc-2017-279-AC1-supplement.pdf

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