Response to REFEREE-2 (marked-up version of paper at bottom)

We thank the referee for the comments, and in light of the new publications on this subject have truncated discussion of previous methodologies to limit text and expound the unique SRM focus of this paper.

This is my second review of the brief communication, “The significance for the IPCC targets of 1.5°C and 2.0°C temperature rise for an ice-free Arctic.” This version of the manuscript is much improved, but unfortunately, I still don’t think it is ready for publication, as some of the newly added text is confusing, some of it is incorrect, and the figures are still all out of focus and not acceptable (despite a reply to review that stated these figures were updated in response to review). Figures should be vector graphics (eps or pdf) to avoid them being this pixelated at a normal print and screen resolution (100%). Furthermore, since the first review, three new papers on this exact same subject have now appeared (see below for the new references), with another in open review in earth system discussions (Iversen et al., see below). Those need to discussed in a further review cycle (at least the published ones, the under review one maybe not, not sure on the policy for those articles in open review). I don’t think these new studies preclude the publication of this paper, as they use different models and methodologies, and the solar radiation management approach is unique to this study. And it is very interesting that the results agree quite well. But these studies need to be discussed, and the introduction needs to be rephrased in order to reflect that there are previous answers to this question, and that the main contribution here is to look at the impact of solar radiation management, as alternative to reduced emissions, as mentioned in the reply to review. I think this will actually help the article to be more interesting and significant.

We now refer to the latest 3 publications, and as a result do not specifically mention differences in methodology. Instead, they are grouped together as mitigation studies for reference to the specifically geo-engineering study of this paper. The refocus of the paper specifically on SRM has necessitated a major reworking of the manuscript, although the figures and basic results remain the same.

Specific comments:

Page 1,Line 1: I would recommend reconsidering the title to better reflect the unique aspects of this study. Maybe “Brief Communication: Probabilities of an ice-free Arctic for limiting warming to 1.5C and 2.0C though solar radiation management”

The title is changed to “Solar Radiation Management not as effective as mitigation for Arctic sea-ice loss in hitting the 1.5°C and 2°C COP climate targets.”

This is to emphasise a caution that SRM is not a cure-all

Page 1, Line 8-9: It is unclear to me what “is used to improve the signal to noise associated with the internal variability” means, so that is not good in an Abstract, which should convey the main message clearly and concisely.

The abstract is rewritten to reflect the changed storyline of the paper. This phase above is removed.

Page 1, Line 9-10: I don't think this statement is correct, based on the analysis presented: "It is found that the continuing loss of Arctic sea ice can be halted if the Paris Agreement temperature goal of 1.5oC is achieved". The paper only assessed September ice extent, whereas this statement implies any ice loss, which can include winter month and/or ice volume. Also, arguably also the 2C stabilization stops the ice-loss (in September), but at a lower level. So this statement is just not correct and can't be in the Abstract. Instead there should be a statement on the actual finding, as stated in the conclusions (incorrectly, as increased rather than decreased, see comment later) and supported by the analysis presented: "The risk for a seasonally ice-free Arctic is reduced for a target temperature for global warming of 1.5°C (0.1%) compared to 2.0°C (42%)."

The suggested phrase has been adopted

Page 1, line 18-19: Given that there are now three more 2018 published studies on this subject, and a News and Views text by Screen (2018), in addition to the cited two 2017 studies (Screen and Williamson and Sanderson et al), "Here we investigate if Arctic sea ice cover is one such system." Really doesn't seem appropriate anymore. All of these studies have shown that the Arctic sea ice cover is such a system. So while this may have been the initial motivation, I would suggest re-casting it in terms of whether global temperature control through solar radiation management also shows such large impacts between 1.5C and 2.0C for Arctic sea ice, or whether solar radiation management would lead to different results. That requires re-writing large parts of the initial paragraph, but I think it will make the paper much stronger.

The paper has been heavily re-written throughout to focus on the geoengineering aspect

Page 2, line 11-12: This is incorrect "Sanderson et al., 2017) used a climate model emulator, calibrated against CESM1, to produce simulations at constant 1.5°C and 2.0°C". They used a climate model emulator to design emission scenarios that lead to CESM1 simulations at constant 1.5°C and 2.0°C. But the results shown are from the CESM1, not from an emulator. This needs to be correctly stated.

Statement is removed as commentary on the individual techniques is superseded by the range of new papers on the topic. Instead we reference the Screen (2018) commentary.

Page 2, line 12-14: This is also incorrect "Another study (Screen & Williamson, 2017) used all the CMIP5 model simulations and regressed the September sea ice extent for 1.5°C and 2.0°C against the 2007-2016 mean sea ice extent. Bayesian statistics were then used to estimate the probability of an ice-free Arctic for 1.5°C or 2.0°C.". Screen & Williamson used CMIP5 simulations until the year before they first reached a global warming of 1.5°C and 2.0°C and regressed those against the 2007-2016 mean sea ice extent.

With the additional 3 studies it no longer makes sense, to review the individual methodologies of the 5 existing papers, so this section is removed.

Page 2, line 14: A discussion of the new three studies need to go here.

The reorganisation of the paper to address geoengineering has required all these studies grouped together as mitigation simulations.

Page 2, line 15: Now of six different approaches

New studies referenced

Page 3, line 6-7: I know this was added in response to reviewer 3 (The use of an ensemble mean will not be available in reality to plan implementation of SRM.), but without context, this is not very useful and should be expanded upon, so the reader can understand why this is here, without having to read the reviews.

The statement about '..in reality to plan implementation of SRM' is incongruous with the rest of the paper, and the line has been removed This paper is not about discussing the practical implementation of SRM – there have been other papers on such.

Page 3, line 12-16: This is an important and very interesting point, but I needed to read it three times to get it. Please re-write it in shorter, more precise sentences, so it is easier to follow.

Rewritten slightly.

Page 4, line 17-19: In order to really understand Figure 3b, one need to know how many years contribute to each of the pdfs. I would recommend adding the temperature bands in Figure 1, so it is clear how many years of ensemble 1, 2, and 3 end up in those bands and are used for the assessment of these probabilities. Because Sigmond et al showed that this probability increases the longer the sample period is, as also discussed by Screen (2018).

As Jahn suggests this is related to the ensemble size and hence the sampling due to the members rather than the length of time. If it were just due to length of time then the probability would continue to increase beyond the first 10 years in Sigmond et al. With an ensemble of 48 members in these experiments it is clear from Fig 3 that the spread is far greater than for the four member RCP ensemble. We now mention in the text the sample size of the histograms in Fig 3 (1000 at 1.5C and 300 at 2.0C). An increase of variability in time could also occur if the ice continues to thin, perhaps in response to an initial shock at the start of the simulations (unless the simulations have started from a spun-up state).

In addition, (or alternately, if those boxes make Figure 1 too busy), the authors should mention how many years are in each of the bands, and from which ensembles they are (RCP2.6, RCP4.5, ensemble-1, ensemble-2, ensemble-3). This is important to understand the methodology.

We cannot distinguish, statistically (as a function of global mean temperature – noting that global temperature drifts in ensembles 2 & 3)), any difference in the standard deviation between the three ensemble categories, so we have lumped all the ensemble (and RCP) members together. To avoid crowding figure 3 we have mentioned the number of years (sample size) in the results section of the text.

Page 4: Line 21: This is the central finding, but there is a typo: The risk is significantly DECREASED, not increased as stated, for a target temperature of 1.5C.

Thanks for spotting this. Text now says “A significantly reduced risk…”

Page 4, Line 22: It is unclear to me how this statement fits here, as the first sentence isn’t about timing, but general probabilities. So “Another climate model, with a thicker Arctic sea ice in its mean state, would be expected to produce a later date for an ice-free Arctic (Bitz, 2008) “ doesn’t fit here. Please either remove it or add a sentence that actually refers to the date of ice-free conditions. But that wasn’t analyzed here, so really I think this needs to go.

I agree, models can vary in the ice-free date but that could be due to a variety of reasons such as climate sensitivity, polar amplification and initial state. Although polar amplification is now mentioned, in relation to SRM, we do not infer anything that might relate to different models. The sentence is removed.

Page 4, line 23-24: Screen and Williamson assessed the probability of any ice-free conditions before reaching 1.5C and 2.0C, not the probability in a given year, as is done here, and was done in Sanderson et al. (2017). That needs to be clarified. See Screen 2018 (see below for ref) for an explanation of the differences of those probabilities.

Methodologies of different papers no longer discussed here. Section removed.

Page 4, Line 25: Sanderson et al did not use a climate model emulator for these results, as stated here incorrectly, but used a climate model emulator to develop the emission scenarios that would lead to stabilized warming at 1.5C and 2.0C in the CESM1. That’s clearly explained in Sanderson et al.

Methodologies of different papers no longer discussed here. Section removed.

Figures: All figures are still low quality and out of focus. They need to be vector graphics.

I have no problem with the figures (resolution) when I download the paper from the Cryosphere. In any case the final graphics will be high resolution.

Minor comments:

Figure 2: As noted last time, figure 2 does not show the “spatial pattern of the Arctic sea ice extent”, but the “spatial pattern of the sea ice edge”. Other changes were made, but this one wasn’t.

Changed as suggested

Figure 3: The caption now better explains the figure. But the newly added line for ice-free is a purple line, not a dark blue line.

Caption changed to ‘purple’

Page 3, line 18: As for the next two lines, this should read: Ensemble-1 : starts at 1.5C on RCP2.6 and levels out at 1.5C above pre-industrial

Implemented changes as suggested

Page 3, line 29: “with ice retreating further in the Atlantic sector” In which ensemble, ensemble-1 or ensemble-2?

This refers to HadGEM2-ES in general (now clarified in the text) and is associated with the modelled ice rheology as well as weak (compared with observations) atmospheric blocking in the North Pacific.

Page 1, line 21: This is not a “salinity freezing point”, but “salinity-dependent freeze point” or “freezing point of the ocean”.

Changed to ‘freezing point of the ocean’

Page 1, line 23: Missing “a” before “warmer atmosphere” The revised version of "The significance for the IPCC targets of 1.5°C and 2.0°C temperature rise for an ice-free Arctic." addresses some, but not all of the concerns I had with the original paper.

Inserted ‘a’

Response to REFEREE 3 (Marked up version of paper at bottom)

We thank the referee for the insightful comments to improve this brief communication. We have endeavoured to incorporate all suggestions and yet limit the text to maintain the Brief Communication

My major concern was that an SRM experiment was being used as a proxy for climate impacts at 1.5 and 2 degrees, with particular reference to those temperatures as described in the Paris Agreement. This remains the case with this version, and it is troubling for 2 reasons:

The high latitude warming at a given stabilization level will be greater in a simulation where some greenhouse gas forcing is offset with SRM. This is supported by the paper's new Figure 3a, which clearly shows that the mean sea ice extent at 1.5 degrees in the geoengineered simulations is less than that seen in the mitigation-only experiments (i.e. the mean of the distribution of black points is less than the mean of the distribution of red points at the 1.5 degree warming level). However, the authors argue the opposite - that their analysis demonstrates that the SRM simulation is a good proxy for mitigation only experiments.

The paper is completely re-written with a focus on SRM. New analysis has shown that, as expected, the polar amplification under SRM is higher and thus the rate of sea ice loss is increased. We do not have a sufficiently large ensemble of RCP scenarios to determine what the probabilities for ice-free at 1.5 and 2.0C would be if no SRM were used (in the same model).

This is potentially misleading to the community. The Paris Agreement targets are usually interpreted as a mitigation goal - not as targets for SRM geo-engineering. This paper is too quick to dismiss the difference between the climates which would be achieved in the two cases, despite the fact that their results show clear differences.

See above

As I said in my initial report, this paper would be quite acceptable if it acknowledged that there are differences in SRM simulations and mitigation only experiments (and categorized them in detail for Arctic sea-ice) - but the paper still reads as if SRM and mitigation are interchangeable. This is a strong statement, with huge policy implications - and it is not even supported by the author's own results.

This comment, and the focus of the paper on SRM, has led to a more though statistical analysis of the impact of mitigation vs SRM. Despite the narrow temperature range (+- 0.1C) around the target temperatures of 1.5 and 2.0C, the sample size is large and the difference is statistically significant. The results show a higher polar amplification for SRM than Mitigation, for the same global mean temperature, consequently the sea ice area is less. Clearly, although SRM can make the world cooler than 1.5C (very difficult for mitigation) this is not the purpose of this brief communication.

Minor Issues:

- Remove apostrophes in "RCP's"

Done

- Section 3, last but 1 para " SRM itself is not having an effect on the Arctic sea ice " - this statement is not supported by the plot, the two distributions are clearly distinguishable at the 1.5 degree threshold.

- "Sandersen et al. (2017)" -> "Sanderson et al. (2017)" throughout

Done

- Section 4 - to say Sanderson et al used a climate model emulator is misleading - the emulator was only used to produce the emission pathways. The relationship between global mean temperature and arctic sea ice found in that paper was derived from a full GCM.

Description removed as it is no longer necessary to highlight differences in the methodologies

- Section 4 - 2nd para - "independent" is a strong word with statistical implications which do not apply here. Consider using simply "different"

Changed to ‘different’

Response to Editor Comment

In addition, the issue that most of the current GCM-based simulations underestimates the currently observed sea ice decline in Arctic is still not yet discussed as well as a validation of the model used over current climate/sea ice trend.

It is generally agreed that about half the current observed sea ice trend is associated with multi-decadal variability. As such a model only needs to demonstrate that it can reproduce 30/20/10 year trends, compatible with observations within an ensemble of historical simulations. There are plenty of papers that demonstrate this principle. Thus, I don't feel this a fruitful avenue of discussion in the paper.

https://www.nature.com/articles/nclimate2483

https://www.sciencedirect.com/science/article/pii/S092181811530093X?via%3Dihub

https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016GL070067

Marked up version of manuscript with major changes in red

Brief Communication: Solar Radiation Management not as effective as CO_2 mitigation for Arctic sea-ice loss in hitting the 1.5°C and 2°C COP climate targets.

Jeff K. Ridley, Edward W. Blockley

Met Office, Exeter, EX1 3PB, UK

Correspondence to: Jeff Ridley (jeff.ridley@metoffice.gov.uk)

Abstract. An assessment of the risks of a seasonally ice-free arctic at 1.5 and 2.0°C global warming above pre-industrial is undertaken using model simulations with solar radiation management to achieve the desired temperatures. An ensemble, of the CMIP5 model HadGEM2-ES uses solar radiation management (SRM) to achieve the desired global mean temperatures. It is found that the risk for a seasonally ice-free Arctic is reduced for a target temperature for global warming of 1.5°C (0.1%) compared to 2.0°C (42%), in general agreement with other methodologies. The SRM produced more ice loss, for a specified global temperature, than for CO_2 mitigation scenarios, as SRM produces the higher polar amplification. .

1 Introduction

The 21st Conference of Parties (COP) to the UN Framework Convention on Climate Change held in Paris in 2016 made a commitment to limiting global-mean warming since the pre-industrial era to well below 2.0°C and to pursue efforts to limit the warming to 1.5°C (UNFCCC, 2015). The 1.5 ˚C target reflects a threshold at which the likely local impacts of climate change are beyond the ability of society to cope with. This is especially applicable to the small island states that are susceptible to sea-level rise, ground-water salinification and loss of coral reefs. One such risk is the loss of Arctic sea ice, for which previous studies (Sanderson et al., 2017; Screen & Williamson, 2017; Jahn, 2018; Niederdrenk & Notz, 2018; Sigmond et al., 2018) used a number of methodologies with various climate models under CO_2 mitigation scenarios. The findings are broadly similar, that there is a low chance of an ice–free Arctic if global temperatures are limited to 1.5°C and a moderate chance at 2°C.

It has been suggested that geoengineering, otherwise known as solar radiation management (SRM), may be a stopgap measure to halt these impacts, stabilising Earth's temperature at 1.5 K, before CO_2 mitigation can take effect (Chen & Xin, 2017). Here we evaluate the impact of SRM on Arctic sea ice decline and compare with mitigation methods alone, through the implementation of SRM, in our climate model HadGEM2-ES. We use the SRM strategy of stratospheric aerosol injection, which mimics large volcanic eruptions (Crutzen, 2006).

Arctic sea ice area declines and thins in summer due to surface melting and solar absorption in open water resulting in warming and melting at the ice base. In the absence of incoming solar radiation, ice thickens and spreads in winter caused by heat loss to the colder atmosphere cooling the ocean to its freezing point, with new ice formation in open water and freezing to the base of existing ice. As the planet warms, the summer thinning is enhanced through extension of the melt season, and the winter freeze-up reduced though a warmer atmosphere and lower heat loss. The result is an annual net thinning of the sea ice. The thinner the ice the less that survives the summer melt and consequently the area of perennial ice declines. The albedo of open water (0.07) is less than that of bare sea ice (0.5) and so the regional heat uptake increases, warming the Arctic and resulting in increased ice melt – the albedo-temperature feedback.

Sea ice hits its smallest extent sometime in September and since the satellite record began in 1979, the Arctic sea ice cover in the month has declined by around 11% per decade (Comiso et al., 2017). The current record low was recorded on 16 September 2012, when sea ice extent was 3.41 million square kilometres. Such a sharp drop off in sea ice has prompted the question of when the Arctic will first see an ice-free summer. By "ice-free" we mean a sea ice extent of less than one million square kilometres, rather than zero sea ice cover. We make this choice because although the central Arctic Ocean is free of ice, the thick ice along the North coast of Greenland can take some further decades to melt.

The impacts of a seasonally ice-free Arctic include increased ice loss from Greenland (Day et al., 2013; Lui et al., 2016), and hence sea level rise, and may contribute to extreme weather events in the northern mid-latitudes (Overland et al., 2016; Francis et al., 2017). Thus, storms and waves in the open water may cause coastal erosion, impacting marine ecosystems, infrastructure and local communities (Steiner et al., 2015; Radosavljevic et al., 2016).

With the objective to limit the increase in global average temperature to well below 2.0°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, we need to ascertain the costs of mitigation and associated climate risks. It is suggested that SRM may be a means to reduce the immediate costs of climate mitigation, especially to reach the 1.5C target (Sugiyama et al., 2017). There have been a number of proposed mechanisms to reduce the solar radiation reaching the Earth's surface through geoengineering (Shepherd, 2009; Ming et al., 2014). Here we employ the SRM methodology of increasing sulphate aerosols in the stratosphere, which in the CMIP5 climate model HadGEM2-ES, is achieved through uniformly increasing the number density of volcanic aerosols. This work expands on the methodology of Jones et al. (2018) where SRM is applied in HadGEM2-ES. Although this method can stabilise global temperatures, it produces a spatial temperature pattern with over-cooling in the tropics and slight warming at high latitudes (Kravitz et al., 2017). This means it may be effective in reducing ice loss compared to doing nothing, as SRM cools everywhere, but not so effective compared with reducing greenhouse gas emissions. Here we evaluate this by comparing a geo-engineered 1.5 and 2.0°C worlds with the equivalent temperature CO_2 mitigated worlds. The use of modelled SRM in this paper does not endorse or advocate either testing or actual implementation of geoengineering. Our purpose here is to study and inform.

2 Method

HadGEM2-ES is a coupled AOGCM with atmospheric resolution of N96 (1.875°×1.25°) with 38 vertical levels and an ocean resolution of 1° at mid-latitudes (increasing to 1/3° at the equator) and 40 vertical levels (Jones et al., 2011). The ocean grid has an island at the North Pole to avoid the singularity caused by a convergence of the meridians. The sea ice component uses elastic-viscous-plastic dynamics, five ice thickness categories, and zero-layer thermodynamics (McLaren et al., 2006). The HadGEM2-ES simulation produces a good representation of Arctic sea ice, thickness, trends, seasonal cycle and variability, when compared against observations (Martin et al., 2011; Baek et al., 2013; Huang et al., 2017). Simulated temperature changes are referenced against the mean global temperature from a 400 year section of a pre-industrial control simulation with constant forcing at 1860 levels of greenhouse gases.

The objective is to explore several SRM scenarios branching from the transient simulations of Representative Concentration Pathway (RCP) scenarios (van Vuuren et al., 2011). RCP scenarios start from the year 2005 and continue to 2100. The mean of the four RCP2.6 scenario simulations reaches a peak global mean temperature of +2°C while that of RCP4.5 reaches +2.9°C. Each scenario is allowed to develop without SRM adjustment until a global temperature of +1.5°C is reached in RCP2.6 (year 2020), +2.0°C and +2.5°C in RCP4.5 (years 2040 and 2060 respectively in the ensemble means). New simulations, using SRM, are started from these points using continuous injection of SO_2 into the model stratosphere between 16 and 25 km. This SO_2 is oxidised to form sulphate aerosols that reflect incoming solar radiation and thus cool the climate. As HadGEM2-ES does not have a well-resolved stratosphere, SO_2 is injected uniformly across the globe to reduce any problems with stratospheric transport. Since the global temperature of the RCPs varies in time, the SO_2 required to maintain a constant global temperature will also vary in time. The difference between the RCP ensemble mean and target temperatures (e.g. 2.0°C), calculated at 10-year intervals, was used to determine the time-profile of SO_2 injection in combination with calibration simulations to assess the amount of cooling for a given level of SO_2 injection (-0.115 °C/Tg [SO_2] yr^{-1}). Provided the temperature differences are small, a single value for climate sensitivity to SO_2 may be applied. The same SO_2 time profile was injected into each of the ensemble members with the same target temperature.

For CMIP5 a historical + scenario initial condition ensemble of four HadGEM2-ES members was completed. A larger ensemble is required to generate a probability distribution of sea ice decline. To achieve this we take the four separate RCP ocean and atmosphere start conditions and intermix them (e.g. RCP ensemble member-1 atmosphere with RCP ensemble member-2 ocean) to provide 16 perturbed members for each start date of 2020, 2040, and 2060. The application of a random atmosphere on an ocean state equilibrates within a few days (Griffies & Bryan, 1997). The resulting ensemble spread in global mean temperature is larger than that for the initial 4-member ensemble, indicating that the resulting initial perturbations are sufficient to generate a wide range of climate trajectories.

The ensembles analysed in this study are as follows:

- Ensemble-1 : starts at 1.5°C on RCP2.6 and levels out at 1.5°C above pre-industrial control (1860).
- Ensemble-2 : starts at 2.0°C on RCP4.5 and levels out to 1.3°C above pre-industrial control (1860).
- Ensemble-3 : starts at 2.5°C on RCP4.5 and levels out to 1.7°C above pre-industrial control (1860).

3 Results

The September sea ice extent in the three ensembles (Figure 1) remains stable in Ensemble-1 but recovers in Ensemble-2 and Ensemble-3. The recovery is in line with the downward drift in global mean temperatures as indicated by the reversibility and decadal temperature sensitivity of Arctic sea ice change (Ridley et al., 2012). The spatial pattern of sea ice edge (Figure 2) shows that the model represents a low ice extent for present day in the Greenland Sea when compared with observations. This is because the ice modelled in HadGEM2-ES, in common with many CMIP5 models (Stroeve et al., 2014), is thin in the Atlantic sector and too thick in the Beaufort Gyre, consequently the sea ice retreats in the Atlantic sector with global warming. The ice edge, at equilibrium, is nearly identical in Ensemble-1 and Ensemble-2, with ice retreating further in the Atlantic sector. Meanwhile Ensemble-3 has members with discontinuous ice cover, with a patch of ice in the Beaufort Gyre, where the ice was originally too thick, and extending along the North Greenland and Canadian Archipelago coasts. That Ensemble-3 has a different spatial pattern of the ice edge, and yet is only a few tenths of a degree warmer than the other two ensembles at 2100, associated with the 15% threshold used to derive the ice edge. The summer ice cover in the central Arctic has an extensive marginal ice zone and so the threshold definition of the ice edge at 15% ice concentration is noisy.

The time-drift in September ice extent in Ensemble-2 and Ensemble-3 leads us to conclude that attempting to create a mean state for specific global temperatures, without precise tuning of the SRM for each RCP, is not sensible. Instead, all ensembles are combined to form a continuum of annual global temperature and September Arctic sea ice states. The scatter-plot of all 48 ensemble members and 2880 simulated years is shown in Figure 3. It is expected that the use of SRM will change the regional energy budget, with many models showing an enhanced warming in the Arctic (Kravitz et al., 2017; Jones et al., 2018). To compare SRM and GHG-scenarios for the same global temperature rise, in addition to the SRM ensembles, the data from the transient RCP2.6 and RCP4.5 is added to the scatter-plot. The RCPs climate is moderated by greenhouse gas emissions, and so serve as a reference for the SRM ensembles. The data from the transient simulations shows broadly similar characteristics to the ensemble members, with high scatter in sea ice extent at low global temperature and less at higher temperatures. However, it is evident that the RCP simulations show a marginally greater sea ice extent than for SRM, and we assess this through model polar amplification. The polar amplification, as defined by $\Delta T_{(60\text{-}90°N)}//\Delta T_{(global)}$ (where ΔT is a 20 year time mean temperature rise - in this case a global rise of 1°C), is 2.48±0.08 for the RCPs and 2.89±0.12 for the SRM ensembles. The higher polar amplification for the SRM case is in agreement with Kravitz et al.(2017). In principle, the higher SRM polar amplification should result in a faster decline of the Arctic sea ice, so we investigate if the sea ice extent is lower for SRM then RCPs at 1.5°C. The mean sea ice extent in the temperature band 1.5±0.1°C (Figure 3a) above preindustrial, is 2.45±0.02 x 10^6 km^2 with SRM and 2.90±0.09 x 10^6 km^2 in the RCPs (with CO_2 mitigation). This result shows a higher sea ice loss in the SRM experiments than with mitigation at 99.7% confidence.

The probability distribution function (PDF) is derived for sea ice extent within temperature bands; 1.5±0.1 (sample size 1068 of which 77 are RCP) and 2.0±0.1°C (sample size 341 of which 112 are RCP) above preindustrial. The probability of a single year with an ice extent less than one million square kilometres at +1.5°C is 0.1% and that at +2.0 °C is 42%.

4 Conclusions

Similar to previous studies we find a significantly reduced risk of a seasonally ice-free Arctic with a target temperature for global warming of 1.5°C (0.1%) than for 2.0°C (42%). The approach described here differs from other studies which use climate mitigation to limit global temperature (Sanderson et al., 2017; Screen & Williamson, 2017; Jahn, 2018; Niederdrenk & Notz, 2018; Sigmond et al., 2018), and who report broadly similar probabilities. Here, CO_2 is allowed to increase and the global mean temperatures are limited by SRM. We show that, as a result, the Arctic sea ice declines faster using SRM than for an equivalent global mean temperature under greenhouse gas (GHG) mitigation scenarios (RCP). The internal variability of Arctic sea ice is high at 1.5°C, but because of the size of our ensembles we can show a significant difference between SRM and RCP.. In common with the studies of Haywood et al. (2013), Jones et al. (2017), Jones et al (2013) and Trisos et al (2018) our study provides another cautionary aspect for SRM implementation. These studies showed counterbalancing deleterious impacts on Sahelian drought and N. Atlantic hurricane frequency if SRM were applied in a hemispherically asymmetric manner, and a significant termination effect that ecosystems may not have the capacity to deal with should high levels of SRM be relied on. Here we show that while SRM provides a partial solution, it is not as effective as conventional mitigation in reducing sea-ice loss.

References

Baek, H. J., Lee, J., Lee, H. S., Hyun, Y. K., Cho, C., Kwon, W. T., Marzin, C., Gan, S. Y., Kim, M. J., Choi, D. H., Lee, J., Lee, J., Boo, K. O., Kang, H. S. and Byun, Y. H.: Climate change in the 21st century simulated by HadGEM2-AO under representative concentration pathways, Asia-Pacific J Atmos Sci. 49: 603. https://doi.org/10.1007/s13143-013-0053-7 , 2013.

Chen, Y., & Xin, Y. : Implications of geoengineering under the 1.5∘C target: Analysis and policy suggestions.

Advances in Climate Change Research, 8, 123–129. https://doi.org/10.1016/j.accre.2017.05.003, 2017.

Comiso, J. C., Meier, W. N., and Gersten, R. : Variability and trends in the Arctic Sea ice cover: Results from different techniques, J. Geophys. Res.,122, 6883-6900. doi: 10.1002/2017JC012768, 2017.

Crutzen, P. : Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?

Climatic Change, 77, 211–220. https://doi.org/10.1007/s10584-006-9101-y, 2006.

Day, J.J., Bamber, J.L., and Valdes, P.J.: The Greenland Ice Sheet's surface mass balance in a seasonally sea ice-free Arctic, J. Geophys. Res.-Earth, 118, 1533–1544, https://doi.org/10.1002/jgrf.20112, 2013.

Francis, J. A., Vavrus, S. J. and Cohen, J.: Amplified Arctic warming and mid-latitude weather: new perspectives on emerging connection, Wiley Interdisciplinary Reviews-Climate Change, 8, UNSP e474, doi: 10.1002/wcc.474, 2017.

Griffies, S. and Bryan, K. : A predictability study of simulated North Atlantic multidecadal variability, Climate Dynamics 13: 459, https://doi.org/10.1007/s003820050177, 1997.

Haywood, J.M., Jones, A., Bellouin, N., and Stephenson, D. B. : Asymmetric forcing from stratospheric aerosols impacts Sahelian drought, Nature Climate Change, 3, 7, 660-665, doi: 10.1038/NCLIMATE1857, 2013.

Huang, F., Zhou, X. & Wang, H.: Arctic sea ice in CMIP5 climate model projections and their seasonal variability, Acta Oceanol. Sin., 36: 1. https://doi.org/10.1007/s13131-017-1029-8, 2017.

Jahn, A. : Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming, Nature Climate Change, 8, 409–413, doi:10.1038/s41558-018-0127-8, 2018.

Jones, A., Haywood, J.M., Alterskjær, K., Boucher, O., Cole, J. N. S., Curry, C. L., Irvine, P. J., Ji, D., Kravitz, B., Kristjánsson, J. E., Moore, J., Niemeier, U., Robock, A., Schmidt, H., Singh, B., Tilmes, S., Watanabe, S., and Yoon, J.-H. : The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP), J Geophys. Res., DOI: 10.1002/jgrd.50762, 2013.

Jones, A.C., Haywood, J. M., Dunstone, N., Hawcroft, M. K., Hodges, K., Jones, A. and Emanuel, K. : Impacts of hemispheric solar geoengineering on tropical cyclone frequency, Nature Communications, 8, 1382, doi:10.1038/s41467-017-01606-0, 2017.

Jones, A. C., Hawcroft, M. K., Haywood, J. M., Jones, A., Guo, X., & Moore, J. C. : Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering, Earth's Future, 6, 230–251, https://doi.org/10.1002/2017EF000720, 2018.

Jones C.D. et al.: The HadGEM2-ES implementation of CMIP5 centennial simulations. Geosci Model Dev., 4:543–570, 2011.

Kravitz, B., D. G. MacMartin, M. J. Mills, J. H. Richter, S. Tilmes, J. -F. Lamarque, J. J. Tribbia, and F. Vitt, F. : First simulations of designing stratospheric sulfate aerosol geoengineering to meet multiple simultaneous climate objectives. J. Geophys. Res. Atmos., 122, 12,616–12,634. https://doi.org/10.1002/2017JD026874, 2017.

Liu J, Chen Z, Francis J, Song M, Mote T, Hu Y.: Has Arctic sea-ice loss contributed to increased surface melting of the Greenland ice sheet? J. Clim. 29: 3373–3386. https://doi.org/10.1175/JCLI-D-15-0391.1, 2016.

Martin, G. M., Bellouin, N., Collins, W. J et al.: The HadGEM2 family of Met Office Unified Model climate configurations, Geosci. Model Dev., 4, 723-757, https://doi.org/10.5194/gmd-4-723-2011, 2011.

McLaren, A. J., Banks, H. T., Durman, C. F., Gregory, J. M.,Johns, T. C., Keen, A. B., Ridley, J. K., Roberts, M. J., Lipscomb, W. H., Connolley, W. M., and Laxon, S. W.: Evaluation of the sea ice simulation in a new coupled atmospheric-ocean climate model (HadGEM1), J. Geophys. Res., 111, C12014, doi:10.1029/2005JC003033, 2006.

Overland, J., J. Francis, R. Hall, E. Hanna, S. Kim, and T. Vihma: The melting Arctic and midlatitude weather patterns: Are they connected? J. Climate, 28, 7917–7932, doi:https://doi.org/10.1175/JCLI-D-14-00822.1, 2015.

Ming, T., de Richter, R., Liu W. and Caillol, S. : Fighting global warming by climate engineering: Is the Earth radiation management and the solar radiation management any option for fighting climate change? Renewable and Sustainable Energy Reviews, 31, 792-834, https://doi.org/10.1016/j.rser.2013.12.032, 2014.

Niederdrenk, A. L., & Notz, D : Arctic sea ice in a 1.5∘C warmer world. Geophysical Research Letters, 45, 1963–1971. https://doi.org/10.1002/2017GL076159, 2018

Radosavljevic, B., Lantuit, H., Pollard, W., Overduin, P., Cout Haywood, J.M., A. Jones, N. Bellouin, and D.B. Stephenson, Asymmetric forcing from stratospheric aerosols impacts Sahelian drought, Nature Climate Change, 3, 7, 660-665, doi: 10.1038/NCLIMATE1857, 2013.

ure, N., Sachs, T., Helm, V. and Fritz, M. : Erosion and Flooding-Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada, Estuaries and Coasts, 39, 900-915. doi: 10.1007/s12237-015-0046-0, 2016.

Res. 108, 4407 doi: 10.1029/2002JD002670, 2003.

Ridley, J.K., Lowe, J.A., and Hewitt, H.T.: How reversible is sea ice loss?, The Cryosphere, 6, 193-198, https://doi.org/10.5194/tc-6-193-2012, 2012.

Sanderson, B. M., Xu, Y., Tebaldi, C., Wehner, M., O'Neill, B., Jahn, A., Pendergrass, A. G., Lehner, F., Strand, W. G., Lin, L., Knutti, R., and Lamarque, J. F.: Community climate simulations to assess avoided impacts in 1.5 and 2 °C futures, Earth Syst. Dynam., 8, 827-847, https://doi.org/10.5194/esd-8-827-2017, 2017.

Sigmond, M., Fyfe, J .C. & Swart, N.C. : Ice-free Arctic projections under the Paris Agreement, Nature Climate Change, 8, 404–408, doi:10.1038/s41558-018-0124-y, 2018.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., Kaplan, A. : Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Screen, J. A. and Williamson, D. : Ice-free Arctic at 1.5◦C?, Nat. Clim. Change, 7, 230–231,https://doi.org/10.1038/nclimate3248, 2017.

Shepherd, J. G. : Geoengineering the climate: Science, governance and uncertainty (Policy Document No. 10/09). London: Royal Society, 82 pp, 2009.

Stroeve, J., Barrett, A., Serreze, M., and Schweiger, A.: Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness, The Cryosphere, 8, 1839-1854, https://doi.org/10.5194/tc-8-1839-2014, 2014.

Sugiyama, M., Arino, Y., Kosugi, T., Kurosawa, A. & Watanabe, S. : Next steps in geoengineering scenario research: limited deployment scenarios and beyond. Climate Policy, 1-9, doi: 10.1080/14693062.2017.1323721, 2017.

Trisos, C.H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L. and Zambri, B. : Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. Nature Ecology & Evolution, 2, 475–482, https://doi.org/10.1038/s41559-017-0431-0, 2018.

UNFCCC: Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev.1, http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf, 2015

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. & Rose, S. K. : The representative concentration pathways: an overview, Climatic Change 109: 5. https://doi.org/10.1007/s10584-011-0148-z, 2011.

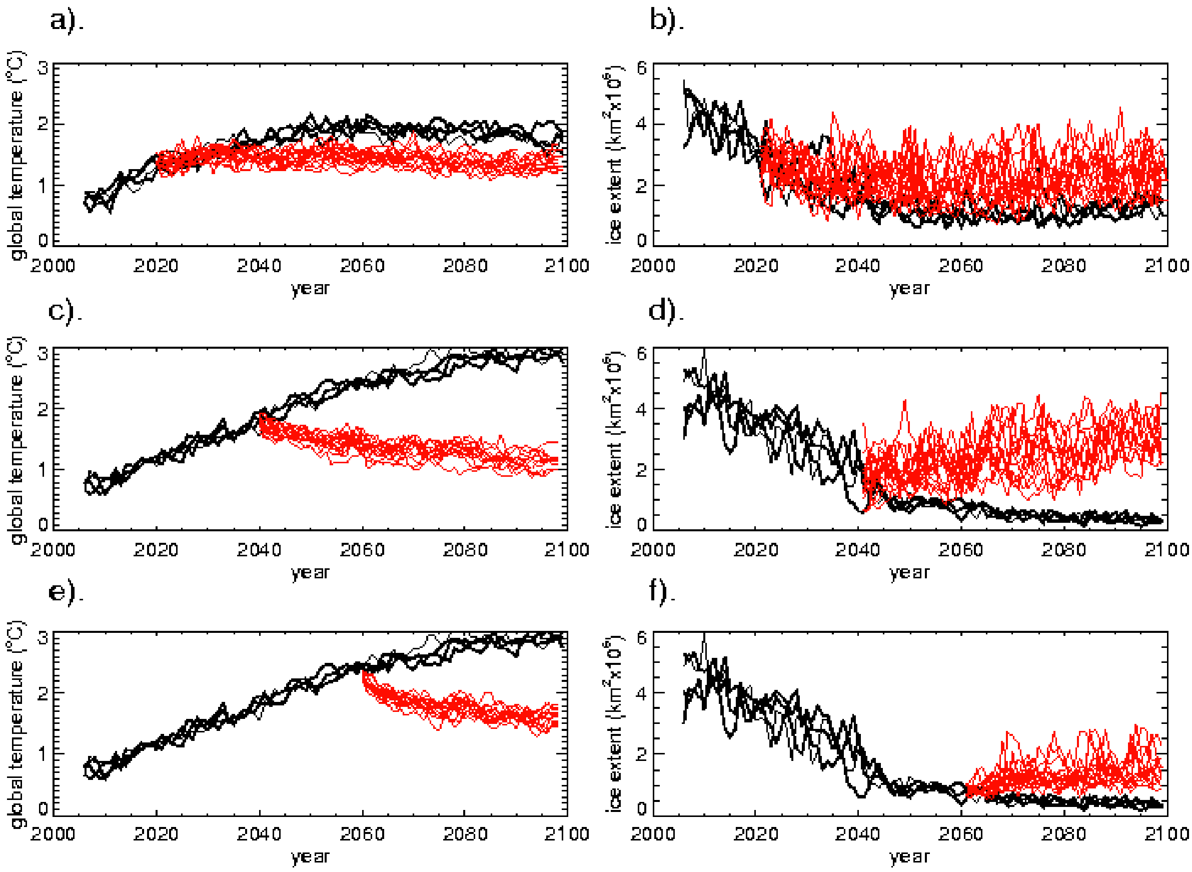

Figure 1 (a) Global mean 1.5m temperature and (b) Arctic sea ice extent for the four ensemble RCP2.6 simulations (black) and the 16 member ensemble-1 initiated from +1.5°C (red). (c) Global mean 1.5m temperature and (d) Arctic sea ice extent for the four ensemble RCP4.5 simulations (black) and the 16 member ensemble-2 initiated from +2°C (red). (e). Global mean 1.5m temperature and (f) Arctic sea ice extent for the four ensemble RCP4.5 simulations (black) and the 16 member ensemble-2 initiated from +2.5°C (red).

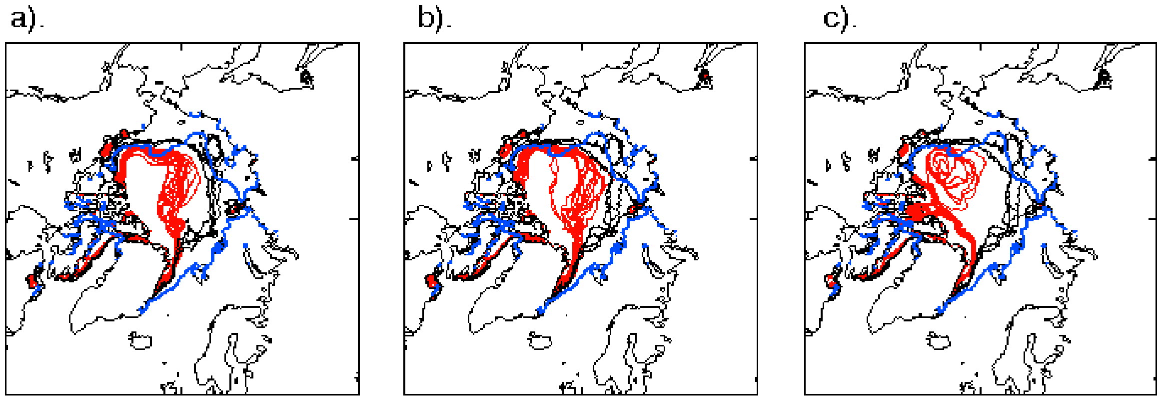

Figure 2. The spatial pattern of the sea ice edge (the 15% concentration contour) with the observations mean for the period 2006-2015 from HadISST (Rayner et al., 2003) in blue, the four-member model RCP ensemble for the equivalent period in black and the 16 member ensemble simulations for the mean of years 2080-2099 in red. (a) The RCP2.6 simulations and ensemble-1; (b) the RCP4.5 simulations and ensemble-2; (c) the RPC4.5 simulations and ensemble-3.

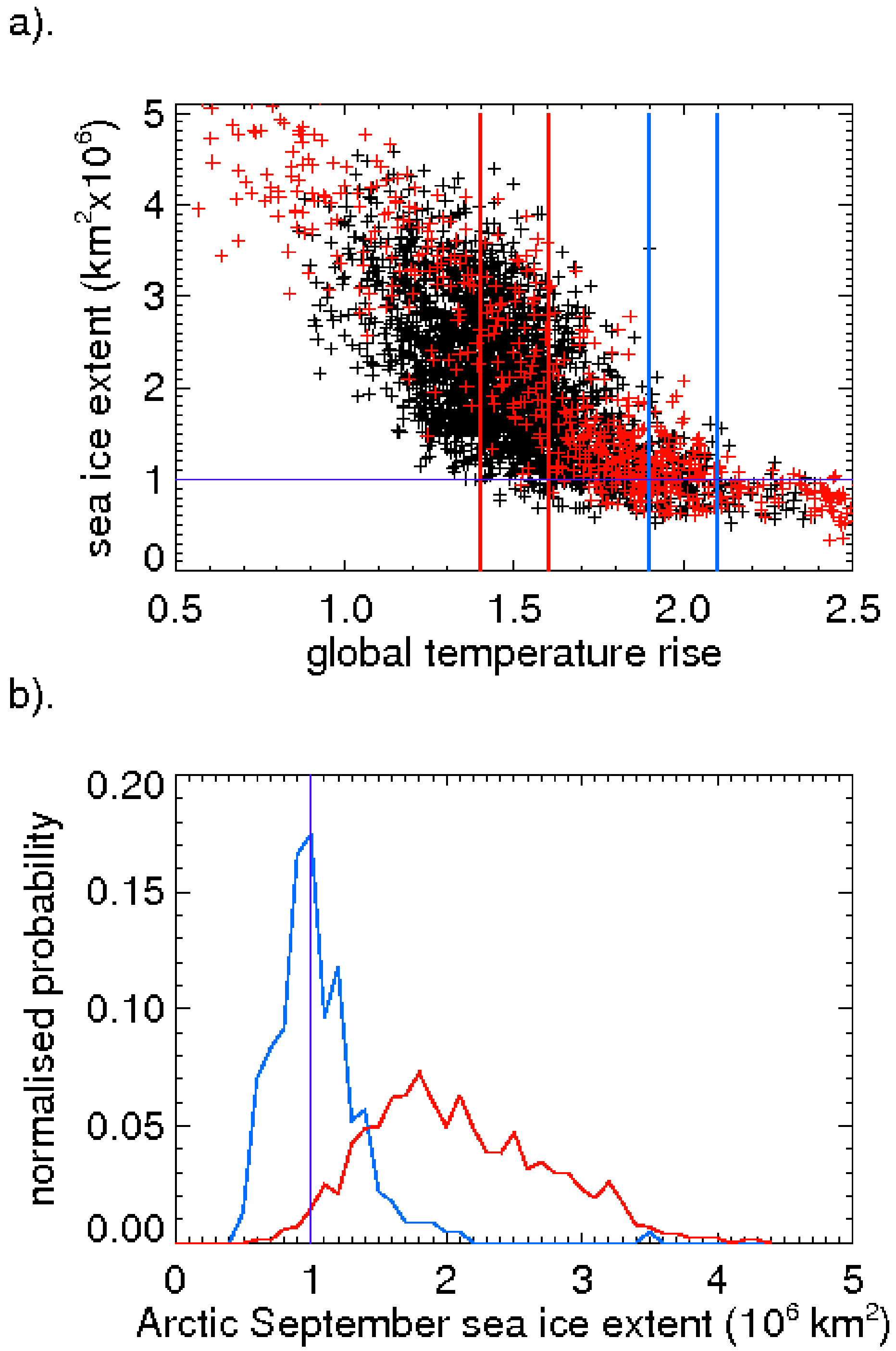

Figure 3. (a) All 48 ensemble members are combined to derive a September ice extent vs global temperature scatterplot (black symbols) with the complete four member RCP2.6 and four member RCP4.5 simulations included (red symbols). The threshold of one million square kilometres signifying an almost ice-free Arctic is shown with the purple horizontal line. The data points used to evaluate the probability distribution function of (b) are selected from the global temperature thresholds of 1.5±0.1°C (red vertical lines) and 2.0±0.1°C (blue vertical lines). (b) The normalised probability

distribution functions of Arctic sea ice extent at global temperature rises of 1.5±0.1°C (red) and 2.0±0.1°C (blue) associated with the ensemble members shown in (a). The one million square kilometre threshold for an ice-free Arctic is indicated by the purple vertical line.