Response to Anonymous Referee #1

We thank the reviewer for their useful comments

The paper is short, well written and scientifically sound.

The main concern I have is to clarify what the actual contribution of the paper is. The paper should be better positioned wrt state of the art. In particular the intro should make clear what were the findings from Screen and Williamson (2017) and Sandersen et al. (2017), how the present study differs from those, and how the present methodology brings something different from / completes these studies.

If a clear added value can be defended, then the paper can be published nearly as is. I would add that, if the contribution is an independent evaluation of the likelihood of an ice-free Arctic under 1.5, 2 and 2.5◦C targets, using an alternative method (ensemble vs multi-model vs emulator), I'm quite supportive for the paper to be published, even if the final result duplicates previous findings. Independent, repeated tests are in my view as important as original studies.

In practice, this would probably mean moving material from the end of the paper to the end of the introduction, and complete what is only being suggested at the moment by being more explicit.

Material moved forward to introduction as suggested

More specific comments below.

• The advantages / specificities of the SRM method should be clearer and the reason why it has been chosen as well.

The use of SRM is arguably a plausible mechanism to attain the 1.5C target. It is also a simple mechanism, compared with Sanderson et al (2017), as it requires no new emissions scenario (which would be inconstant with the RCPs). This is an idealised temperature sensitivity study and not suggesting how SRM might be employed. An alternative approach might be to fix CO2 in RCP4.5 when temperatures reach 1.5, 2.0 and 2.5C, but this would leave residual effects from secondary greenhouse gases, aerosols and feedbacks (comparing the 2 methodologies might be an interesting study) SRM is a tried and tested methodology for HadGEM2-ES and the other models of the GeoMIP. We add:

"Here we take a different approach with the intention of assessing if the outcome of three different approaches, including the above, can provide a robust answer to the probability of a seasonally ice-free Arctic at 1.5 and 2.0ºC above pre-industrial. Our methodology is to construct an ensemble of simulations of the CMIP5 model HadGEM2-ES using solar radiation management (SRM) to restrict the global temperature rise. We employ SRM because of its simplicity in requiring a change in just one component to the model, hence maintaining traceability. It is also a plausible scenario, in addition to mitigation, to the 1.5°C target (Sugiyama et al., 2017). This work expands on that of Jones et al (2018) where the SRM methodology is established for HadGEM2-ES. "

- I find the methodology not fully clear. In particular the story of the time dependence of SO2 emissions. Could you illustrate or better describe how SO2 emission depends on time? Is this constant then stabilised? Is it ramped up? Is it non-linear?

The explanation has now been expanded. The injected SO2 volume is time varying to offset the time-varying difference in temperature between RCP4.5 and say the target temperature (say 2.0C). In practice the process (SO2 loading and climate feedbacks) is non-linear with temperature, but for small Delta T this does not matter (as now shown in Figure 3).

- It is well known that the rate of Arctic sea ice decrease depends on mean state, in particular ice volume. Do you expect a model with less volume and the same experimental setup to give higher probability of sea ice volume loss at 1.5◦C ?

A brief comment to this effect, and reference to Bitz (2008), is now included in the conclusions.

- p. 1 l. 23 I would say that there is a net increase in winter growth because ice is thinning (Bitz and Roe, 2004), but I'm not sure which effects dominates. You should come up with more references or more arguments (for instance a mass balance study in CMIP-X).

A comment added to the conclusions refers to the need for such a mass budget analysis.

- p.1 l. 22. "With global, and regional, warming" sounds weird to my ears.

Removed 'and regional'

- p. 1 l. 28 "increased" instead of "increase"

This has been corrected

- p. 1 l. 29. I think the increase in extreme weather due to reduced sea ice is quite challenged, in particular the quite convincing study of Blackport and Kushner J. Clim 2016.

This is still debated e.g Smith et al. (2017) https://doi.org/10.1175/JCLI-D-16-0564.1 and Blackport and Kushner (2017). I think it is still reasonable to say 'may cause'

- p. 2 l. 7. Replace "this is because" by "we make this choice" or reference others to clarify whether you propose this or whether this is standard practice.

This has been corrected as suggested

- p. 2 l. 20. Explain why you use this method.

Have added to the justification at the end of the introduction. Please see response at the start of this response

- One inconsistency is how ◦C is spelt. Sometimes without the ◦, sometimes with space, sometimes not. Make it consistent.

Changed to be consistent throughout

Response to Referee 2

We thank the referee for their useful comments

This brief communication shows results on the likelihood of an ice-free Arctic under the low-warming IPCC targets, using experiments with solar radiation management with the HadGEM2-ES model. It shows that limiting the global temperature rise to around 1.5◦C reduces the likelihood of an ice-free Arctic to 0.2%, compared to 43% for warming around 2◦C. This study is interesting and shows similar results to previous work using other models, in particular with the CESM in Sandersen et al. (2017) and the CMIP5 RCPs in Screen and Williamson (2017). This shows that those results are robust across different models. So while the results are not new, they are worthwhile to be published, in particular in light of the upcoming IPCC report on the low warming targets. However, I find the submitted manuscript not publishable in its current form. Even for the category "Brief communication" I find the results section too short – it is shorter than the methods and about the same length as the conclusions and introduction individually. This paper really seems to be pushing the "least publishable unit" into the unacceptable category, and I cannot support that. There is lots of additional analysis that could easily be done with these simulations, even expanding directly on the figures shown. For example Figure 2 is not discussed much and that could be expanded to add new insights not previously shown to this discussion (the spatial aspect of the ice edge under these targets). That said, I have a long list (as long as the paper...) of things that need to be addressed, detailed below. Furthermore, the article has many typos, fuzzy figures, and imprecise and confusing statements and captions. The figures also need to be revised. Overall, I see merit in publishing these results as brief communication, but not in the present form, and therefore recommend major revisions.

- Results section expanded

- Figure quality and information content improved

- More motivation provided

Detailed comments:

Page 1, Line 8-9: Why would we want to "reduce the internal variability" if we want to produce a probability density function of an ice-free state? Is this a typo, and it should be "deduce"?

Clarified with 'improve the signal to noise associated with the internal variability'

Page 1, line 18: Seems to be missing a noun at the end of the sentence? Should be "one such system"

This has been corrected

Page 1, Line 25: Should be "uptake", not "up-take"

This has been corrected

Page 1, Line 28: Should be "increased", not "increase"

This has been corrected

Page 1, Line 3: Why "then" here, doesn't really make sense, as it does not relate to the previous sentence ("Sea ice then hits its smallest extent sometime in September…")

This has been corrected

Page 2, Line 13: two .. at the end of the section

This has been corrected

Page 2, Line 13: I think the introduction needs to reference the of previous work on this topic, and not make it sound like this hasn't been done yet (Screen and Willamson, 2016, Sanderson et al. 2017)

This has been corrected

Page 2, Line 15: Degree symbol is incorrect, should be ◦ not â˚U ̧e . This is correct for◦ C, but not for degree related to N/S.

This has been corrected

Page 2, Line 30 to Line 2 Page 3: Is there just one simulation for each RCP? Sounds like it, since just one year is given for reaching these target temperatures.

The appropriate sulphate loading was calculated just once for each target temperature from the mean of the relevant 4-member RCP scenario ensemble. This was initially mentioned P3 line 1+2 but has been moved up and expanded for clarification. Thus, it is indeed the case that ensemble mean is used to determine the dates for the temperature thresholds.

But then it says "For CMIP5 a historical + scenario initial condition ensemble of 4 HadGEM2-ES members was completed.". So does the ensemble mean of these four cross the threshold at that time? That needs to be made clearer. The figure 1 only shows one line for each RCP. But then says that that is the ensemble mean of 4 RCP members. But then each member of the 16 member ensemble for reduced temperatures is shown. Why is that done? It makes no sense to me. The 4 ensemble members for each RCP should be shown as well, so it is clear whether the new ensemble is outside the internal variability of the initial RCP. That would help to substantiate the statement on page 3, line 5 that (The resulting ensemble spread in global mean temperature is larger than that for the initial 4-member ensemble). Not that I doubt that, but it is always nice to see this, and to see how much larger the spread is. Adding the ensemble members for the RCPs would also explain why some of the red lines start well above or below the black line.

As per the reviewer's suggestion, the figures have been updated to show all 4 RCP scenario ensemble members (rather than the mean as before)

Page 2, Line 30 to Line 2 Page 3: What is the reference period for the 1.5C and 2C and 2.5C warming? That's not mentioned and various papers use different periods.

The reference for pre-industrial is the mean of the parallel pre-industrial control simulation for the period 2005-2100. Pre-industrial refers to 1860 forcing and this has now been added to the ensemble description summaries on page 3.

Page 3, line 3-6: This seems like quite a large perturbation, mixing the ocean initial conditions with an atmosphere that it isn't equilibrated with it. Has this approach been tested before? I have only heard of others using much smaller initial condition perturbations.

The imposition of a random atmosphere on an ocean state has been demonstrated by Griffies, S. & Bryan, K. Climate Dynamics (1997) 13: 459. https://doi.org/10.1007/s003820050177. The atmosphere equilibrates in days and the ocean loses memory of its initial state within 20 years.

This is now mentioned, and cited, in the text.

Page 3, line 7-10: Why were these target temperatures of 1.3 and 1.7C chosen, when the IPCC target is 1.5C?

The idea was to investigate the region around the 1.5C target to sample for thresholds in the temperature sensitivity. Internal variability was expected to bracket the 1.5 target.

Page 3, Results section: This is a VERY short result section, shorter than the methods and about the same length as the conclusions. That seems to me to be very much below the "least publishable unit" standard, and while interesting, I can't support publishing research in such minimal increments. There is lots of additional analysis that could easily be done with these simulations related to Arctic sea ice to make this acceptable, or even expanding the current description of the results. I know this is a "Short communication", but even for that I find the results too brief.

The results section has been expanded to include further discussion of the updated Figure 2.

Page 3, line 29: Extra "In" at start of sentence

Corrected

Page 3, line 30: Why is the "quantitative result described here" only listed a paragraph later? That makes it hard to compare it with the other studies. Which should be discussed in the introduction already, in my opinion.

Page 4, line 4: Should be "to", not "do"

Corrected

Page 4, Line 1-7: Didn't Screen and Williamson (2017) look at the probability of just one ice-free Arctic, while here and in Sandersen et al. (2017) the overall probability is assessed?

Screen and Williams use a regression line to produce a single value but then apply Bayesian statistics to obtain a probability.

Page 4, Conclusions in general I think these need to be more carefully written. I don't think the statement "since the Arctic sea ice in CMIP5 models is effectively in equilibrium with the instantaneous global temperature" is defensible, as that would mean that Arctic sea ice in a given year is dependent on the global temperature. The cited work shows that this is true in the long-term sense, but not for year-to-year variability. Furthermore, this doesn't apply to all properties of Arctic sea ice, so this needs to be more precisely formulated (September, extent).

Agreed. This comment and associated references has been removed

Generally: Please use a consistent number of significant digits, and not 1.5C and 2.5C but then 2C.

Consistency corrected throughout

References: Please check these for inconstant formatting – not my job as a referee to fix those

Done

Figure 1: As mentioned earlier, this figure should either show the ensemble mean or the individual members, not a mix of both. Unless there is a good reason for that, but none is articulated. Furthermore, the figure is fuzzy, so it doesn't seem to be saved in a vector format. Need to be switched out to be acceptable.

Figure 2: It is not clear to me what this figure really shows. First of all, this figure does not show the "spatial pattern of the Arctic sea ice extent", but the "spatial pattern of the sea ice edge". Which is only the 15% contour, and hence is very noisy. Furthermore, it is unclear to me what both the red and black lines are. It says early on that it shows the "mean of years 2080-2099", for certain temperature thresholds in certain simulations. But then it goes on to say it shows "the mean (years 2006-2025) of the four" RCPs. I also don't understand "starting at +1.5◦C above preindustrial in RCP2.6 (left), +2◦C in RCP4.5 (centre) and +2.5◦C in RCP4.5 (right)." This clearly needs to be rewritten to make sense to a reader who hasn't made the figure. It says the red lines are for the 16 individual ensemble members, but those are not the RCPs. Going back to how the ensembles are defined, I think that's what the red lines show, but then these are not for temperatures 1.5C, 2.0C and 2.5C, but for 1.5C, 1.3C and 1.7C? Panels also should have labels (a) and (b) and (c) for ease of reading/referencing. Furthermore, based on what I see, the black line in each panel is different. I assume that is because it is for the different temperature thresholds in the two RCPs mentioned above, and probably for 2006-2025, as they look like present-day. But why use different baselines for each, and what is the third one, since there are only two RCPs? That all makes no sense to me. It would make more sense to use the present-day period for all of them, potentially both for the model and observations, to show how realistic the model is. And then show the ice edge for the 2080-2099 for each of the three ensembles. But since their temperatures aren't that different, and are lumped together in the next figure, why they should be shown is unclear. To show the difference between the ones that end at 1.5 and 1.3 degree C versus ensemble 3 that ends at 1.7 degree C?

Figure 3: This figure is also fuzzy and out of focus. It needs to include a higher resolution figure to be considered for publication. Furthermore, it is unclear what exactly it shows. The caption needs to state what the size of the boxes is (+/- 0.1 degree C around the mentioned thresholds, according to my reading of the graph), as it does not show the probability right at the quoted temperature thresholds. Otherwise, this figure is the most interesting one. I do wonder how it compares to the transient RCPs with that model though, and hence how much it adds to just using those. Can those be added here? They all cross the same temperature range, so could be included in the PDF. Currently it seems to only include the 3 ensembles with 16 members each (3*16=48). That leads to

many fewer members that are in the 2 degree warming box than in the 1.5 degree warming box, and hence could be influencing the probability distributions shown in panel 2. Adding the RCPs in here would help to rectify this. Panels also should have labels (a) and b.

The figures have all been updated in line with all the above suggestions

Response to Referee 3

We thank the referee for their insight into the Geoengineering aspect of the paper

The submitted paper discusses the response of Arctic Sea ice September coverage at global mean temperatures of 1.5 or 2 degrees Celsius above pre-industrial, the targets referred to in the Paris climate agreement.

In contrast to previous studies, which have focussed on scenarios which achieve these targets through greenhouse gas mitigation alone, the present study considers joint mitigation and solar radiation management (SRM) to achieve global mean temperature goals.

The study is potentially interesting, but does not address the most interesting issue which could potentially be discerned from this dataset: is there a difference in the projected avoided sea-ice loss which can be obtained through solar radiation management, compared to greenhouse gas mitigation alone?

Firstly - the authors have considered only one target in their geo-engineering experiment: the global mean temperature, and the authors have used globally uniform sulphate distributions to represent their SRM. It has long been noted that such compensation of uniform sulphate increase, whose effect peaks in the tropics combined with increased CO2, whose effect peaks at the pole - results in significant warming at the poles relative to the CO2 mitigation case (Ricke 2010). This would imply that the author's estimates of ice distribution at 1.5 or 2 degrees are likely to show more loss than a pure mitigation case. This is undiscussed in the paper - and is a central point.

Moreover, recent studies have highlighted that targeted injection patterns can mitigate the polar warming effect (Kravitz 2017, Modak 2013) by increasing choosing injection sites which increase the relative sulphate loading over the poles or summer hemisphere. Even if the authors' model is not capable of resolving interactive aerosols, a non-uniform sulphate loading distribution could quantify the efficacy of such approaches for sea ice conservation.

A clear possibility here is to quantify minimum sea ice cover not just as a function of global mean temperature - but as a function of forcing type and transient forcing history (is there any detectable lag in the response of sea ice to falling temperatures as the sulphate loading is increased?).

This is an interesting dataset, but it has been interpreted as a straightforward assessment of climate at 1.5 and 2 degrees, although there are strong reasons to believe that the geoengineered climates considered here would be unlike those observed at global mean temperatures of 1.5 or 2 degrees during a conventional RCP. The paper should acknowledge this, and consider more deeply how climate targets achieved using SRM differ from those achieved using mitigation.

We would agree that there is more that could be looked at in these experiments related to geoengineering, much of which could be made relevant to the impacts on the cryosphere. Another paper, Wiltshire et al. (in preparation), looks at the impacts of different pathways to a target global temperature through geoengineering and mitigation. In the longer term the impacts of different injection patterns may also be investigated, probably using our CMIP6 model which has a well resolved stratosphere and complex chemistry scheme. However, our choice in the format of a Brief Communication, is to focus on a single topic; the response of the Arctic sea ice to 1.5C and 2C global temperatures. The SRM approach is different than other published methodologies and in that context the SRM is the means to an end in our case using existing methodologies and simulations.

Figure 3 now shows the RCP4.5 (mitigated to 2.8 degrees C) and RCP2.6 (mitigated to 2 degrees C) scenarios as well as the SRM simulations. Reference is made to Kravitz et al (2017) and Jones et al. (2018), which remarks on the reduction of polar amplification using SRM. We note that at 1.5 C there is a difference in ice cover in the transient simulations over those of the SRM ensembles, but it is not statistically significant (also mentioned in Results section). In essence the Arctic sea ice appears to simply be responding to global temperature in a time averaged sense.

Minor Issues:

The injection quantities use information derived from the multi-model mean - which is a piece of information which would not be known in the real world.   This should be acknowledged.

Now mentioned in the Methods section.

There are multiple typos. Please proof read before resubmission.

Many typos corrected.

Ricke, K. L., Morgan, M. G., & Allen, M. R. (2010). Regional climate response to solar-radiation management. Nature Geoscience, 3(8), 537.

Kravitz, Ben, Douglas G. MacMartin, Michael J. Mills, Jadwiga H. Richter, Simone Tilmes, Jeanâ A R Francois Lamarque, Joseph J. Tribbia, and Francis Vitt. "First simulations of designing stratospheric sulfate aerosol geoengineering to meet multiple simultaneous climate objectives." Journal of Geophysical Research: Atmospheres 122, no. 23 (2017).

Modak, A., and G. Bala. "Sensitivity of simulated climate to latitudinal distribution of solar insolation reduction in SRM geoengineering methods." Atmos Chem Phys Discuss, 13 (2013): 25387-25415.

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194

Text changes highlighted

Brief Communication: The significance for the IPCC targets of 1.5°C and 2.0°C temperature rise for an ice-free Arctic.

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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, is used to improve the signal to noise associated with the internal variability and produce a probability density function of an ice-free state. 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. A comparison with other methodologies and models shows that the result is robust.

1 Introduction

The 21st Conference of Parties 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. There may be other aspects of the climate system that show substantially increased risk of change between 1.5°C and 2.0°C warming. Here we investigate if Arctic sea ice cover is one such system.

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. Ice thickens and spreads in winter (no incoming solar) due to heat loss from the ocean cooling it to below the salinity freezing point (~ -1.8°C) with new ice formation in open water and freeze to the base of existing ice. With global warming the summer thinning is enhanced through extension of the melt season, and the winter freeze-up reduced though warmer atmosphere and lower heat loss. The result is an annual net thinning of the sea ice. The thinner the ice the less the amount 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. When no perennial ice survives the summer melt then the Arctic is said to be seasonally ice-free.

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).

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.

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. A previous study (Sanderson et al., 2017) used a climate model emulator, calibrated against CESM1, to produce simulations at constant 1.5°C and 2.0°C. 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. Here we take a different approach with the intention of assessing if the outcome of three different approaches, including the above, can provide a robust answer to the probability of a seasonally ice-free Arctic at 1.5 and 2.0ºC above pre-industrial. Our methodology is to construct an ensemble of simulations of the CMIP5 model HadGEM2-ES using solar radiation management (SRM) to restrict the global temperature rise. We employ SRM because of its simplicity in requiring a change in just one component to the model, hence maintaining traceability. It is also a plausible scenario, in addition to mitigation, to the 1.5°C target (Sugiyama et al., 2017). This work expands on that of Jones et al (2018) where the SRM methodology is established for HadGEM2-ES.

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° (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. The sea ice component uses elastic-viscous-plastic dynamics, multiple 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).

The objective is to explore several mitigation scenarios branching from the transient simulations of Representative Concentration Pathway (RCP) scenarios (van Vuuren et al., 2011) RCP2.6 and RCP4.5 at 1.5, 2.0 and 2.5°C. To achieve this, we utilize solar radiation management (SRM) which is simulated by 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 was 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 can be applied. The same SO_2 time profile was injected into each of the ensemble members with the same target temperature. The use of an ensemble mean will not be available in reality to plan implementation of SRM. RCP scenarios start from the year 2005 and continue to 2100. The mean of the 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 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 are started from these points. For CMIP5 a historical + scenario initial condition ensemble of 4 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 ocean and atmosphere start conditions and intermix them, providing a total of 16 perturbed members for both RCP2.6 and RCP4.5. The application of a random atmosphere on an ocean state has been shown to equilibrate 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 : takes 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 global 1.5m temperature and sea area fraction, subsequently converted to ice extent, are extracted from the three ensembles. 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 temperature sensitivity of Arctic sea ice change (Ridley et al., 2012). The spatial pattern of sea ice extent (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 modelled ice, in common with many CMIP5 models (Stroeve et al., 2014), is thin in the Atlantic sector and too thick in the Beaufort Gyre. The sea ice retreats in the Atlantic sector with global warming. The ice extent, 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 ice 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, is associated with the threshold technique to derive the ice extent. 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 can be expected to be 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 can be 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 might be expected that the use of SRM would change the regional energy budget, with many models showing a reduced warming in the Arctic (Kravitz et al., 2017; Jones et al., 2018). Thus, in addition to the ensembles, the data from the transient RCP2.6 and RCP4.5 is added to the scatter-plot. The data from the transient simulations shows similar characteristics to the ensemble members, with high scatter in sea ice extent at low global temperature and less at higher temperatures. This characteristic is due to the less extensive marginal ice zone in the warmer world when the remaining ice is the thick ice, taking longer to melt, along the North Greenland coast and Canadian Archipelago. If the implementation of the solar radiation management technique, to constrain global warming, was influencing poleward heat transport (Kravitz et al., 2013) one might expect sea ice to respond differently in the RCP's and the SRM ensembles. However, although the ice extent is lower, for a particular global mean temperature, in the SRM ensembles than in the RCPs the difference is not statistically significant, and consequently we conclude that SRM itself is not having an effect on the Arctic sea ice (figure 3a).

The probability distribution function (PDF) is derived for sea ice extent within temperature bands; 1.5±0.1 and 2.0±0.1°C 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 increased 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%). 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). It is thus surprising that the quantitative result described here is similar to that found by Screen and Williamson (2017), of 0.001% and 39%, who used the CMIP5 transient simulations, and that of Sandersen et al. (2017), of 2.5% at 1.5°C and 33% at 2.0°C, who used a climate model emulator. A sea ice mass budget analysis, similar to that conducted by Keen et al. (2013), across many climate would be required to ascertain the mechanisms behind this agreement.

The approach described here is independent to that of Sandersen et al. (2017) in that CO_2 is allowed to continue to increase and the global mean temperatures are limited by SRM. The use of SRM is merely a means to an end and not an endorsement of SRM being applied in practice to minimise the temperature impacts of greenhouse gas emissions. The three methodologies provide similar results; that it is highly unlikely for an ice-free Arctic at 1.5°C and an approximately 33-43% chance at 2.0°C. The agreement across multiple methodologies and climate models suggests that collectively the evidence is robust that meeting the lower Paris Agreement temperature goal of 1.5°C would likely prevent the eventual loss of Arctic sea ice.

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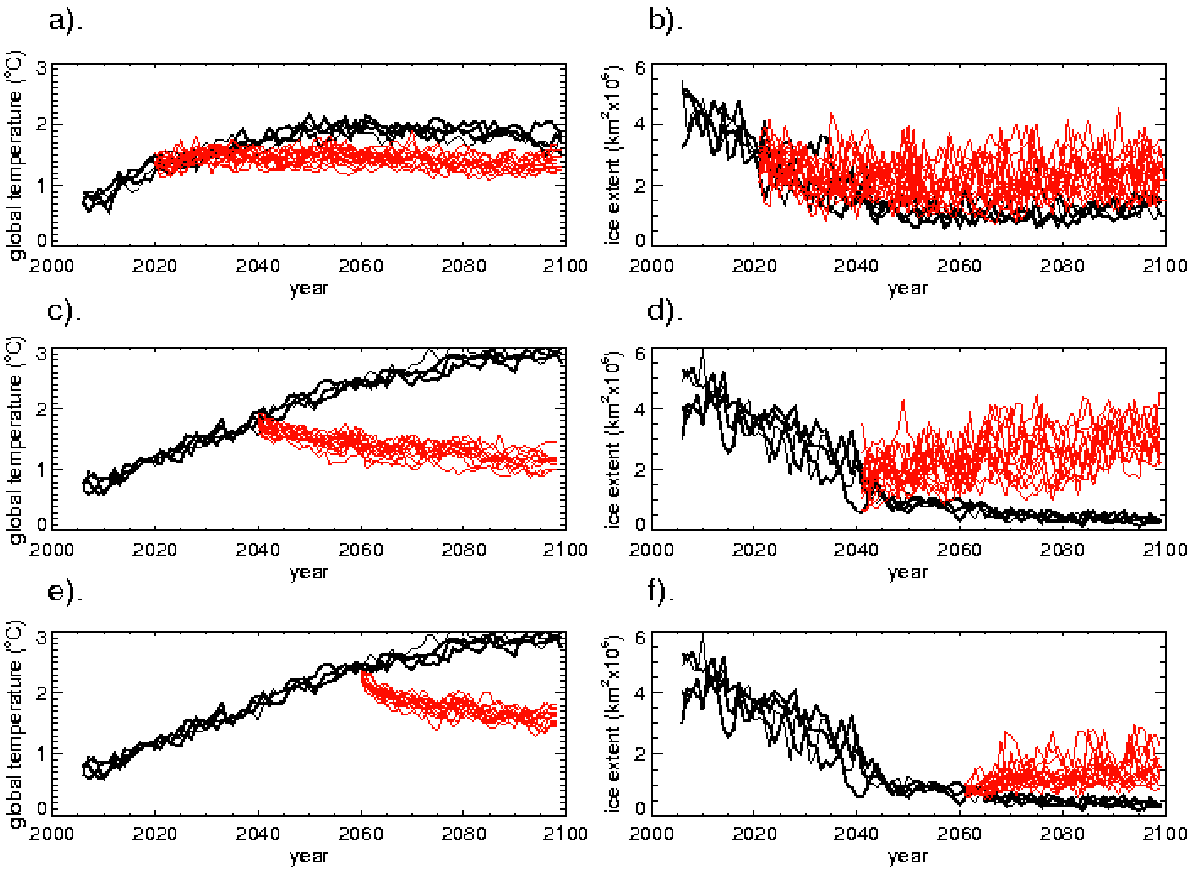


Figure 1 (a) Global mean 1.5m temperature and (b) Arctic sea ice extent for the four ensemble RCP2.6 simulations (black) and the 16 member ensemble-1 initiated from +1.5°C (red). (c) Global mean 1.5m temperature and (d) Arctic sea ice extent for the four ensemble RCP4.5 simulations (black) and the 16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

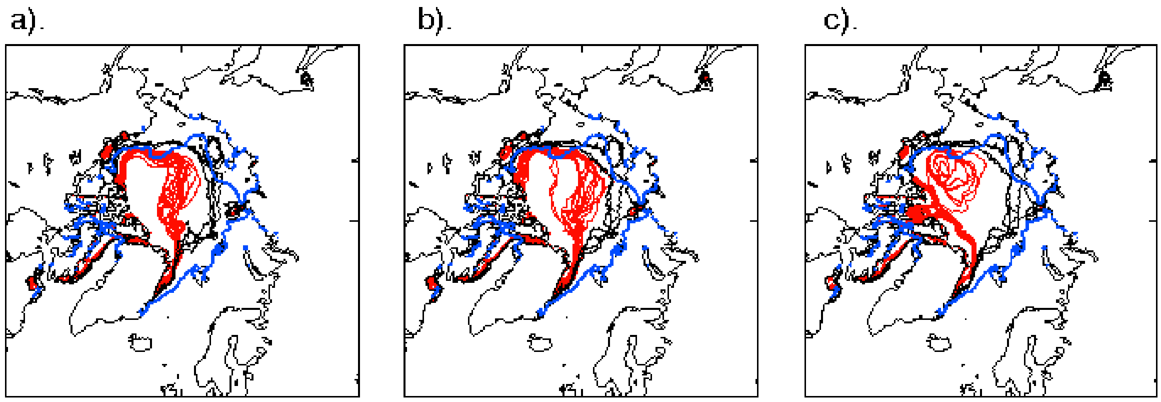
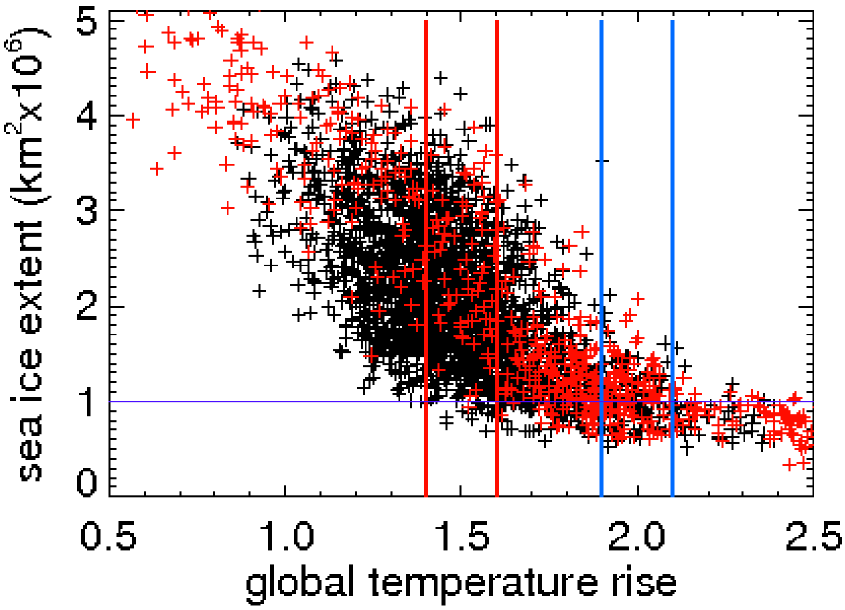


Figure 2. The spatial pattern of the Arctic sea ice extent (the 15% concentration contour) with the observations mean for the period 2006-2015 from HadISST (Rayner et al., 2003) in blue, the four-member model RCP ensemble for the equivalent period in black and the 16 member ensemble simulations for the 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.

a).



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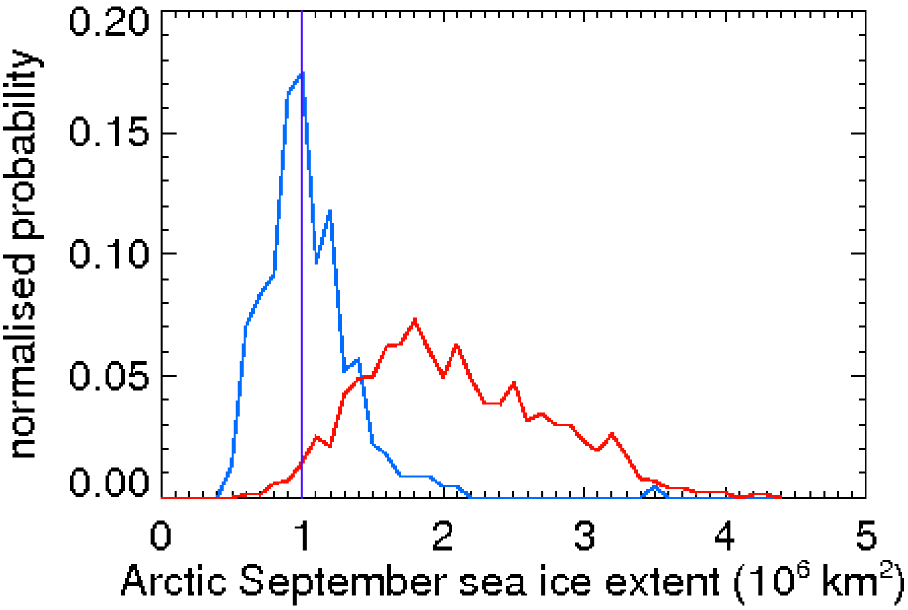

Figure 3. (a) All 48 ensemble members are combined to derive a September ice extent vs global temperature scatterplot (black symbols) with the complete four member RCP2.6 and four member RCP4.5 simulations included (red symbols). The threshold of one million square kilometres signifying an almost ice-free Arctic is shown with the dark blue 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 solid dark blue vertical line.