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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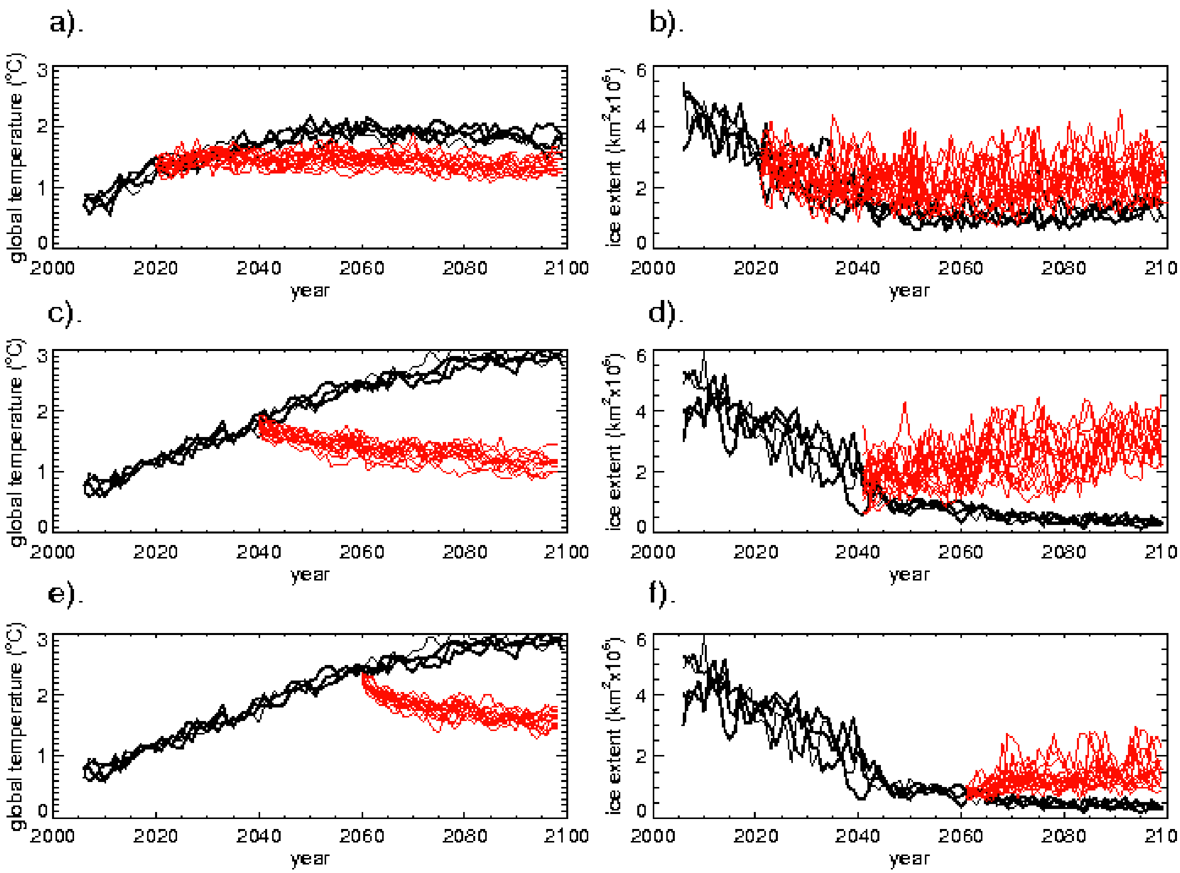


Figure 1 (a) Global mean 1.5m temperature and (b) Arctic sea ice extent for the four ensemble RCP2.6 simulations (black) and the 16 member ensemble-1 initiated from +1.5°C (red). (c) Global mean 1.5m temperature and (d) Arctic sea ice extent for the four ensemble RCP4.5 simulations (black) and the 16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

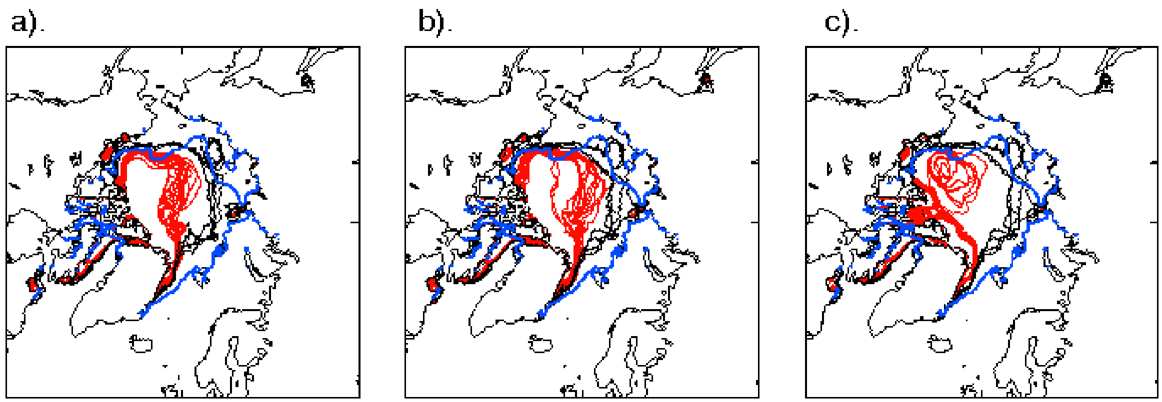
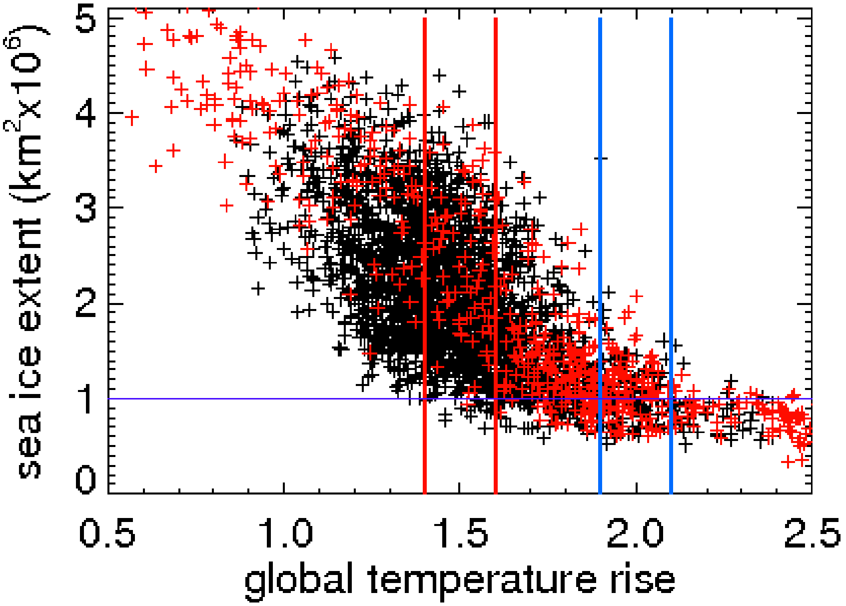


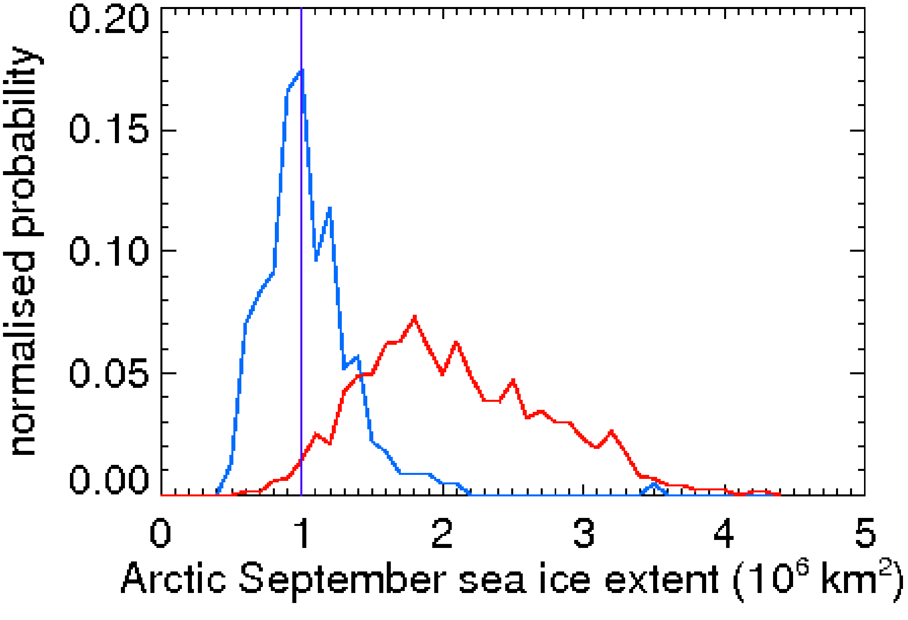
Figure 2. The spatial pattern of the Arctic sea ice extent (the 15% concentration contour) with the observations mean for the period 2006-2015 from HadISST (Rayner et al., 2003) in blue, the four-member model RCP ensemble for the equivalent period in black and the 16 member ensemble simulations for the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



5
4
3
2
1
0
sea ice extent (km^{2}x10^6)
0.5
1.0
1.5
2.0
2.5
global temperature rise

b).



0.20
0.15
0.10
0.05
0.00
normalised probability
0
1
2
3
4
5
Arctic September sea ice extent (10^6 km^2)

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.