Brief Communication: Temperature based probability 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, was used to reduce the internal variability and produce a probability density function of an ice-free state. It is found, in agreement with other studies using different methodologies indicating that the conclusion that the continuing loss of Arctic sea ice can be halted if the Paris Agreement temperature goal of 1.5C is achieved, is robust against methodology and climate model.

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°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 which are susceptible to sea-level rise, ground-water salinification and loss of coral reefs. There may be other global systems within the climate system which show substantially increased risk of change between 1.5°C and 2.0°C, and here we investigate if Arctic sea ice cover is one such.

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, and regional, 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 up-take 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 increase 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). 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 then 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. This is 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 °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. Here we determine, within an ensemble of simulations of the CMIP5 model HadGEM2-ES, the probability of a summer ice-free Arctic rise at 1.5 and 2.0C above pre-industrial..

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 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 which 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. A time series of the amount by which the transient scenario exceeded the target stabilisation temperature, 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}). The RCP scenarios start from the year 2005 and continue to 2100. The RCP2.6 scenario 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°C and +2.5°C in RCP4.5 (years 2040 and 2060 respectively). New simulations are started from these points. For CMIP5 a historical + scenario initial condition ensemble of 4 HadGEM2-ES members was completed. The SRM time series is calculated from the mean of these simulations.

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 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.
- Ensemble-2 : starts at 2°C on RCP4.5 and levels out to 1.3°C above pre-industrial.
- Ensemble-3 : starts at 2.5°C on RCP4.5 and levels out to 1.7°C above pre-industrial..

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 (Figure 2) as indicated by the reversibility and temperature sensitivity of Arctic sea ice change (Ridley et al., 2012). The spatial pattern of sea ice extent is near identical in ensemble-1 and ensemble-2 while ensemble-3 has members with discontinuous ice cover (Figure 3). The sea ice in ensemble-3 has some members with a patch of ice in the Beaufort Gyre and all members with ice extending along the North Greenland and Canadian Archipelago coasts. That ensemble-3 has a different spatial pattern of ice, 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 is at a concentration close to 15%.

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 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 4. A probability distribution function (PDF) is derived for sea ice extent at 1.5 and 2.0°C above pre-industrial. The probability of a single year with an ice extent less than one million square kilometres at +1.5°C is 0.2% and that at +2.0 °C is 43%.

4 Conclusions

In The difference in choosing a target temperature for global warming of 1.5C and 2.0C has a significant increase in risk that the Arctic will become seasonally ice-free (less than 10^6 km^2 in September). The quantitative result described here is similar to that found by Screen and Williamson (2017) of 0.001% and 39% using the CMIP5 transient simulations and a log-linear regression to derive a PDF. The use of the transient simulations is a reasonable approach since the Arctic sea ice in CMIP5 models is effectively in equilibrium with the instantaneous global temperature (Armour et al., 2011, Ridley et al., 2012). A different method was employed by Sandersen et al. (2017) who used a model emulator do devise emission scenarios to obtain stable temperatures of 1.5 and 2°C and then assessed a 10 member ensemble for each. They found the likelihood of an 'ice-free' Arctic of 2.5% at 1.5°C and 33% at 2.0°C.

The approach described here is different than those described above in that CO_2 is allowed to continue to increase but 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. It is found that the probability of an ice-free Arctic at 1.5°C is 0.2% and 43% at 2°C. The three methodologies provide similar results; that it is highly unlikely for an ice-free Arctic at 1.5C and an approximately 33-43% chance at 2C. The agreement across multiple methodologies and climate models suggests that collectively the evidence is robust that meeting the lower Paris Agreement temperature goal of 1.5C would likely prevent the eventual loss of Arctic sea ice.

5 Code availability

Due to intellectual property right restrictions, we cannot provide either the source code or documentation papers for the UM or JULES.

The Met Office Unified Model is available for use under licence. A number of research organisations and national meteorological services use the UM in collaboration with the Met Office to undertake basic atmospheric process research, produce forecasts, develop the UM code and build and evaluate Earth system models. For further information on how to apply for a licence see http://www.metoffice.gov.uk/research/modelling-systems/unified-model. JULES is available under licence free of charge. For further information on how to gain permission to use JULES for research purposes see https://jules.jchmr.org/software-and-documentation.

6 Data availability

Due to the size of the model data sets needed for the analysis, they require large storage space of order 1 TB. They can be shared via the STFC-CEDA platform by contacting the authors.

7 Competing interests

The authors declare that they have no conflict of interest.

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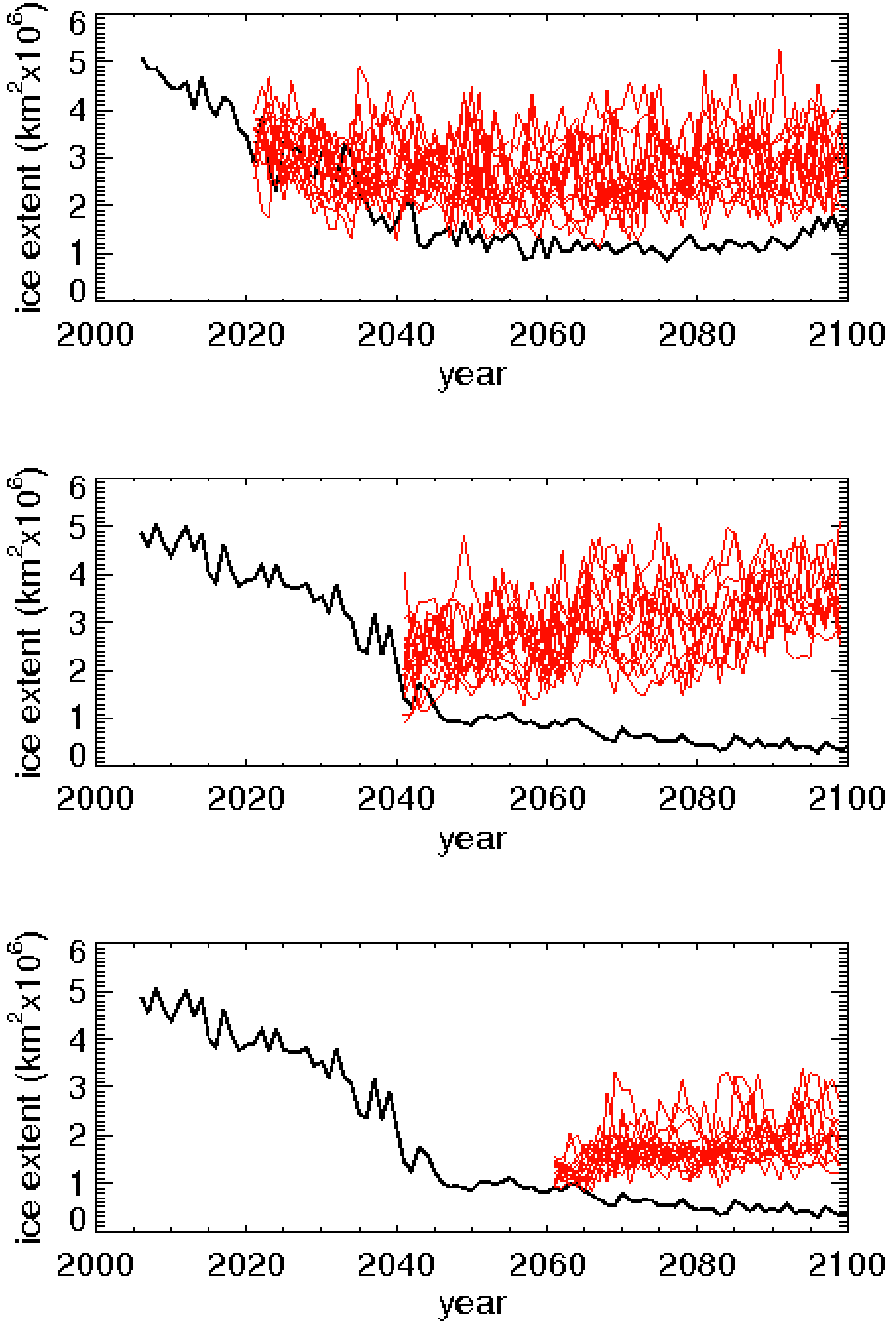
ice extent (km^{2}x10^6)
year
ice extent (km^{2}x10^6)
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ice extent (km^{2}x10^6)
year

Figure 1. The Arctic September mean sea ice extent starting at +1.5°C above preindustrial in RCP2.6 (top), +2°C in RCP4.5 (middle) and +2.5°C in RCP4.5 (bottom). In all cases the mean of the four-member scenario (RCP2.6 or RCP4.5) is shown in black and the individual simulations of the 16 member ensemble in red.

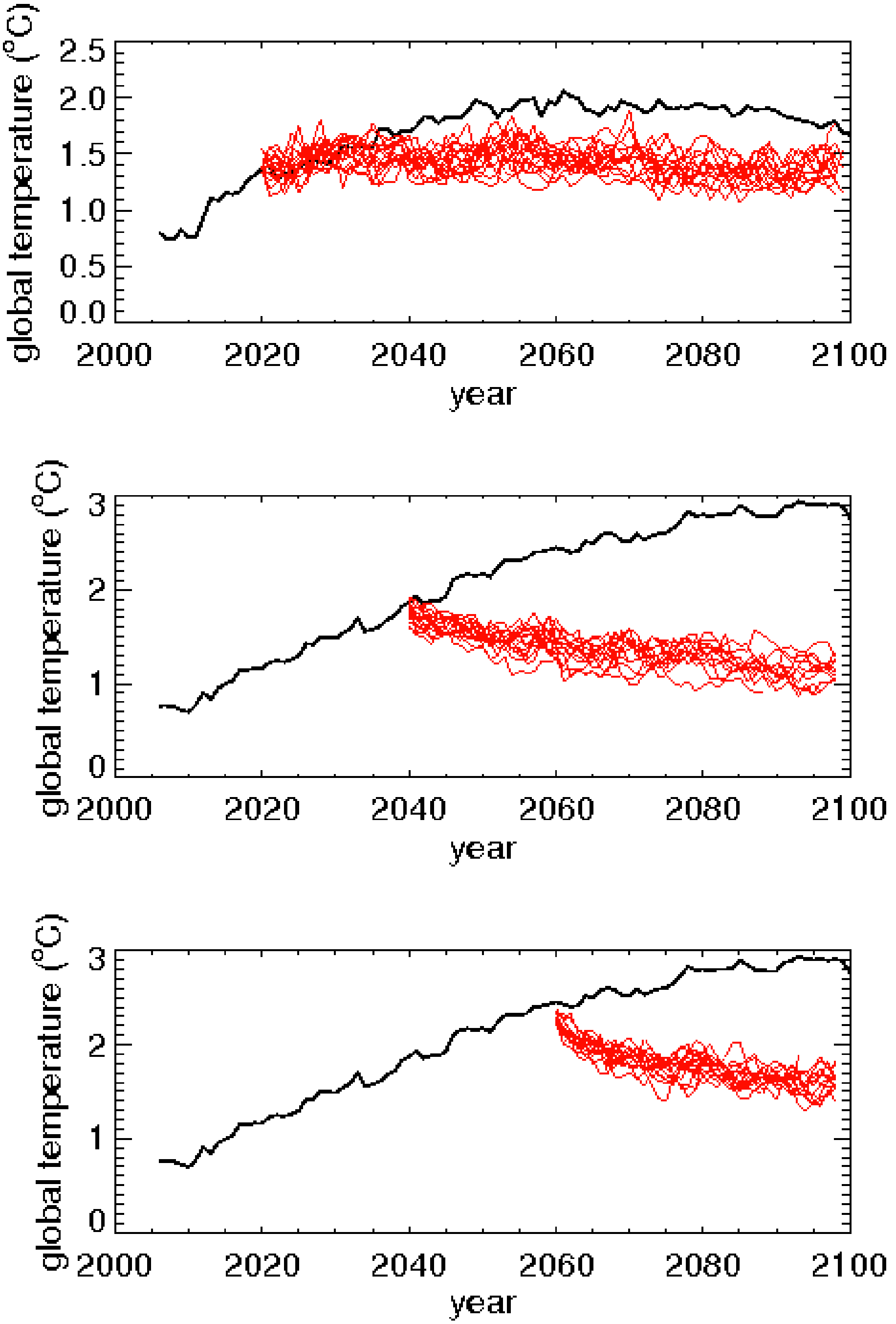
global temperature (°C)
2.5
2.0
1.5
1.0
0.5
0.0
2000
2020
2040
2060
2080
2100
year
global temperature (°C)
3
2
1
0
2000
2020
2040
2060
2080
2100
year
global temperature (°C)
3
2
1
0
2000
2020
2040
2060
2080
2100
year

Figure 2. The global mean 1.5m temperature starting at +1.5°C above preindustrial in RCP2.6 (top), +2°C in RCP4.5 (middle) and +2.5°C in RCP4.5 (bottom). In all cases the mean of the four member scenario is shown in black and the individual simulations of the 16 member ensemble in red.

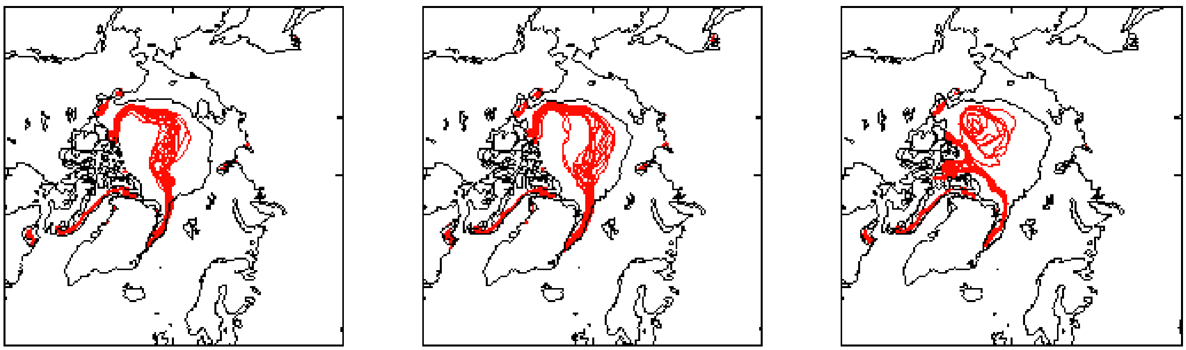

Figure 3. The spatial pattern of the Arctic sea ice extent (15% ice concentration), as a mean of years 2080-2099, starting at +1.5°C above preindustrial in RCP2.6 (left), +2°C in RCP4.5 (centre) and +2.5°C in RCP4.5 (right). In all cases the mean (years 2006-2025) of the four RCP2.6 (left) and RCP4.5 (centre and right) ensemble members is shown in black and the individual simulations of the 16 member ensemble in red.

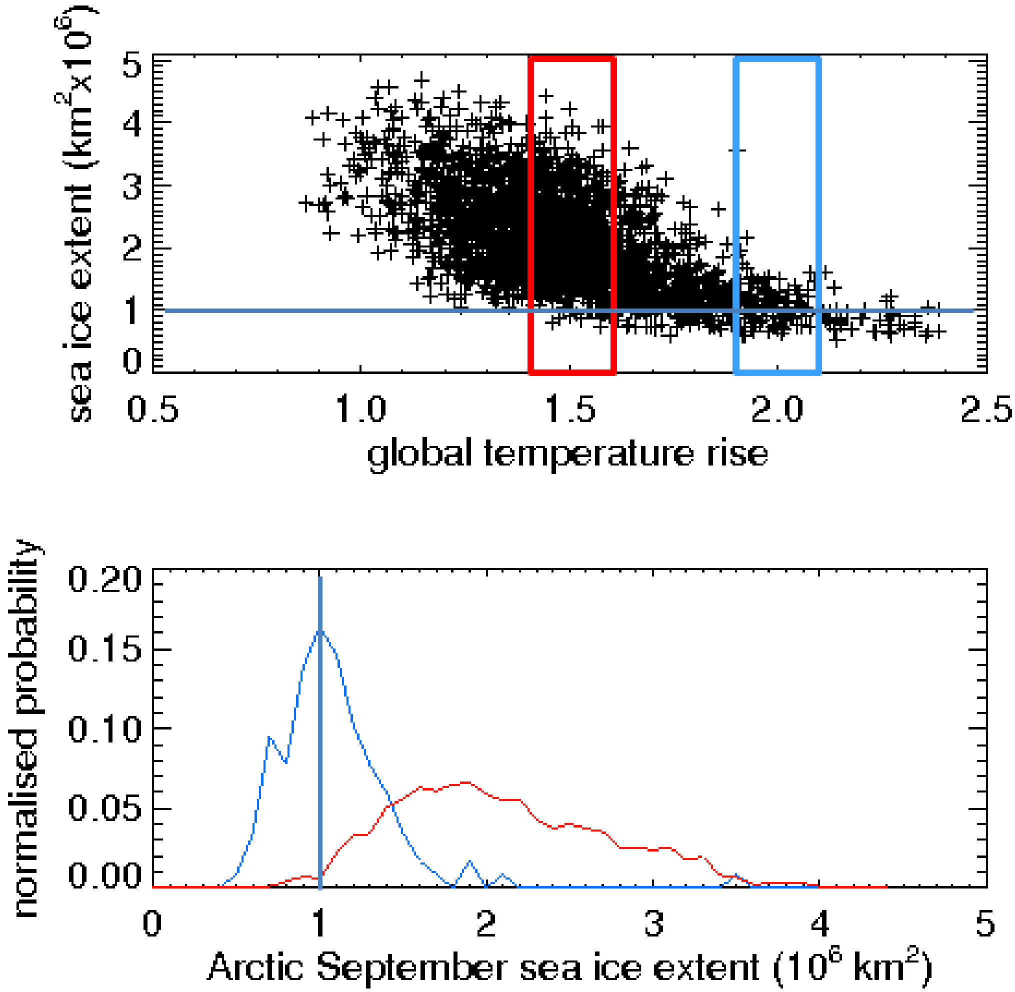

Figure 4. Forty Eight ensemble members are combined to derive a September ice extent vs global temperature scatterplot (top). The probability distribution functions at global temperature rise of 1.5±0.1°C (red) and 2.0±0.1°C (blue) are shown bottom. The solid blue line depicts the one million square kilometre area of ice defining an 'ice-free' Arctic