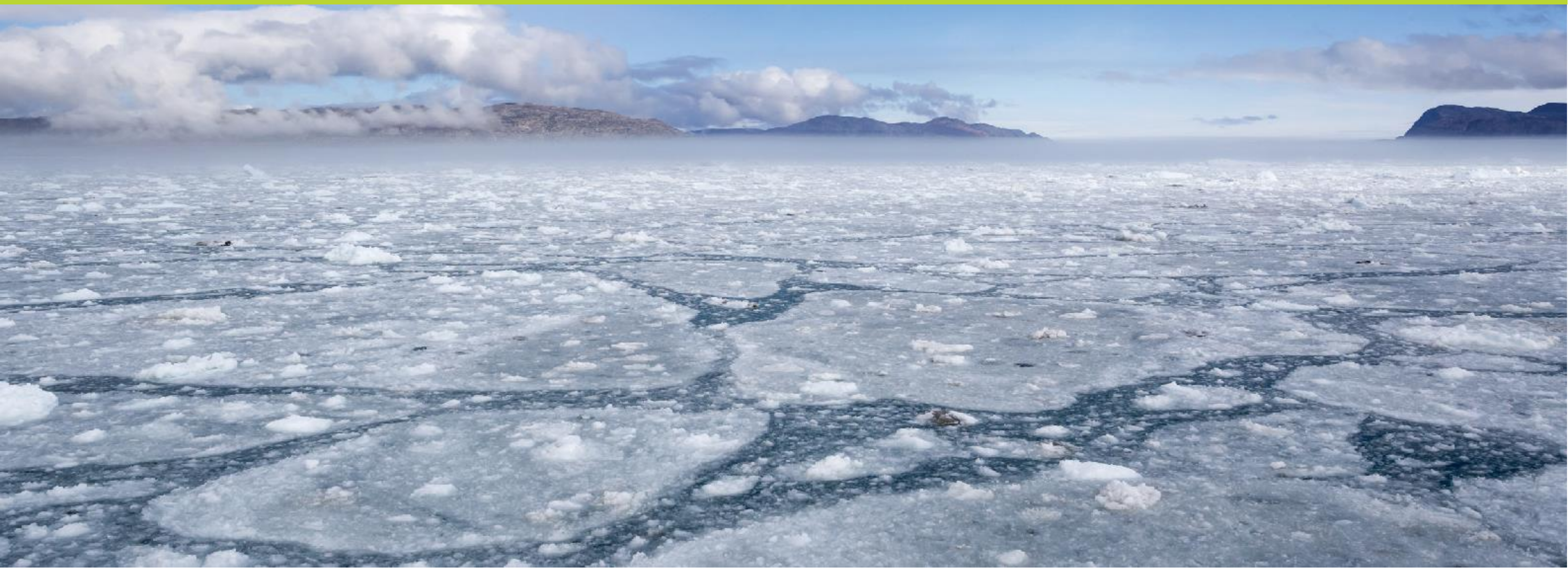
Risk management of climate thresholds and irreversible change: **A Seasonally Ice-free Arctic**



What is the nature of the threshold?

Arctic sea ice fluctuates on a yearly basis with a minimum coverage in September. The past few decades have seen a considerable reduction in Arctic ice extent and thickness throughout the year. September sea ice extent has been declining at an average rate of over 12% per decade since satellite records began (Fig. 1)[1] and is one of the most rapidly changing components of the global climate system.

If the Arctic Ocean becomes seasonally ice-free*, this will happen first in September when Arctic sea ice cover reaches its seasonal minimum. The eventual loss of summer sea ice is part of the gradual long-term decline in Arctic ice cover. This threshold is therefore not a tipping point, but more of a noteworthy milestone in the story of Arctic sea ice demise.

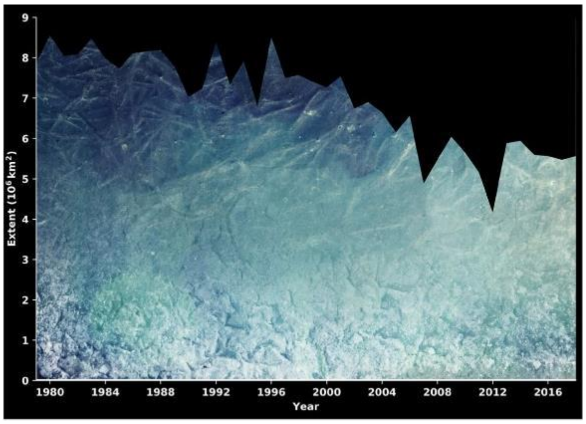


Figure 1. Change in 1979-2018 September Arctic sea ice extent.

What impacts might be expected if a threshold were crossed?

As a seasonally ice-free Arctic is not a tipping point, many impacts will likely be felt irrespective of the precise date when the Arctic is declared seasonally ice-free. The loss of Arctic summer sea ice could be an important ecological threshold because many animal species rely on the presence of sea ice, ranging from algae[2] to large mammals such as the polar bear[3]. The decline in Arctic sea ice cover will also have socioeconomic impacts and will likely lead to increased human activity in the Arctic owing to easier access for shipping, and longer ice-free seasons in all areas of the Arctic[4].

If a threshold is crossed, are the changes irreversible?

Whilst theoretically possible, there is no evidence to suggest that Arctic sea ice decline is irreversible. Climate models suggest that the Arctic becomes ice-free during summer as temperatures increase, and that ice cover returns to its previous state when the temperature is reduced again[5]. Other studies have shown that the decline in Arctic sea ice extent is related to atmospheric CO_2 concentration[6, 7] and suggest that if global temperatures were to level out sea ice extent would stabilise[5, 8].

*The IPCC AR5 report[9] defines 'nearly ice free' conditions in summer as having a sea ice extent of less than 1 million square km in September for at least 5 consecutive years.

How likely is such a threshold to be crossed?

In the CMIP5 models used for the IPCC AR5 report[9], the rate of decline, and whether the Arctic becomes ice-free in summer at some point this century, depend on the scenario of future greenhouse gas emissions. Under a low emissions scenario (consistent with keeping global temperature rise to below 2°C) sea ice is projected to remain even in late summer, whereas higher emissions scenarios result in the Arctic being nearly ice-free in late summer during the 21st Century (Fig. 2). Climate models project that Arctic sea ice will continue to decline over the 21st Century in response to increasing global temperatures. Within this broad picture, there are a wide range of projections from individual climate models but the AR5 report concludes that an ice-free summer is projected before mid-century, under a high emissions scenario.

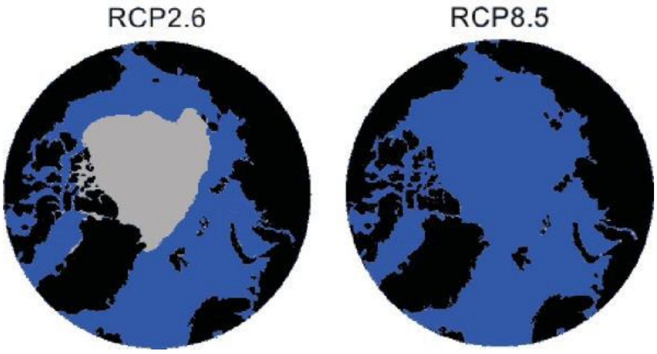


Figure 2. 2081-2100 September Arctic sea ice extent (grey) projected by IPCC AR5 models. Left: low emissions scenario RCP 2.6 (roughly 1.6°C global temperature rise). Right: high emissions scenario RCP 8.5 (roughly 4.3°C global temperature rise).

Several studies[8, 10] have focussed on the impact of 1.5 and 2.0°C warming scenarios on Arctic sea ice extent, finding that the continuing loss of Arctic sea ice can be halted if the Paris Agreement temperature goal is achieved. For a 1.5°C scenario a seasonally ice-free Arctic was found to be highly unlikely (< 2.5% chance), and for a 2.0°C scenario the chance is around 33-43% (Fig. 3).

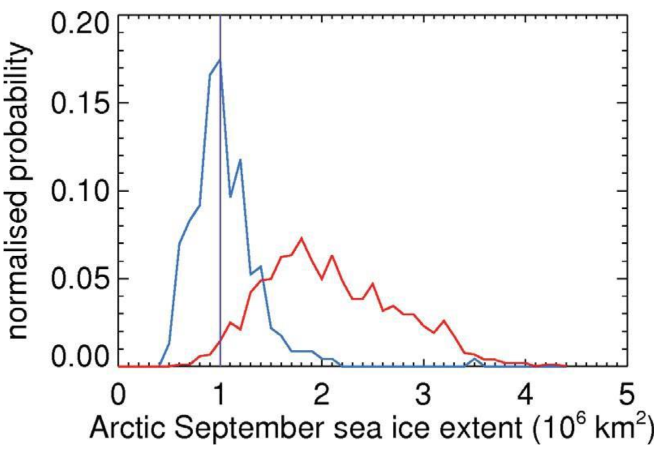


Figure 3. Probability functions of Arctic sea ice extent for global temperature rise of 1.5°C (red) and 2.0°C (blue) above preindustrial levels. The threshold for an ice-free Arctic is shown by the vertical line.[8]

However, most of the CMIP5 models used for the AR5 report do not capture the relationship between temperature and ice melt that has been observed and underestimate the ice loss for a given amount of global warming[11]. For CMIP6 (the next generation of models, which will feed into the IPCC AR6 report), updates have been made to some of the physical mechanisms that influence sea ice. However, more work is needed to understand the implications of these changes, because early results from CMIP6 models suggest that an ice-free Arctic may not be as scenario-dependant as was predicted by the CMIP5 models.

What are the prospects for early warning and what long-term observing systems need to be maintained?

Observations of sea ice concentration obtained from passive-microwave satellite instruments have been providing large-scale coverage of sea ice cover (for both poles) since 1979. This dataset has already provided the scientific community with considerable understanding about the long-term decline and inter-annual variability of Arctic sea ice, and so it is very important for this observing system to be maintained.

Monitoring of Arctic sea ice thickness is also important because ice volume provides a more complete picture of the long-term decline through changes in sea ice mass-balance. Thickness also provides predictability for sea ice on much longer time scales than does extent. Historically, observations of ice thickness have been patchy, but with the launch of ESA's CryoSat-2 radar altimeter we now have data available with good coverage which will allow a more complete picture of ice thickness, and volume, to be built. It is important therefore that this functionality is maintained.

What future research is planned at the Met Office Hadley Centre?

Research has shown that the large natural variability of Arctic sea ice extent means that the date when summers will become ice-free can only be projected with an uncertainty of about 20 years. Future Met Office Hadley Centre work will focus on analysing the output from the CMIP6 models, which will be assessed alongside a range of other lines of evidence to feed into the IPCC AR6 report.

References – Met Office papers in **bold**

[1]IPCC (2019) SROCC; [2]Søreide et al., (2010) Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic; [3]Amstrup et al., (2010) Greenhouse gas mitigation can reduce sea-ice loss and increase polar bear persistence; [4]Meier et al., (2014) Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity; **[5]Ridley et al., (2012) How reversible is sea ice loss?**; [6]Notz and Stroeve, (2016) Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission; [7]Notz and Marotzke, (2012) Observations reveal external driver for Arctic sea-ice retreat; **[8]Ridley and Blockley, (2018) The significance for the IPCC targets of 1.5°C and 2°C temperature rise for an ice-free Arctic**; [9]IPCC (2014) AR5 report; [10]IPCC (2018) SR1.5; [11]Rosenblum and Eisenman, (2017) Sea ice trends in climate models only accurate in runs with biased global warming.