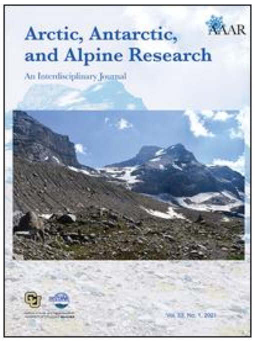

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When will the Arctic Ocean become ice-free?

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ARCTIC ANSWERS

When will the Arctic Ocean become ice-free?

THE ISSUE. There is increasing interest in knowing when seasonally ice-free conditions will emerge in the Arctic. Although the region is heading toward *ice-free conditions* (Figure 1) during summer, estimates differ greatly on when this will occur[1] due to various sources of uncertainty.

WHY IT MATTERS. Many stakeholders require accurate forecasts of future sea ice conditions to prepare for changing geopolitical relations, emerging opportunities for shipping and resource development, disruptions to Arctic ecosystems, and other factors. For example, if decision-makers know when ships will be able to dependably traverse the Arctic Ocean, then plans to design new shipping routes and develop ports in the region can be made more confidently.

STATE OF KNOWLEDGE. Scientists are grappling with several questions to improve predictions:

(1) *What factors contribute to the uncertainty in predictions for a future ice-free Arctic?*
(2) *How accurate are climate model simulations of past sea ice conditions?*
(3) *How precisely can models predict when the Arctic Ocean will be become seasonally ice-free?*

Recent research has revealed an irreducible uncertainty of about two decades in scientists' ability to forecast the emergence of a seasonally ice-free Arctic[1]. Why? Predicting changes in climate is limited by three main sources of uncertainty[2]. First, *forcing uncertainty*: scientists cannot know precisely the future course of drivers that influence the climate system, such as the concentration of atmospheric greenhouse gases, land cover changes, or a powerful volcanic eruption. Second, *model differences*: different climate models that are run with identical assumptions about future influencing drivers still produce varying predictions, because of differences in the representation of climatic processes such as clouds or ocean circulation. Third, *internal variability*: even a hypothetically perfect climate model run with exact knowledge of future drivers would still produce varying outcomes, due to inherent random fluctuations in the climate system. These variations cannot be predicted reliably on long time scales, but they are generally weaker and shorter-lived than the long-term trends controlled by climate drivers.

Scientists assess and quantify the first two sources of uncertainty by considering projections based on a number of plausible future scenarios (especially greenhouse gas emissions) and from multiple climate models driven by the same scenario. This strategy refines estimates of when a warming climate will cause the Arctic Ocean to become ice-free during summer. However, knowing the precise timing is always thwarted by random fluctuations, which are superimposed on human-driven changes, such as the downward trend of sea ice coverage during recent decades caused by rising greenhouse gases.

The presence of internal variability has complicated efforts to evaluate the accuracy of climate models. Simulations have generally produced a slower decline in Arctic sea ice coverage than has been observed[4], but these results are affected by both uncertainty from model differences and from internal variability. Models suggest that the observed decline in September sea ice during the past few decades is caused by rising greenhouse gas concentrations enhanced by the influence of internal climate variability[5]. The downward trend and eventual loss of summer

Figure 1. Scientist define the Arctic as *ice-free* even if a small amount of remnant sea ice remains – less than 1 million square kilometers. This is analogous to considering a lake to be ice-free, even when some scattered ice floes still exist along the shore. For perspective, the record-low Arctic sea ice cover was 3.4 million square kilometers in 2012.[4] Photograph by Patrick Kelley, U.S. Coast Guard – "Blue sky begins to break through the clouds over Arctic Ocean ice Sept. 9, 2009."

sea ice in a warming climate could be strongly amplified or dampened by the presence of internal variability in the atmosphere and ocean. Moreover, internal variability of ice coverage is expected to increase as ice thickness and extent decrease, which hinders efforts to pinpoint when ice-free summers will emerge.

WHERE THE RESEARCH IS HEADED.

Acknowledging the limits of predictability imposed by internal variability is enabling more realistic assessments of future Arctic sea ice conditions. At the same time, climate models containing increasingly sophisticated representations of sea ice, atmosphere, and ocean processes are improving the accuracy of sea ice projections. For example, the representation of sea ice progressively includes realistic features such as melt puddles, deposition of soot, and fine-scale ice thickness variations. The emergence of more reliable sea ice simulations is coinciding with efforts to refine estimates of future societal development and associated greenhouse gas emissions. In addition, ongoing research is improving our understanding of how sea ice interacts with other components of the Arctic climate system, such as radiation and circulation patterns, to quantify complex relationships that affect the rate of ice loss.

There is also promising new research to assess the relative importance of human-induced climate influences and internal variability on the future sea ice cover. Expanding computational power has recently allowed scientists to quantify internal variability by generating "ensembles" of dozens or more simulations from a single climate model that are affected by the same climate drivers but possess unique internal variability[5]. Similar large ensembles completed with various climate models[6] are providing a better understanding of how inter-model differences influence simulations of future sea ice conditions. For example, Figure 2 shows how the projected emergence of a seasonally ice-free Arctic Ocean differs among five state-of-the-art climate models (denoted by different colors), as well as among individual ensemble members from the same model (the spread in timing within a single color bar). The most likely timing based on this analysis covers a wide range that spans from the 2020s to the 2060s. Overall, these advances in the science indicate that predictions of when the Arctic may experience ice-free summers will probably be limited to an accuracy of a few decades.

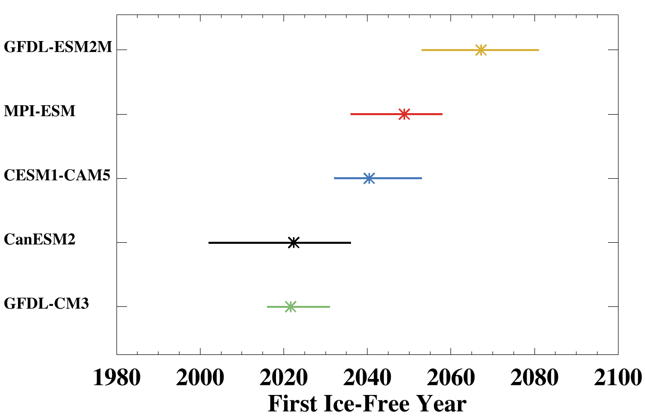

Figure 2. Timing of a seasonally ice-free Arctic simulated by five climate models[3] and based on high future carbon emissions. Colored lines represent varying estimates across models, due to different representations of climatic processes (the second source of uncertainty described in the text). Each model's average estimate is denoted by an asterisk, while the range within each model is indicated by the width of the line and is due to internal variability in the climate system that cannot be predicted (the third source of uncertainty). For example, 100 runs of the MPI-ESM model (red bar) predict a seasonally ice-free Arctic as early as 2036 and as late as 2058 (mean date 2049) as a result of tiny differences in simulation starting conditions. Note the large spread of timing based on the average estimates among models, ranging from as early as 2022 to as late as 2067.

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Supplementary material

Supplemental material for this article can be accessed on the publisher's website

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