Arctic Answers
Science briefs from the Study of Environmental Arctic Change
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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** during summer, projections 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, etc. 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 the following questions as they strive to improve predictions:

1. What factors contribute to the spread in predictions for a future ice-free Arctic?
2. How accurate are climate model simulations of past sea ice conditions, and can such evaluations be used to inform predictions of future sea ice conditions?
3. What level of precision is possible when estimating when the Arctic Ocean will be become seasonally ice-free?

> * Scientists 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 shore. For perspective, the record-low Arctic sea ice cover was 3.4 million square kilometers in 2012[3].

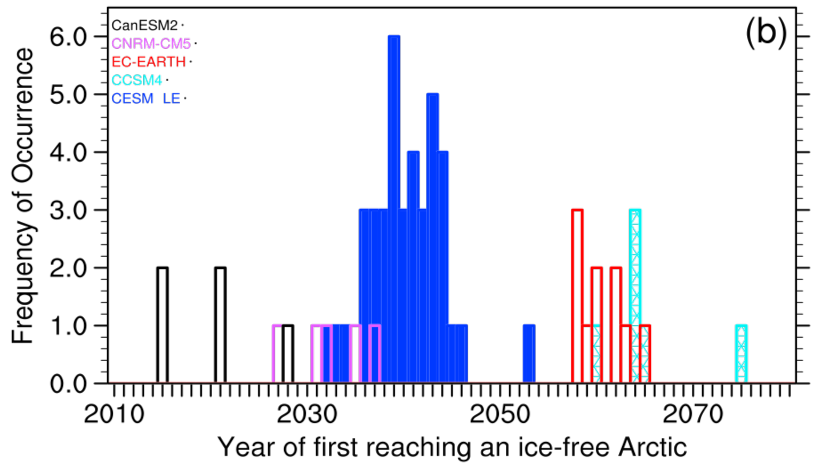
Scientists' ability to predict changes in any climate component is limited by three main sources of uncertainty[2]. First, *"forcing uncertainty"*: scientists cannot know precisely the future course of climate "forcings", which are the factors that influence the climate system, such as the concentration of greenhouse gases in the atmosphere. Second, *"process uncertainty"*: different climate models that run with identical scenarios of future climate forcings still produce varying predictions, due partly to differences in their representation of physical processes. Third, *"internal variability"*: even a hypothetically perfect climate model driven by complete knowledge of future forcings would still be limited by internal variability, which represents random fluctuations intrinsic to 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 driven by climate forcings.

Scientists assess and quantify the first two sources of uncertainty by considering projections based on a number of plausible future climate forcing scenarios (especially greenhouse gas emissions) and from multiple climate models driven by the same climate forcing 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 limited by internal variability, which is superimposed on the processes that are well understood, such as the downward trend of sea ice coverage during recent decades. Internal variability causes an irreducible uncertainty of about two decades in scientists' ability to forecast the emergence of a seasonally ice-free Arctic[1].

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 process uncertainty and 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 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 SCIENCE IS HEADED. Recent recognition of the role played by internal variability enables more efficient strategies toward anticipating future Arctic sea ice conditions. At the same time, climate models containing increasingly sophisticated representations of sea ice, atmosphere, and ocean processes improve the accuracy of sea ice projections. For example, the representation of sea ice progressively includes realistic features such as melt ponds, aerosol deposition, and fine-scale ice thickness variations. The development of more reliable simulations on regional- and pan-Arctic scales is coinciding with efforts to refine future climate forcings that account for a range of future societal development pathways and their corresponding greenhouse gas emissions. In addition, observational evidence of past Arctic climates provides insight on the sensitivity of the ice cover, such as the occurrence of ice-free beaches along the currently ice-bound north Greenland coast 8000 years ago, when solar energy during summer was modestly stronger than present[6].

There is also promising new research to assess the relative importance of anthropogenic climate forcing and internal variability on the future sea ice cover. Expanding computational power has recently allowed scientists to quantify internal variability by generating "ensembles" of 40 or more simulations possessing unique internal variability from a single climate model driven by the same climate forcings[7], while also developing a better understanding of how inter-model differences influence simulations of future sea ice conditions. For example, the figure at right 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). The probable outcomes in this analysis cover a wide range in the collective ice-free timing, but they produce an overall clustering between the 2030s-2060s. Overall, these advances in the science indicate that predictions of when the Arctic may experience ice-free summers will be limited to an accuracy of a few decades.



Timing of a seasonally ice-free Arctic simulated using five climate models and assuming high future carbon emissions. Bars represent how many individual simulations (y-axis) reach ice-free conditions in a particular year (x-axis). The range of estimates across models—distinguished by different colors—is largely due to different representations of physical processes (the second source of uncertainty described in the text). The range of estimates within each model is due to internal variability in the climate system that cannot be predicted (the third source of uncertainty). For example, 40 runs of the CESM LE model (dark blue bars) predict a seasonally ice-free Arctic as early as 2032 and as late as 2053 as a result of tiny differences in initial conditions specified at the start of each simulation. (Figure from Jahn et al. 2016; Data from NOAA/ NCEP/ESRL)

Key References

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