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Introduction

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Arctic sea ice reduction: the evidence, models and impacts

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Recent years have seen dramatic changes in the state of the Arctic sea ice cover. The last 8 years (2007–2014) have seen the eight lowest sea ice summer area extents in the continuous satellite record, which extends back to 1979. The decrease in sea ice area has also been accompanied by a decrease in sea ice volume, as measured by satellite altimetry and field observations.

Arctic sea ice reduction has become a totemic indicator of climate change, provoking discussion in many circles of life: lay people, scientists, industrialists, politicians, journalists and others. The Arctic is home to iconic species such as polar bears and the Beluga whale, and the ice cover is an essential fishing platform for Inuit populations. In addition to the influence of Arctic sea ice loss on the global climate, there are impacts on indigenous peoples, local ecology and socio-economics including trade and oil exploration. Reduction in the sea ice cover is already opening up trade routes and the potential for oil exploration has generated political statements and actions including, for example, the placement of the Russian flag at the North Pole and Denmark's declaration of sea bed rights up to the North Pole.

The sea ice cover comprises blocks of frozen seawater known as floes, typically of 10–5000 m wide and 0.5–5 m thick, that, depending upon the time of year and location, may float separately or be welded together to form a continuous, but heterogeneous, cover permeated by cracks and ridges of thicker ice. The evolution of sea ice is mediated by mechanical and thermodynamic processes, such as pressure ridging resulting from floes being pressed together and internal phase change due to internal dissolution at brine pocket interfaces. The sea ice cover forms a mechanical barrier to transports of heat, moisture and momentum between the atmosphere and ocean, its high albedo (reflectivity) relative to the ocean water causes it to significantly affect the surface radiative budget, and the formation and melt of sea ice, through its impact on buoyancy forcing of the ocean, is implicated in deep water formation and the thermohaline circulation.

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In addition to being an important component of the climate system, sea ice is a sensitive indicator of climate change, as even small imbalances in the atmosphere and ocean heat fluxes can dramatically alter ice extent. The study of processes affecting sea ice and its evolution form a scientifically rich subject.

The Royal Society meeting on sea ice brought together experts in four broad areas: the evidence for Arctic sea ice reduction; the climate system understanding of sea ice; the processes controlling sea ice; and the impacts of Arctic sea ice loss. Scholarly discussions of these issues are found in the associated *Philosophical Transactions of the Royal Society A* papers split across two parts.

In this issue, Serreze & Stroeve [1] discuss the strong downward trend of Arctic sea ice area extent, accompanied by pronounced interannual variability, and discuss some of the feedback processes affecting this trend. They argue that the level of variability associated with the chaotic nature of the atmosphere places a fundamental constraint on the degree to which sea ice area extent may be forecast. Kwok & Cunningham [2] present evidence from the CryoSat2 altimeter on sea ice thickness and volume, finding that the estimates are consistent with other measurements from moorings, submarine drafts, electromagnetic sensors and the ICESat laser altimeter. Analysis of the evidence shows variability in the mass budget, associated both with the radiation balance and with sea ice drift and convergence. Perovich & Richter-Menge [3], noting the dramatic loss of sea ice area extent, examine field evidence from 41 sites on top and bottom melting of sea ice over the last six decades. While they find large spatial and temporal variations, they also concluded that increases in bottom melting have contributed to substantial sea ice thinning in the Beaufort Sea.

Turning to climate simulations, Holland & Landrum [4] used ensemble simulations from the US Community Earth System Model to examine the relationship between enhanced surface shortwave solar radiation absorption in the Arctic Ocean and changing ice conditions. They found that increases in the duration of the snow-free season and enhanced surface melt ponding have a considerable impact on shortwave heating in the early twenty-first century, with projected losses of sea ice area in the latter twenty-first century dominating shortwave heating as the exposed ocean fraction area increases. Hewitt *et al.* [5], working with the UK Met Office climate model, examined the detailed energy budget in their simulations. This analysis indicated the significant impact of early summer conditions, such as cloud cover and surface melt ponding on sea ice, on both the seasonal cycle and the trend in modelled sea ice decline.

While climate simulations are a valuable tool for understanding the spatial and temporal pattern of past changes in sea ice, and most agree they are the best tool for predicting future changes, they do contain, by necessity, a large number of simplifications, some of which can be important to their simulations. Worster & Rees Jones [6] note the new dominance of younger first-year sea ice in the Arctic Ocean and discuss how salt loss from such ice is improperly accounted for in the existing generation of climate models. A new model of salt release is described, promising to enhance simulations of buoyancy forcing of the Arctic Ocean.

Providing perspective on Arctic sea ice loss, Turner *et al.* [7] discuss sea ice extent in the Southern Ocean, which, in contrast to that in the Arctic Ocean, has increased since the late 1970s. The overall increase, however, is a sum of contrasting regional trends, with a notable decrease in the Amundsen–Bellingshausen Sea and increase in the Ross Sea, the latter being significantly correlated with the Amundsen Sea Low. Analysis of some climate model simulations suggests that the increase in Antarctic sea ice extent may be within the bounds of internal variability.

The loss of Arctic sea ice has many local impacts and impacts on the wider climate system. Francis & Skific [8] discuss a possible connection between the changing Arctic sea ice cover and mid-latitude weather patterns. They present evidence suggesting that Arctic warming, by reducing the poleward temperature gradient, is causing the Northern Hemisphere atmospheric circulation to become more meridional, leading to highly amplified jet stream patterns associated with extreme weather events. They suggest that continued loss of Arctic sea ice may lead to an increase in such extreme events.

The topic of Arctic sea ice loss is hugely complex, and integrates a wide variety of disciplines in elucidation of the observed changes themselves, the mechanisms responsible, the representation of these mechanisms in models, and the local and regional implications for both the Arctic and rest of the world. While containing fundamental and applied scientific interest, the topic has also long since emerged as central to the decision making of local communities, industry and commerce, and national and international interests in future impacts and opportunities. The Royal Society meeting associated with this discussion meeting issue was widely reported in the national and international press, and was tweeted extensively. During this meeting, there were 2800 tweets, 348 000 people viewed these tweets and 1.4 million tweets were viewed. The poet William Blake suggested, in his 'Auguries of Innocence', that it was possible to see a world in a grain of sand, and I would contest that the same may also be said of sea ice.

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