Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity

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Abstract

Sea ice in the Arctic is one of the most rapidly changing components of the global climate system. Over the past few decades, summer areal extent has declined over 30%, and all months show statistically significant declining trends. New satellite missions and techniques have greatly expanded information on sea ice thickness, but many uncertainties remain in the satellite data and long-term records are sparse. However, thickness observations and other satellite-derived data indicate a 40% decline in thickness, due in large part to the loss of thicker, older ice cover. The changes in sea ice are happening faster than models have projected. With continued increasing temperatures, summer ice-free conditions are likely sometime in the coming decades, though there are substantial uncertainties in the exact timing and high interannual variability will remain as sea ice decreases. The changes in Arctic sea ice are already having an impact on flora and fauna in the Arctic. Some species will face increasing challenges in the future, while new habitat will open up for other species. The changes are also affecting peoples living and working in the Arctic. Native communities are facing challenges to their traditional ways of life, while new opportunities open for shipping, fishing, and natural resource extraction. Significant progress has been made in recent years in understanding of Arctic sea ice and its role in climate, the ecosystem, and human activities. However, significant challenges remain in furthering the knowledge of the processes, impacts, and future evolution of the system.

1. Introduction

The Arctic is a region in transition to a warmer climate and one of the most visible signs of that change is in the declining sea ice cover. Ice extent has decreased in all months over the past 30+ years, particularly during summer, reaching levels that likely have not been seen in several thousand years. The ice cover is also thinning and becoming more dominated by thinner, younger ice types. The decline in extent is faster than most models have forecast, leading to possible near ice-free summer conditions sometime in the coming decades. Feedback mechanisms are accelerating the loss of ice although there are some negative feedbacks that may slow the loss. The declining sea ice is already impacting Arctic ecosystems and humans living and working in the Arctic. It is expected that these impacts will grow and broaden as the loss of sea ice continues.

Sea ice is defined as ice that grows and melts within ocean waters. Ice formation is primarily thermodynamically driven, but ice may also thicken via dynamic redistribution of the ice cover from ice motion and deformation. Much of the ice cover drifts in response to wind and ocean current forcing, density gradients in the ocean surface, and the Coriolis effect. Divergent motion of the ice opens up linear cracks in the ice, called leads, within the ice pack. Convergent motion deforms ice into ridges that may be several meters thick. In many places near the coast, non-drifting landfast, or simply 'fast', ice grows anchored along the shoreline and/or shallow shelf waters. On lee sides of coasts, ice shelves, or fast ice, persistent winds can keep regions ice-free for long periods of time even in winter as winds continually push ice away from stationary features. These open water regions, called polynyas, typically recur regularly in certain locations; some polynyas may also form due to upwelling of warm ocean waters to the surface.

Sea ice represents the interface between the ocean and the atmosphere and thus substantially modifies heat, moisture, and momentum fluxes at the surface. In addition, it is a unique ecosystem that numerous species have adapted to over the millennia. Humans also interact with the sea ice environment in a variety of ways. Native communities in the Arctic have long relied on sea ice as a platform for hunting, fishing, and transportation. Sea ice is an impediment and/or threat to many commercial activities in and around the Arctic, including: shipping, fishing, tourism, and natural resource extraction.

Sea ice coverage varies considerably with season, reaching a maximum areal extent in late February or March and declining through the spring and summer to a seasonal minimum extent in September. At its maximum extent, sea ice coverage can reach well south of areas typically considered 'Arctic' to the northern coast of Japan in the Sea of Okhotsk and the southern portions of the Canadian Maritime Provinces. At its minimum extent, the sea ice cover largely retreats to within the boundaries of the Arctic Ocean proper.

In 2011, the Snow, Water, Ice, Permafrost in the Arctic (SWIPA) Assessment Report (AMAP, 2011), with contributions from over 200 scientists and experts, was released, including a comprehensive review of sea ice conditions and impacts (Meier et al., 2011). However, the Arctic is rapidly changing and recent observations and research are revealing new aspects of the sea ice cover.

Here we update the SWIPA report with summaries of research and data that has accumulated since the drafting of the report in 2009. This review and update follows a similar organization as the SWIPA report. Section 2 describes the observed physical changes and model simulations of the historical changes and projections for the future state of the sea ice cover (Meier and Haas, 2011), including feedbacks and thresholds in the sea ice system (Perovich and Makshtas, 2011). Section 3 presents results on the biological impacts of changes in sea ice in the Arctic (Kovacs and Michel, 2011). Section 4 elucidates the effects of sea ice change on human society (van Oort et al., 2011). Finally, we provide a brief summary, including discussion of potential impacts of sea ice change beyond the Arctic.

2. Changes in the physical state of sea ice

2.1 Changes in sea ice extent and concentration

The spatial coverage, time period, frequency, and quality of sea ice data varies over time depending on parameter and type of measurement. The most complete sea ice observations exist for sea ice extent (defined here as areal coverage with at least 15% ice coverage) based on a series of satellite-borne multichannel passive microwave radiometers beginning in late 1978. Careful intersensor calibration and quality control have enabled the production of consistent timeseries of basin-scale and regional extents. Several algorithms have been developed to retrieve sea-ice extent estimates and time series and several products can be obtained from different organizations (Table 1). There are some important differences in the products (as described by Andersen et al., 2007 and Meier, 2005), but there is good overall consistency in estimates of long-term trends and variability. The sea-ice extent/concentration imagery and total extent statistics quoted here are derived from passive microwave imagery using the NASA Team sea-ice concentration algorithm (Cavalieri et al., 1996; Cavalieri et al., 1999; Maslanik and Stroeve, 1999; Cavalieri and Parkinson, 2012), distributed by the National Snow and Ice Data Center's Sea Ice Index (http://nsidc.org/seaice_index/; Fetterer et al., 2011).

Total Arctic sea ice extent shows a declining trend through all months over the passive microwave satellite record since 1979, with the smallest trends in March and the largest trends in September (Figure 1, Table 2). The downward trends are larger in magnitude over the past decade, indicating an acceleration in ice loss due to feedback mechanisms, natural decadal variability, or a combination of the two.

The decline during summer has been particularly striking over the past decade. Of the 34 years in the passive microwave record, the 9 lowest September extents have occurred in the last 9 years of the record (2004-2013). While September has the largest declining trends, other summer and early autumn months also have significant trends of -6% decade^{-1} or steeper. All trends are statistically significant at the 99% confidence level. September concentration (fractional area coverage) has also been low over the past several years in much of the ice-covered areas, though some areas have positive concentration anomalies, mostly due to local convergent ice motion packing the ice more tightly) (Figure 2).

The extent decline is pan-Arctic with almost all regions of the Arctic showing statistically significant decreasing trends during months where ice cover in the given region can vary (i.e., not completely ice-covered or completely ice-free). The primary exception is in the Bering Sea during winter and spring (December – May) where trends are positive or not statistically significant at the 95% confidence level (Cavalieri and Parkinson, 2012; Meier and Haas, 2011).

Estimates of sea ice extent before the passive microwave record become increasingly sparse through the preceding decades. Such estimates that exist for the Arctic are primarily from operational ice charts produced by national ice analyses centers, particularly in Russia, Canada, and the United States. These charts were produced to support ships and other human activities in the Arctic and were based primarily on ship reports, aircraft reconnaissance and, starting in the 1960s, early satellite imagery. Some analyses date back to the late 1920s, but hemispheric did not start until the early 1950s. These analyses indicate reduced concentrations in some regions at some times of the year during the warm period of the