Arctic sea ice - When will the Arctic Ocean become ice-free and what will be the effects?

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It seems inevitable that the Arctic will lose its summer sea ice cover as air temperatures continue to rise in response to increased concentrations of atmospheric greenhouse gases. Over the last 33 years for which we have high quality records from satellite remote sensing, the September (end-of-summer) sea-ice extent has declined at a rate of 13% per decade. The five lowest September extents in the satellite record have all been in the past five years; average extent for this period represents a 35% reduction compared to conditions in the 1980s. Although there will likely be winter sea ice for centuries to come, the ice that forms in winter will be too thin to survive the summer melt season.

Emerging results from the latest generation of coupled global climate models indicate that essentially ice-free conditions (with some residual ice surviving in favored locations) could be realized as early as 2030. However, we may get to an essentially ice free Arctic Ocean, only to see temporary recovery. Modeling work argues for both decadal-scale periods of especially rapid ice loss in the future and periods of increasing ice extent. This implies that concern over a tipping point in ice thickness that, when crossed results in a rapid slide to an ice-free state, is likely unfounded.

Given that environmental impacts of ice loss will be realized well before one gets to a truly ice-free state, the year at which we first see a blue Arctic Ocean is not as important as when the bulk of the ice is gone. Some within-Arctic impacts of sea-ice loss are already here. This includes loss of species habitat, northward migration of marine species, and increased coastal erosion along the Beaufort Sea coasts and elsewhere due to increased wave action and thermal erosion of permafrost-rich coastal bluffs (Overeem et al. 2011). The observed greening of the Arctic coastal tundra, as determined from satellite measurements of photosynthetic activity, is at least in part a response to loss of the local chilling effect of coastal ice (Bhatt et al. 2010).

Simulations with the first generation of global climate models projected that as the climate system responds to an increased level of carbon dioxide, there would be an outsized warming of the Arctic compared to the globe as a whole (Manabe and Stouffer 1980), a phenomenon termed Arctic amplification. While a number of processes can lead to Arctic amplification, summer sea-ice loss is a major driver: as the ice retreats in summer, there are ever larger areas of open water that readily absorb solar radiation and add heat to the ocean mixed layer. When the sun sets in autumn, this heat is released upwards, warming the overlying atmosphere. Arctic amplification has emerged strongly over the past decade of anomalously low summer sea-ice conditions.

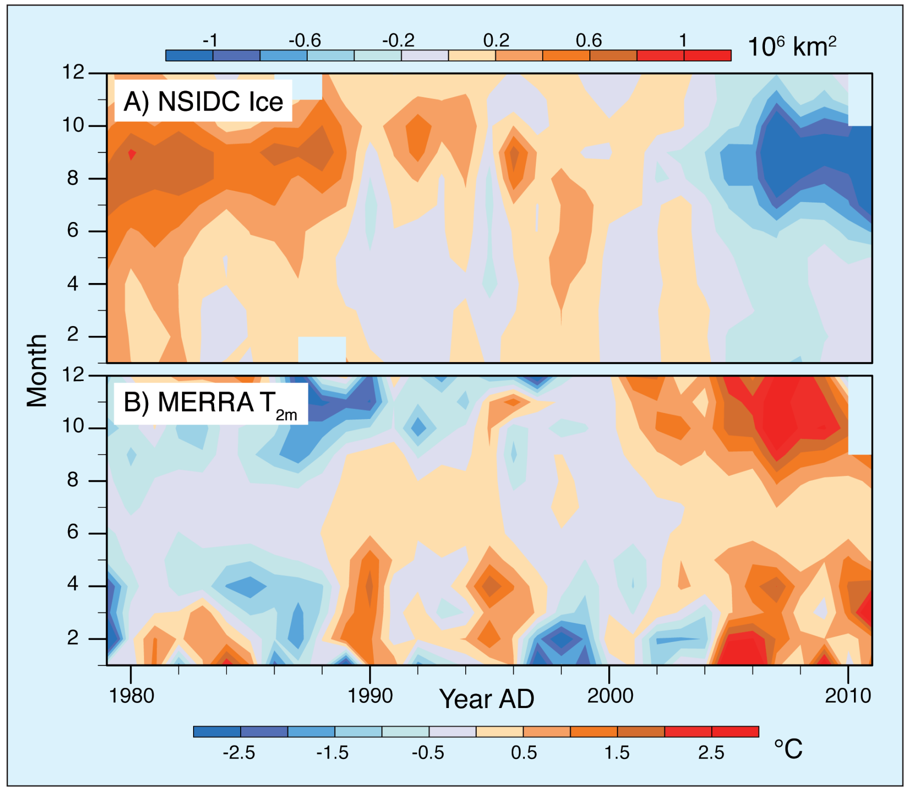

Figure 1: Time series by month (y-axis) and year (x-axis) of (top) anomalies in Arctic sea ice extent based on the satellite passive microwave record and (bottom) corresponding anomalies in 2-meter air temperate for the Arctic Ocean based on the NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA). Anomalies are calculated with respect to the period 1979-2010.

There is growing recognition that Arctic amplification, through altering the static stability of the atmosphere, water vapor content and horizontal temperature gradients, will influence the character of weather patterns within and beyond the Arctic. Observational evidence suggests that high-latitude atmospheric circulation is already responding to ice loss, and a variety of studies indicate that these effects will become more pronounced in the coming decades (Serreze and Barry 2011). At least one modeling study finds that the warming effects of sea-ice loss will extend far inland, contributing to warming of the tundra soil column, hastening permafrost thaw and the release of stored carbon to the atmosphere (Lawrence et al. 2008). In short, there seem to be many reasons why we should care about losing the summer Arctic sea-ice cover.

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As Arctic sea ice is shrinking at an accelerating speed for the fourth decade in a row and summer ice extent numbers are falling well below the range of historical observations, much attention is placed on paleoclimatic reconstructions based on long-term time series. This situation necessitates a clear understanding of the nature and limitations of paleo records that can be employed in the Arctic Ocean. The most direct long-term records of sea-ice changes could be derived from seafloor sediments. Not surprisingly, Arctic paleoceanographic research is currently on the rise (Polyak and Jakobsson 2011). However, very low sedimentation rates in the central Arctic Ocean and the predominant lack of deposits older than the last deglaciation (last ca. 15 ka) on the continental shelves narrow the application of paleo data from these sedimentary archives for evaluating future changes (Polyak et al. 2010, and references therein). Useful information is also derived from coastal records and related paleoclimatic archives such as continental ice cores at the Arctic Ocean periphery (e.g. Macias-Fauria et al. 2009; Funder et al. 2011; Kinnard et al. 2011); but none of them can provide a continuous long-term record.

Due to these limitations one should not expect too accurate predictions of the future course and rate of ice retreat from paleo records; nevertheless, they contain a plethora of information on the state of the Arctic system at different climatic conditions of a much wider range than that of the recent centuries (Fig. 1). Notably, paleo data could shed light on the functioning of the seasonally mostly ice free Arctic and its role in the global climatic ensemble, which is essential for predicting environmental change in the very near future (e.g. Serreze and Barry 2011). One critical set of questions relates to the fate of Arctic biota, from microscopic organisms to polar bears, uniquely adapted to live in or in connection with a perennially ice-covered ocean. Disruption of habitats and life cycle of many Arctic species with shrinking sea ice and increasing temperatures is already underway, along with a northward migration of lower-latitude biota from both the Atlantic and Pacific oceans (Wassmann 2011, and references therein). Striking examples are the penetration of the Pacific diatom *Neodenticula seminae* via the Arctic into the North Atlantic (Reid et al. 2007) and the distribution of the coccolithophore *Emiliania huxleyi* from the Atlantic to the northern edge of the Barents Sea (Hegseth and Sundfjord 2008). Stratigraphic data indicate that these migrations likely happen for the first time since the end of the Early Pleistocene (ca. 800 ka) and the Last Interglaciation (ca. 130 ka), respectively.

Investigation of these and other relatively warm, low-ice time intervals of the past few million years, from the current interglaciation (Holocene) to Pliocene, when the Arctic paleogeography was generally similar to modern, has a potential to clarify questions related to the survival of Arctic biota and other impacts of reduced sea ice. This task, however, is complicated by the paucity of paleobiological/biogeochemical proxies in Arctic sediment records because of low marine primary production, overwhelming inputs of terrigenous organic matter, and widespread dissolution of both calcareous and siliceous material, as well as problems with reconstructing sea-ice conditions, which cannot yet be definitively evaluated by any known single proxy. Another complication arises from difficulties with establishing age constraints for Arctic Ocean sediments due to various adverse impacts of the ice cover. Recent achievements in developing sea-ice proxies and improving age controls are encouraging (Polyak and Jakobsson, 2011, and references therein), but much more needs to be done. Promising steps in this direction are underway such as the ESF program Arctic Paleoclimate and its Extremes (APEX) and the newly created PAGES working group on Sea Ice Proxies (SIP), and we can hope for exciting breakthroughs in the near future.

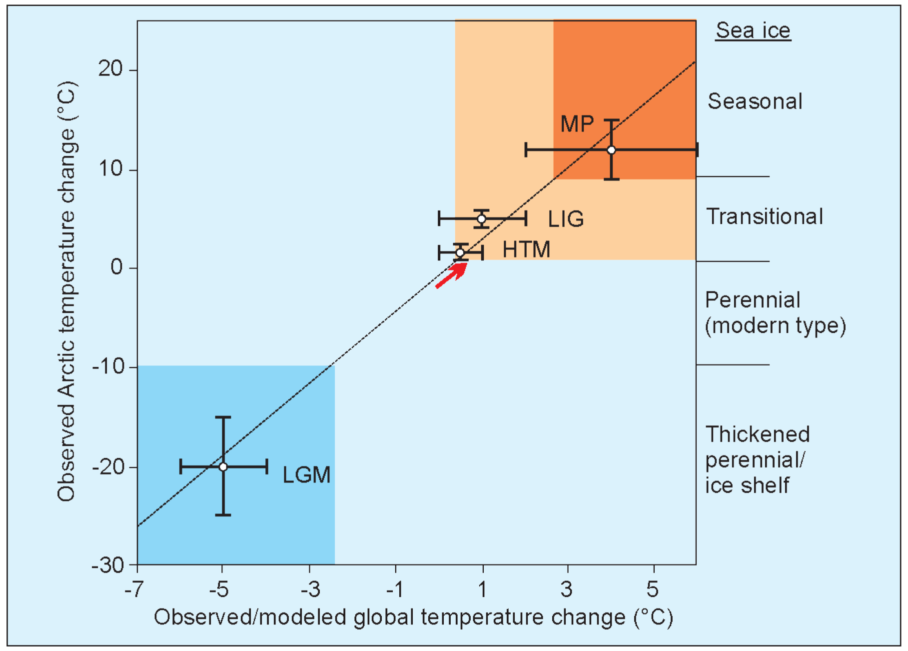

Figure 1: Schematic representation of Arctic sea-ice conditions inferred from paleoclimatic data (e.g. Polyak et al. 2010; Funder et al. 2011; Polyak and Jakobsson 2011). Paleo-temperature anomalies are shown for Last Glacial Maximum (LGM; ~20 ka), Holocene Thermal Maximum (HTM; ~8 ka), Last Interglaciation (LIG; ~130 ka), and middle Pliocene (MP; ~3.5 Ma) (from Miller et al. 2010). Punctured trend line represents the Arctic Amplification. Red arrow shows instrumentally observed temperature change, consistent with observed loss of sea ice approaching the "transitional" state with increasingly large seasonally ice-free areas (see accompanying paper by Serreze and Stroeve).

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