Perspectives on the Arctic's Shrinking Sea-Ice Cover

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REVIEW

Perspectives on the Arctic's Shrinking Sea-Ice Cover

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Linear trends in arctic sea-ice extent over the period 1979 to 2006 are negative in every month. This ice loss is best viewed as a combination of strong natural variability in the coupled ice-ocean-atmosphere system and a growing radiative forcing associated with rising concentrations of atmospheric greenhouse gases, the latter supported by evidence of qualitative consistency between observed trends and those simulated by climate models over the same period. Although the large scatter between individual model simulations leads to much uncertainty as to when a seasonally ice-free Arctic Ocean might be realized, this transition to a new arctic state may be rapid once the ice thins to a more vulnerable state. Loss of the ice cover is expected to affect the Arctic's freshwater system and surface energy budget and could be manifested in middle latitudes as altered patterns of atmospheric circulation and precipitation.

The most defining feature of the Arctic Ocean is its floating sea-ice cover, which has traditionally ranged from a maximum extent of about 16×10^6 km^2 in March to a minimum extent of 7×10^6 km^2 at the end of the summer melt season in September (Fig. 1). Consistent satellite-derived monthly time series of sea-ice extent are provided by the Nimbus-7 Scanning Multichannel Microwave Radiometer (October 1978 to August 1987) and the Defense Meteorological Satellite Program Special Sensor Microwave/Imager (1987 to present). Based on regression analysis of the combined record over the period 1979 to 2006, ice extent has declined for every month (Fig. 2), most rapidly for September, for which the trend is –8.6 ± 2.9% per decade or about 100,000 km^2 per year. Ice extent is defined as the area of the ocean with a fractional ice cover (i.e., an ice concentration) of at least 15% (*1–3*).

Every year since 2001 has yielded pronounced September minima, the most extreme of which was in 2005 (5.56×10^6 km^2). When compared to the mean ice extent over the period 1979 to 2000, this represents a spatial reduction of 21% (1.6×10^6 km^2), an area roughly the size of Alaska (Fig. 1). Comparisons with earlier records, which combine visible-band satellite imagery and aircraft and ship reports, suggest that the September 2005 ice extent was the lowest in at least the past 50 years. Data for the past few years suggest an accelerating decline in winter sea-ice extent (*4*).

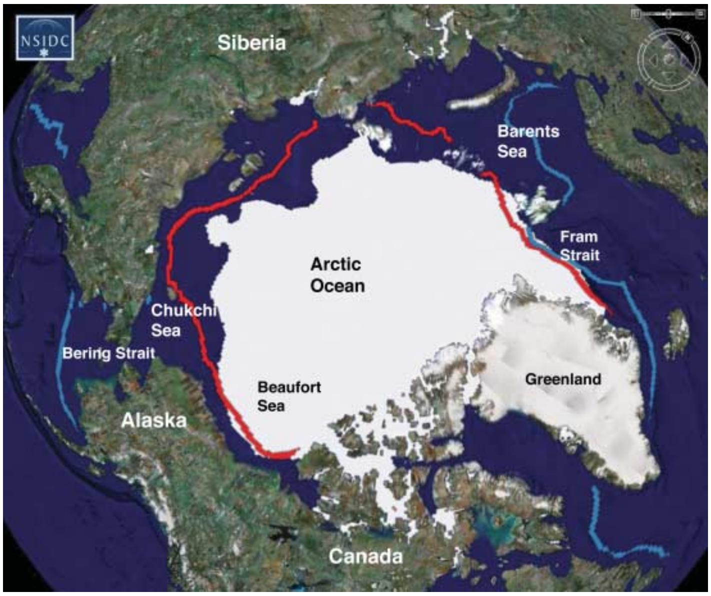

Fig. 1. Sea-ice extent (bright white area) for September 2005. Median ice extents based on the period 1979 to 2000 for September (red line) and March (blue line) illustrate the typical seasonal range. Geographic features referred to in the text are labeled. Credit: NSIDC image in Google Earth.

Evidence for accompanying reductions in ice thickness (*5*) is inconclusive. Upward-looking sonar aboard submarines provides information on ice draft—the component of the total thickness (about 90%) that projects below the water surface. Comparisons between early sonar records (1958 to 1976) and those for 1993 to 1997 indicate reductions of 1.3 m in mean late summer ice draft over much of the central Arctic Ocean (*6*), but sparse sampling complicates interpretation. Further analysis of the submarine-acquired data in conjunction with model simulations points to thinning through 1996 but modest recovery thereafter (*7*). Results from an ice-tracking algorithm applied to satellite data from 1978 to 2003 document decreasing coverage of old, thick ice (*8*).

Understanding the Observed Ice Loss

The observed decline in ice extent reflects a conflation of thermodynamic and dynamic processes. Thermodynamic processes involve changes in surface air temperature (SAT), radiative fluxes, and ocean conditions. Dynamic processes involve changes in ice circulation in response to winds and ocean currents. These include changes in the strength and location of the Beaufort Gyre (a mean annual clockwise motion in the western Arctic Ocean) and characteristics of the Transpolar Drift Stream (a motion of ice that progresses from the coast of Siberia, across the pole, and into the North Atlantic via the Fram Strait). Nearly all of the ice export from the Arctic to the Atlantic occurs through this narrow strait between northern Greenland and Svalbard (Fig. 1).

Estimated rates of SAT change over the Arctic Ocean for the past several decades vary depending on the time period and season, as well as the data source being considered. Although natural variability plays a large role in SAT variations, the overall pattern is one of recent warming, which is in turn part of a global signal (*9*). Using a record that combined coastal station observations with data from drifting buoys (from 1979 onward) and Russian "North Pole" stations (1950 to 1991), Rigor *et al*. (*10*) found positive SAT trends from 1979 to 1997 that were most pronounced and widespread during spring. Although there are biases in the buoy data relative to the North Pole data, especially for October through April (*11*), independent evidence for warming during spring, summer, and autumn since 1981 is documented in clear-sky surface temperatures retrieved from advanced very-high-resolution radiometer satellite imagery (*12*). Further support for warming comes from analysis of satellite-derived passive microwave brightness temperatures that indicate earlier onset of spring melt and lengthening of the melt season (*13*), as well as from data from the Television Infrared Observation Satellites Operational Vertical Sounder that point to increased downwelling radiation to the surface in spring over the past decade, which is linked to increased cloud cover and water vapor (*14*). Our assessments of autumn and winter data fields from the National Centers for

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Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) reanalysis (*15*) point to strong surface and low-level warming for the period 2000 to 2006 relative to 1979 to 1999. Weaker warming is evident for summer.

All of these results are consistent with a declining ice cover. However, at least part of the recent cold-season warming seen in the NCEP-NCAR data is itself driven by the loss of ice, because this loss allows for stronger heat fluxes from the ocean to the atmosphere. The warmer atmosphere will then promote a stronger longwave flux to the surface.

Links have also been established between ice loss and changes in ice circulation associated with the behavior of the North Atlantic Oscillation (NAO), Northern Annular Mode (NAM), and other atmospheric patterns. The NAO refers to covariability between the strength of the Icelandic Low and that of the Azores High, which are the two centers of action in the North Atlantic atmospheric circulation. When both are strong (or weak), the NAO is in its positive (or negative) phase. The NAM refers to an oscillation of atmospheric mass between the Arctic and middle latitudes and is positive when arctic pressures are low and midlatitude pressures are high. The NAO and NAM are closely related and can be largely viewed as expressions of the same phenomenon.

From about 1970 through the mid-1990s, winter indices of the NAO-NAM shifted from negative to strongly positive. Rigor *et al.* (*16*) showed that altered surface winds resulted in a more cyclonic motion of ice and an enhanced transport of ice away from the Siberian and Alaskan coasts (i.e., a more pronounced Transpolar Drift Stream). This change in circulation fostered openings in the ice cover. Although these openings quickly refroze in response to low winter SATs, coastal areas in spring were nevertheless left with an anomalous coverage of young, thin ice. This thin ice then melted out in summer, which was expressed as large reductions in ice extent. Summer ice loss was further enhanced as the thinner ice promoted stronger heat fluxes to the atmosphere, fostering higher spring air temperatures and earlier melt onset.

Given that the NAO-NAM has regressed back to a more neutral state since the late 1990s (*17*), these processes cannot readily explain the extreme September sea-ice minima of recent years. Rigor and Wallace (*18*) argued that recent extremes represent delayed impacts of the very strongly positive winter NAO-NAM state from about 1989 to 1995. As the NAO-NAM rose to this positive state, shifts in the wind field not only promoted the production of thinner spring ice in coastal areas but flushed much of the Arctic's store of thick ice into the North Atlantic through Fram Strait.

Rothrock and Zhang (*19*) modified this view. Using a coupled ice-ocean model, they argued that although wind forcing was the dominant driver of declining ice thickness and volume from the late 1980s through mid-1990s, the ice response to generally rising air temperatures was more steadily downward over the study period (1948 to 1999). In other words, without the NAO-NAM forcing, there would still have been a downward trend in ice extent, albeit smaller than that observed. Lindsay and Zhang (*20*) came to similar conclusions in their modeling study. Rising air temperature has reduced ice thickness, but changes in circulation also flushed some of the thicker ice out of the Arctic, leading to more open water in summer and stronger absorption of solar radiation in the upper (shallower depths of the) ocean. With more heat in the ocean, thinner ice grows in autumn and winter.

Recent years have experienced patterns of atmospheric circulation in spring and summer fa-

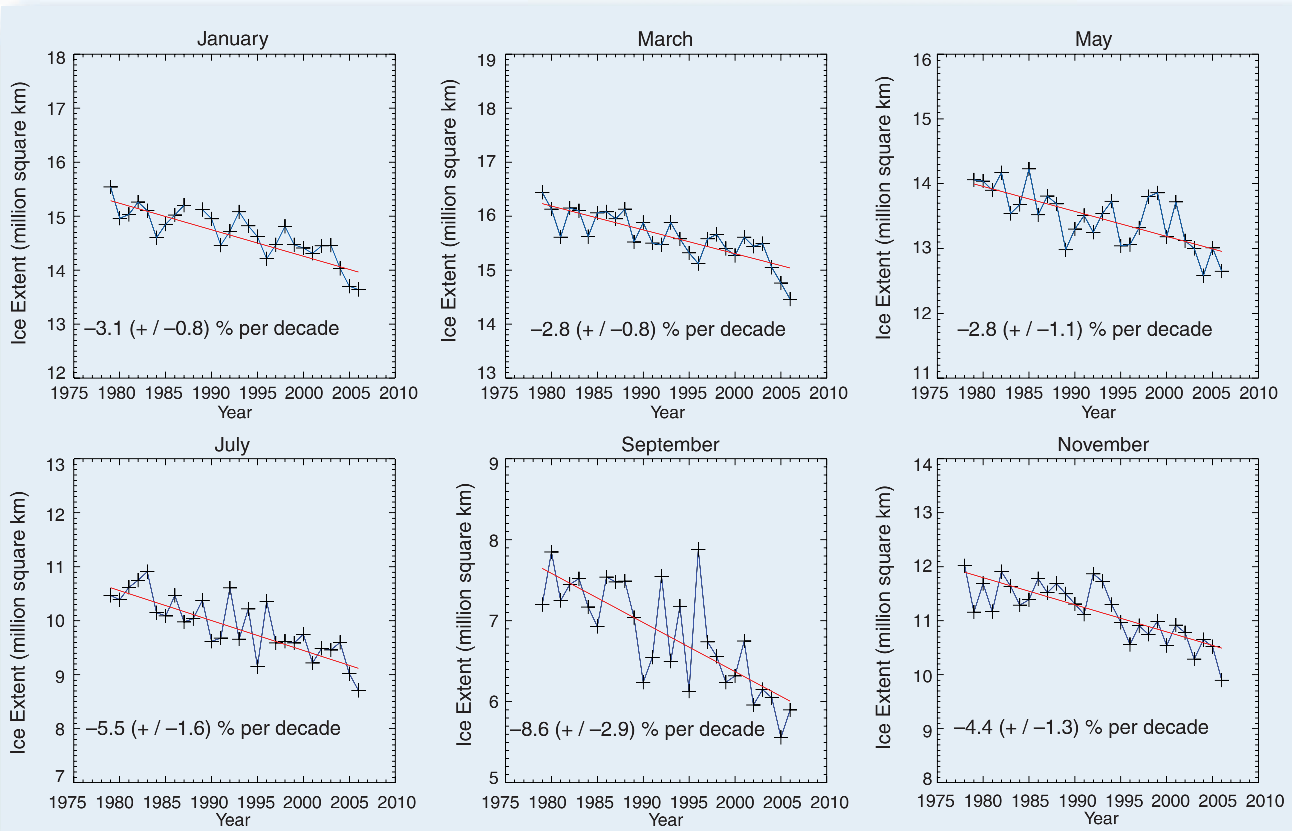

Fig. 2. Time series of arctic sea-ice extent for alternate months and least-squares linear fit based on satellite-derived passive microwave data from November 1979 through November 2006. Listed trends include (in parentheses) the 95% confidence interval of the slope. Ice extent is also declining for the six months that are not shown, ranging from –2.8 ± 0.8% per decade in February to –7.2 ± 2.3% per decade in August.

voring ice loss. By altering both the Beaufort Gyre and Transpolar Drift Stream, these patterns have reduced how long ice is sequestered and aged in the Arctic Ocean (*21*). The strength of a cyclonic atmospheric regime that sets up over the central Arctic Ocean in summer is important. Along with promoting offshore ice motion, the pronounced cyclonic summer circulations of 2002 and 2003 favored ice divergence, as is evident from the low ice concentrations in satellite imagery. Ice divergence in summer spreads the existing ice over a larger area, but enhanced absorption of solar energy in the areas of open water promotes stronger melt. There was also very little September ice in the Greenland Sea (off the east coast of Greenland) for these summers, which may also be linked to winds associated with this summer atmospheric pattern (*22*).

To further complicate the picture, it appears that changes in ocean heat transport have played a role. Warm Atlantic waters enter the Arctic Ocean through eastern Fram Strait and the Barents Sea and form an intermediate layer as they subduct below colder, fresher (less dense) arctic surface waters. Hydrographic data show increased import of Atlantic-derived waters in the early to mid-1990s and warming of this inflow (*23*). This trend has continued, characterized by pronounced pulses of warm inflow. Strong ocean warming in the Eurasian basin in 2004 can be traced to a pulse entering the Barents Sea in 1997 and 1998. The most recent data show another warm anomaly poised to enter the Arctic Ocean (*24*, *25*). These inflows may promote ice melt and discourage ice growth along the Atlantic ice margin. Once Atlantic water enters the Arctic Ocean, the cold halocline layer (CHL) separating the Atlantic and surface waters largely insulates the ice from the heat of the Atlantic layer. Observations suggest a retreat of the CHL in the Eurasian basin in the 1990s (*26*). This likely increased Atlantic layer heat loss and ice-ocean heat exchange. Partial recovery of the CHL has been observed since 1998 (*27*).

Maslowski *et al*. (*28*) proposed a connection between ice loss and oceanic heat flux through the Bering Strait. However, hydrographic data collected between 1990 and 2004 document strong variability in this inflow as opposed to a longer-term trend. An observed increase in the flux between 2001 and 2004 is estimated to be capable of melting 640,000 km^2 of 1-m-thick ice, but fluxes in 2001 are the lowest of the record (*29*). Subsequent analysis (*30*) nevertheless reveals a link between ice loss and increases in Pacific Surface Water (PSW) temperature in the Arctic Ocean beginning in the late 1990s, concurrent with the onset of sharp sea-ice reductions in the Chukchi and Beaufort seas. The hypothesis that has emerged from those observations is that delayed winter ice formation allows for more efficient coupling between the ocean and wind forcing. This redirects PSW from the shelf slope along Alaska into the Arctic Ocean, where it is more efficient in retarding winter ice growth. An imbalance between winter ice growth and summer melt results, accelerating ice loss over a large area.

To summarize, the observed sea-ice loss can in part be connected to arctic warming over the past several decades. Although this warming is part of a global signal suggesting a link with greenhouse gas (GHG) loading, attribution is complicated by a suite of contributing atmospheric and oceanic forcings. Below we review the evidence for an impact of GHG loading on the observed trends and projections for the future, based on climate model simulations.

Simulations from Climate Models

Zhang and Walsh (*31*) showed that most of the models used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) have climatological sea-ice extent within 20% of the observed climatology over their adopted base period of 1979 to 1999, with good simulation of the seasonal cycle. The multimodel ensemble mean realistically estimates observed ice extent changes over this base period, and most individual models also show a downward trend. Our analysis of an IPCC AR4 multimodel ensemble mean hindcast for the longer base period 1979 to 2006 also reveals consistency with observations regarding larger trends in September versus those in winter. These results provide strong evidence that, despite prominent contributions of natural variability in the observed record, GHG loading has played a role.

Rates of ice loss both for the past few decades and those projected through the 21st century nevertheless vary widely between individual models. Our analyses show that in the IPCC AR4 models driven with the Special Report on Emissions Scenarios (SRES) A1B emissions scenario (in which atmospheric CO_2 reaches 720 parts per million by 2100), a near-complete or complete loss (to less than 1×10^6 km^2) of September ice will occur anywhere from 2040 to well beyond the year 2100, depending on the model and the particular run for that model. Overall, about half the models reach September ice-free conditions by 2100 (*32*). Figure 3 shows the spatial pattern of the percent of models that predict at least 15% fractional ice cover for March and September, averaging output over the period 2075–2084. Even by the late 21st century, most models project a thin ice cover in March. By contrast, about 40% of the models project no ice in September over the central Arctic Ocean.

The scatter among models reflects many factors, including the initial (late-20th century) simulated ice state, aspects of the modeled ocean circulation, simulated cloud conditions, and natural variability in the modeled system (e.g., NAO-NAM–like behavior). These tie in strongly to the strength and characteristics of the positive ice-albedo feedback mechanism. In general, GHG loading results in a stronger and longer summer melt season, thinning the ice and exposing more of the dark (low albedo) ocean surface that readily absorbs solar radiation. Autumn ice growth is delayed, resulting in thinner spring ice. This thin ice is more apt to melt out during the next summer, exposing more open water, which results in even thinner ice during the following spring. Negative feedbacks, such as the fact that thinner ice grows more rapidly than thicker ice when exposed to the same forcing, can counteract these changes but are generally weaker.

Although there is ample uncertainty regarding when a seasonally ice-free Arctic Ocean will be realized, the more interesting question is how it arrives at that state. Simulations based on the Community Climate System Model version 3 (CCSM3) (*33*) indicate that end-of-summer ice extent is sensitive to ice thickness in spring. If the ice thins to a more vulnerable state, a "kick" associated with natural climate variability can result in rapid summer ice loss because of the ice-albedo feedback. In

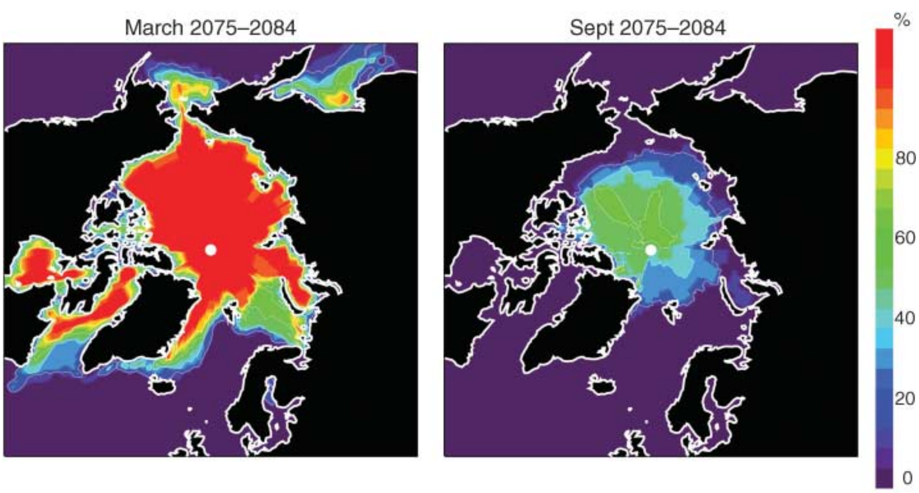

Fig. 3. Spatial pattern of the percent of IPCC AR4 model simulations (SRES A1B scenario) with at least 15% ice concentration for March (**left**) and September (**right**), averaged over the decade 2075 to 2084. For example, a value of 60% at a given location means that 60% of simulations predicted sea ice. Results are based on 11 models with realistic 20th-century September sea-ice extent.

the events simulated by CCSM3, anomalous ocean heat transport acts as this trigger. Such abrupt transitions are typically four times as fast as the observed trends over the satellite record. In one ensemble member, September ice extent decreases from about 6×10^6 to 2×10^6 km^2 in 10 years, resulting in near ice-free September conditions by 2040. A number of other climate models show similar rapid ice loss events.

Impacts

Loss of the sea-ice cover will have numerous impacts. A sharply warmer Arctic in autumn and winter is expected as a result of larger heat fluxes from the ocean to the atmosphere. This is the primary fingerprint of arctic amplification of greenhouse warming (*34*). As ice retreats from the shore, winds have a longer fetch over open water, resulting in more wave action. This effect is already resulting in coastal erosion in Alaska and Siberia. Ice loss is also affecting traditional hunting practices by members of indigenous cultures and contributing to regional declines in polar bear health and abundance (*35*).

In their modeling study, Magnusdottir *et al.* (*36*) found that declining ice in the Atlantic sector promotes a negative NAO-NAM atmospheric circulation response, with a weaker, southward-shifted storm track. Singarayer *et al.* (*37*) forced the Hadley Centre Atmospheric Model with observed sea ice from 1980 to 2000 and projected sea-ice reductions until 2100. In one simulation, mid-latitude storm tracks were intensified, increasing precipitation over western and southern Europe in winter. Experiments by Sewall and Sloan (*38*) revealed impacts on extrapolar precipitation patterns leading to reduced rainfall in the American West. Although results from different experiments with different designs vary, the common thread is that sea ice matters.

Climate models also indicate that by increasing upper-ocean stability and suppressing deepwater formation, North Atlantic freshening may disrupt the global thermohaline circulation, possibly with far-reaching consequences. Increased freshwater export from the Arctic is a potential source of such freshening. Observations implicate an arctic source for freshening in the North Atlantic since the 1960s (*39*). Total freshwater output to the North Atlantic is projected to increase through the 21st century, with decreases in ice export more than compensated by the liquid freshwater export. However, reductions in ice melt and associated freshening in the Greenland-Iceland-Norwegian (GIN) seas resulting from a smaller ice transport through Fram Strait may more directly affect the deepwater formation regions and counteract increased ocean stability due to the warming climate (i.e., a warmer upper ocean is more stable). This outcome could help maintain deepwater formation in the GIN seas (*40*).

Conclusions

Natural variability, such as that associated with the NAO-NAM and other circulation patterns, has and will continue to have strong impacts on the arctic sea-ice cover. However, the observed ice loss for the Arctic Ocean as a whole, including the larger trend for September as compared to that of winter, is qualitatively reproduced in ensemble mean climate model hindcasts forced with the observed rise in GHG concentrations. This strongly suggests a human influence (*31*). However, there is a large amount of scatter between individual simulations, which contributes to uncertainty regarding rates of ice loss through the 21st century. An emerging issue is how a seasonally ice-free Arctic Ocean may be realized: Will it result from a gradual decline with strong imprints of natural variability, or could the transition be rapid once the ice thins to a more vulnerable state? Links between altered ocean heat transport and observed ice loss remain to be resolved, as does the attribution of these transport changes, but pulses such as those currently poised to enter the Arctic Ocean from the Atlantic could provide a trigger for a rapid transition.

In this regard, future behavior of the CHL, which insulates the sea ice from the warm Atlantic layer, is a key wild card. Another uncertainty is the behavior of the NAO-NAM. Despite its return to a more neutral phase, there is evidence, albeit controversial, that external forcing may favor the positive state that promotes ice loss. The mechanisms are varied but in part revolve around the idea that stratospheric cooling in response to increasing GHG concentrations, or through ozone destruction, may "spin up" the polar stratospheric vortex, resulting in lower arctic surface pressures. Another view is that the NAO-NAM could be bumped to a preferred positive state via warming of the tropical oceans (*41*). However, as noted earlier, declining sea ice in the Atlantic sector may invoke a negative NAO-NAM response (*36*).

Given the agreement between models and observations, a transition to a seasonally ice-free Arctic Ocean as the system warms seems increasingly certain. The unresolved questions regard when this new arctic state will be realized, how rapid the transition will be, and what will be the impacts of this new state on the Arctic and the rest of the globe.

References and Notes

1. Ice extent time series are available from the National Snow and Ice Data Center (NSIDC) based on the application of the NASA team algorithm (used here) and a bootstrap algorithm to the passive microwave brightness temperatures (http:/nsidc.org/data/seaice/). Trends computed from both are negative in all months, but those from the bootstrap series are slightly smaller (which yielded a September trend of –7.9% per decade). Trends are computed from anomalies referenced to means over the period 1979 to 2000. Surface melt in summer contaminates the passive microwave signal, resulting in the underestimation of ice concentration. Use of ice extent (a binary ice–no ice classification) largely circumvents this problem.
2. Trends for all months are significant at the 99% confidence level, based on an *F* test with the null hypothesis of a zero trend. Trends are also significant (exceeding the 95% level) based on the approach of Weatherhead *et al.* (*3*), which computes the trend significance from the variance and autocorrelation of the residuals.
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5. Ice thickness can be described from a probability distribution, which has a peak at about 3 m. Although ice at the peak of the distribution is predominantly multiyear ice that has survived one or more melt seasons and thicker than younger first-year ice (representing a single year's growth), ridging can result in very thick first-year ice (up to 20 to 30 m).
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