Taking stock of Arctic sea ice and climate

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Recent change to the Arctic climate system appears to have been forced by both anthropogenic change and natural variability, together with feedbacks between the sea ice, atmosphere and ocean. This was the consensus of discussions and presentations during a Symposium on Arctic Sea Ice and Climate in November 2008 at the Woods Hole Oceanographic Institution (Woods Hole, MA). This article, in summarizing the discussion themes and general conclusions of scientists who participated in the symposium, highlights the immense complexity in the cause and effect relationships between the Arctic atmosphere, sea ice and ocean.

Atmospheric circulation patterns

Arctic climate patterns of this decade are distinct from any other time in the 20th century (Overland et al., 2008). The period 2000-2007 was characterized by unusual meridional flow toward the North Pole (Overland and Wang, 2005; Overland et al., 2008). These anomalous winds resulted in sea-ice loss via enhanced ice transport; analysis of sea-ice drift indicates that the prevailing summer circulation in recent years has resulted in a distinct positive trend in the export of sea ice from the Arctic, contributing up to 30% of the sea-ice retreat during the past several years (Kwok, 2008; Ogi et al., 2008). It is telling that a similar meridional atmospheric pattern occurred in the late 1930s although it did not result in the massive ice losses seen in recent years. It may be that increasing temperatures over the past several decades impede recovery of an ice pack affected by anomalous winds, with ice retreat further enhancing warm autumn temperature anomalies (Overland et al., 2008; Francis et al., 2009). The 2007 and 2008 winter Arctic Oscillation (AO) index was more positive than in previous years (a positive phase of the AO is typically associated with warmer temperatures and export of ice from the Arctic Ocean), although not as strongly positive as in the early 1990s. It remains to be seen whether a future return to a consistently strongly negative AO (typically associated with cooler temperatures and sequestered ice in the Arctic) would be sufficient to reverse the trend of warming and ice decline. While it would seem that increasing temperatures and ice-ocean feedbacks leave the Arctic climate more susceptible to natural atmospheric variability, it is unclear to what extent changes in atmospheric circulation are influenced by global climate change.

A thinner, more vulnerable sea-ice cover

The increased vulnerability of the Arctic system to anomalous atmospheric forcing can be argued from the perspective that recent ice loss is the result of a long-term preconditioning to thinner ice. Lindsay et al. (2009) use a coupled ice-ocean model to show that the record minimum summer sea-ice extents in 2007 and 2008 may be the result of a general thinning of sea ice in a warming climate over past decades. The mean ice thickness and compactness over the entire Arctic basin began to decline consistently beginning in the late 1980s (Lindsay and Zhang, 2005; Rigor and Wallace, 2004). Lindsay et al. (2009) demonstrate that the recent anomalous wind patterns that blew the ice from the Pacific to the Atlantic side of the Arctic basin, where a significant fraction was pushed out of the Arctic Ocean through Fram Strait, would have been less influential without prior thinning of the ice pack - a less compact ice pack is more susceptible to advection by the winds and currents.

While measurements of ice thickness have been elusive, progress has been made since 2003 using satellite observations. Sea-ice freeboard, from which thickness can be inferred after accounting for the hydrostatic load of the snow layer, has been estimated from ICESat (Ice, Cloud, and Land Elevation Satellite) laser altimeter elevation profiles (Kwok and Cunningham, 2008) and satellite radar altimetry data from the European Space Agency (ESA) satellites ERS-1, ERS-2 and Envisat (e.g. Laxon et al., 2003; Giles et al., 2008). The evolution of the multiyear ice thickness between 2002 and 2008 (before and after the September 2007 ice-extent minimum) reveals that the Arctic-wide average value was 0.26 m less during winter 2007-2008 than the average winter ice thickness for the five years preceding (Giles et al., 2008). Giles et al. (2008) also show that the ice-extent minimum in fall 2007 was followed by reduced ice thicknesses the following winter, with the largest decrease of 0.49 m in the Western Arctic. While thinning trends in permanent ice cover are emerging, continuous measurements of ice draft by underwater sonar in the Beaufort Sea since 1990 indicate no trend in seasonal ice thickness (Melling, 2005). This result is consistent with longer-term measurements (since the 1930s) in the seasonal land-fast ice.

Feedbacks and impacts

Perovich et al.'s (2008) analysis of autonomous ice-mass balance buoy (IMB) thickness measurements showed that absorption of solar radiation in the Arctic Ocean surface layer in summer 2007 led to greatly enhanced melting of the bottom surface of multi-year ice in the Beaufort Sea. An increase in the area of open water that summer resulted in a large positive anomaly in solar heat input to the upper ocean, triggering a strong ice-albedo feedback whereby more open water resulted in the absorption of more solar heat, which in turn resulted in more melting and more open water. The excess warming of the upper ocean contributed to delayed freezing in fall 2007 (Comiso et al., 2008) in effect lengthening the melt season.

Observations of atmospheric conditions following summers with anomalous sea-ice conditions suggest that the loss of Arctic sea ice will affect the exchange of heat and moisture between the surface and atmosphere, leading to changes in the boundary layer, clouds, and weather patterns in the ensuing fall and winter (Francis et al., 2009). The substantial ice loss in summer 2007, for example, was followed by a substantial increase in cloud amount over the areas of newly exposed water during autumn (Levinson, 2008), likely due to increased evaporation. Warming of the lower troposphere and increased emission of infrared radiation toward the surface retard the formation of sea ice. Such consequences demonstrate the difficulties inherent in ascertaining how the atmospheric circulation responds to Arctic and global climate change.

Changes in seasonal timing of ice growth and retreat impact Arctic ecosystems and small Arctic communities. Annual primary productivity in the Arctic Ocean has been increasing over the last decade, in part due to a longer growth season that arises under greater open water extent (Arrigo et al., 2008). Further, some events in biology are not prompted by their immediate environment but rather timing, hence in a rapidly changing Arctic a disparity between biology and the physical environment can arise. Later-forming sea ice also leads to less protection from the waves of fall storms, affecting coastal communities such as Kivalina and Shishmaref. Around the Arctic, migration and other demographic indicators often respond quickly to external pressures, and bear

watching through the coming environmental changes (Hamilton and Mitiguy, 2008).

Concluding remarks

The Arctic is characterized by strong natural variability, intricate feedbacks, and a multi-year memory for ocean-ice-atmosphere processes. Although continued Arctic change is expected under present anthropogenic forcing, the rate and consequences of this change are less clear. It may be that the feedback mechanisms, steady warming, and natural fluctuations will cause further dramatic reductions in summer ice, or that the Arctic will remain in a new, stable state of reduced seasonal ice cover for many years. The coming decades will provide new insights into the complexities of the Arctic climate system, and how changes will affect the biological and human communities within and beyond its boundary.

Meeting Participants: C. Ashjian, J. Cassano, J. Francis, J.C. Gascard, L. Hamilton, R. Kwok, S. Laxon, R. Lindsay, P. Matrai, H. Melling, M. Miles, J. Overland, D. Perovich, A. Proshutinsky, V. Smolyanitsky, M.-L. Timmermans, T. Weingartner

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