

Variations in the age of Arctic sea-ice and summer sea-ice extent

Ignatius G. Rigor^{1,2} and John M. Wallace³

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[1] Three of the past six summers have exhibited record low sea-ice extent on the Arctic Ocean. These minima may have been dynamically induced by changes in the surface winds. Based on results of a simple model that keeps track of the age of ice as it moves about on the Arctic Ocean, we show that the areal coverage of thick multi-year ice decreased precipitously during 1989–1990 when the Arctic Oscillation was in an extreme “high index” state, and has remained low since that time. Under these conditions, younger, thinner ice anomalies recirculate back to the Alaskan coast more quickly, decreasing the time that new ice has to ridge and thicken before returning for another melt season. During the 2002 and 2003 summers this anomalously younger, thinner ice was advected into Alaskan coastal waters where extensive melting was observed, even though temperatures were locally colder than normal. The age of sea-ice explains more than half of the variance in summer sea-ice extent. **INDEX TERMS:** 1863 Hydrology: Snow and ice (1827); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 9315 Information Related to Geographic Region: Arctic region. **Citation:** Rigor, I. G., and J. M. Wallace (2004), Variations in the age of Arctic sea-ice and summer sea-ice extent, *Geophys. Res. Lett.*, 31, L09401, doi:10.1029/2004GL019492.

1. Introduction

[2] The Inuits have observed that sea-ice on the Arctic Ocean has changed dramatically during the last decade. “Solid ice has disappeared and there are no longer huge icebergs during fall and winter. The ice now comes later and goes out earlier and it is getting thinner” (J. Wongittilin Sr., Alaska Traditional Knowledge and Native Foods Database, Alaska Native Science Commission and Institute of Social and Economic Research, <http://www.nativeknowledge.org/>, 2000). These changes have a profound impact on the ability of Inuits to hunt and sustain their culture. Quantitatively, this “traditional knowledge” is supported by the observed decreases in sea-ice thickness [Rothrock *et al.*, 1999] and sea-ice extent [Parkinson *et al.*, 1999] (Figure 1a).

[3] The summers of 1998, 2002 and 2003 set records for low sea-ice extent on the Arctic Ocean. The spatial pattern

of these recent trends in summer sea-ice extent (1979–2002; Figure 1b) was different from the pattern of trends noted by Parkinson *et al.* [1999] for the period 1979–1996 (Figure 1a). The summer trends for 1979–1996 [Parkinson *et al.*, 1999] were dominated by large decreases in sea-ice extent on the Eurasian side of the Arctic Ocean, while trends for 1979–2002 were strongest along the Alaskan coast.

[4] The state of the Arctic sea-ice pack is determined by the effects of the atmosphere and ocean upon the sea-ice on various time scales. On time scales of days to weeks, wind stresses from storms produce ridges of sea-ice and areas of open water [e.g., Shy and Walsh, 1996]. Ridging thickens sea-ice and during winter the areas of open water quickly freeze up, increasing the overall volume of sea-ice in a specified area. During spring and summer, the presence of open water allows more solar energy to be absorbed, thereby prolonging the melt season. The number of storms that any given parcel of ice has experienced is cumulative, and hence the amount of ridged ice tends to increase with the age of the ice.

[5] On seasonal time scales, Rigor *et al.* [2002] showed that most of the variability in sea-ice motion is related to variations in the wind, and that the Arctic Oscillation (AO) [Thompson and Wallace, 1998] explains most of the variance in wind (sea level pressure) and sea-ice motion. The winter wind anomalies associated with the high-index AO conditions increases the advection of ice away from the Eurasian and Alaskan coasts. This advection increases the production of thin ice in the flaw leads along the coast, and preconditions the sea-ice to be more prone to melt during the following spring and summer. During summer, low-index AO conditions favor southeasterly wind anomalies which increase the advection of ice away from the Alaskan coast and increase the advection of warm air onto the ocean, both of which act to decrease the amount of ice in the Beaufort and Chukchi seas. However, the impact of the summer AO on sea-ice extent appears to be preconditioned by the state of the AO during the previous winter [Rigor *et al.*, 2002], and in recent years the correlations between the summer AO-index and sea-ice extent are not as strong as they were in prior years. For example, during the summers of 2002 and 2003, the summer AO was in a high-index phase, which favors above normal ice concentrations along the Alaskan coast, and yet record minima were observed during both years.

[6] In this paper, we argue that the changes in surface wind that occurred in association with fluctuations in the AO have dramatically decreased the average age of sea-ice on the Arctic Ocean, thereby setting the stage for the recent minima in Arctic sea-ice extent.

2. Data and Methods

[7] The primary data sets used in this study are monthly gridded fields of sea-ice motion analyzed from tracks of

¹Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.

²Also at Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.

³Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.

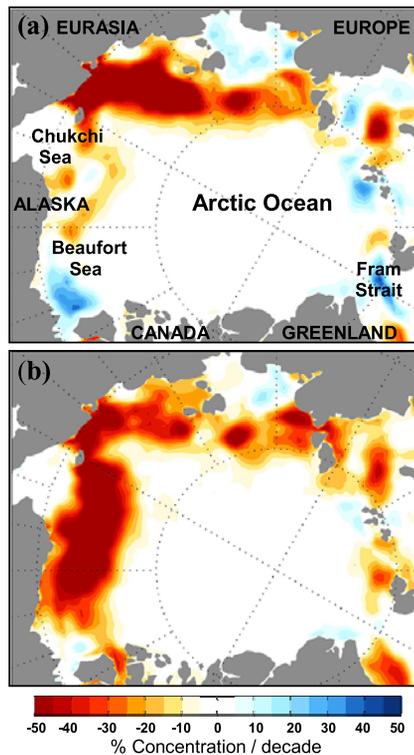


Figure 1. Trends in September sea-ice concentration from microwave satellite data from 1979–1996 (a), and 1979–2002 (b).

drifting buoys and manned stations maintained by the International Arctic Buoy Programme from 1955 to 2002 [Rigor *et al.*, 2002] and summer sea-ice concentration data documented by Walsh [1978] for the period of record 1901–1999 and by Comiso [1995], which has been updated to include the period of record 1979–2002. These data were obtained from the National Snow and Ice Data Center. It should be noted that we use the terms *sea ice concentration* and *sea ice extent* interchangeably since the goal of this study is to understand the changes in summer sea ice along the coast where the sea ice concentrations tend to be either very low or very high.

[8] To estimate the age of sea-ice we used a simple model that tracks a grid of points (ice parcels) as they move about the Arctic Ocean. This model: (1) defines new, first year sea-ice in the areas of open water in September (the month of the climatological annual minimum in sea ice extent); (2) advects these parcels of ice using the monthly gridded fields of ice motion; (3) if these parcels of drifting ice lie within the 90% sea-ice concentration limit in September the following year, they are said to have survived the summer melt, and these parcels are aged 1 year; and (4) we repeat the process for each year from September 1955 to September 2002. The model was initialized by assuming that all of the sea-ice that survived the summer melt in 1955 was 1 year old, so that by 1965 the distribution of the ice ranging in age from 0–10 years was well established. Figure 2a shows the estimated age of ice on the Arctic Ocean in September 1981. Throughout most of the Arctic Ocean the ice is over 10 years old. This estimate is consistent with the drift of the Russian manned drifting station, NP-22, which was

deployed in the Beaufort Gyre in 1973 on thick multi-year ice and abandoned nearly 10 years later in 1982 as it drifted towards Fram Strait (Figure 2a), and by the trajectory of the ice island T-3, which drifted over the Arctic Ocean for over 30 years from 1952–1983 (not shown). Younger ice can be seen in the Transpolar Drift Stream, which quickly advects sea-ice across the Arctic Ocean towards Fram Strait.

3. Results

[9] Our model shows that by September 2002 the area of old ice decreased dramatically and most of the Arctic Ocean was covered by ice less than 5 years old (Figure 2b). We now discuss how these conditions may have evolved.

[10] On inter-annual times scales, during relatively low AO-index conditions, as were observed during the 1980's, ice is shown to recirculate in the large Beaufort Gyre for

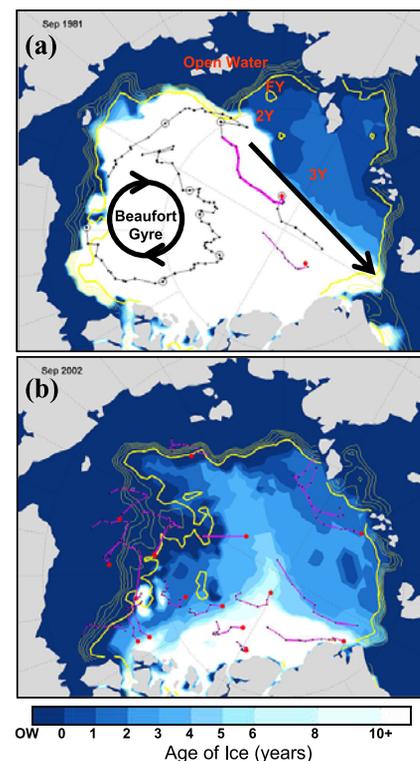


Figure 2. Age of oldest sea-ice in September 1981, and September 2002 based on the simulation. Open water (OW) is shown as dark blue, and the oldest ice is shown as white. The drift of buoys that reported for at least 8 months of the prior 12 months are also shown (magenta lines with black dots), with a large red dot marking the current position. Tracks without large red dots mark buoys that have ceased reporting, while the thicker yellow line marks 90% ice concentration, while the thinner yellow lines mark ice concentrations of 50, 60, 70, and 80% for those months. Figure a) also shows the drift of the Russian manned drifting station, NP-22, from 1973 to 1982 (black trajectory), with dots marking monthly positions, and circles noting the position of the station during September of each year; and areas of open water, first (FY), second (2Y), and third year (3Y) ice are noted in red. The Beaufort Gyre and Transpolar Drift Stream are also shown (black arrows).

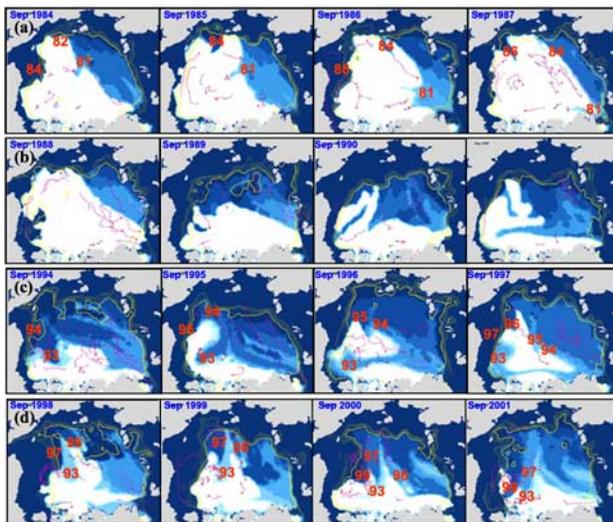


Figure 3. Changes in the age of ice on the Arctic Ocean. Color scale and contours are the same as in Figure 2. The red numbers indicate the year that different anomalies originated from the Beaufort and Chukchi seas. Figure a) shows ice originating along the Alaskan coast drift out of the Arctic Ocean through Fram Strait over 6 years during low AO conditions; b) shows the rapid decrease in the area of old ice on the Arctic Ocean from 1988 to 1990; c) shows the conditioning of sea-ice in the Beaufort and Chukchi seas towards younger, thinner ice from 1994 to 1997; and d) shows additional conditioning of sea-ice in the Beaufort and Chukchi seas from 1998–2001.

over 10 years (Figure 3a), and ice anomalies formed during summer in the Beaufort and Chukchi seas are advected away from the Alaskan coast into the Eurasian Arctic, and drift out of the Arctic Ocean through Fram Strait (Figure 3a). During this period $\sim 80\%$ of the area of the Arctic was covered by thick, multi-year ice. With the transition to extreme high-index AO conditions in 1989, the area of the Arctic Ocean covered by old sea-ice decreased precipitously (Figure 3b). These changes were driven by AO wind anomalies, which reduced the size of the Beaufort Gyre, thus decreasing the drift of ice into the Eurasian Arctic, and increasing the advection of multi-year ice away from the Eurasian coast towards the Canadian Arctic and out through Fram Strait [Rigor *et al.*, 2002]. By the end of summer 1990 in the simulation, the fraction of the Arctic Ocean covered by ice older than three years drops to 30%. The spatial changes in the age of ice as inferred from the model agree with the observed decrease in ice thickness [Rothrock *et al.*, 1999], and the observed and modeled decrease in the amount of ridges on the Arctic Ocean [Makshatas *et al.*, 2003; Y. Yu *et al.*, Changes in thickness distribution of Arctic sea-ice between 1958–1970 and 1993–1997, submitted to *Journal of Geophysical Research*, 2004].

[11] With the reduction of the area covered by the Beaufort Gyre, less old ice from the central Arctic was exported into the seasonal ice zone along the Alaskan coast, reducing the age of sea-ice recirculating back into the seasonal ice zone from ice over 10 years (Figure 2a) to 3–4 years (Figure 3b and 3c). For example, in 1997

(Figure 3c) the model shows recirculation of young ice back into the seasonal ice zone. The two intrusions of young ice along the edge of the old ice area in September 1997 mark new ice formed in areas of open water along the Alaskan coast after the summers of 1995 and 1996. The large area of young ice recirculating back into the seasonal ice zone along the Alaskan coast in 1997 was produced in the large area of open water in the Chukchi Sea during the fall of 1993.

[12] In the simulation, low-index AO conditions during summers of 1997, 1998 and 1999 forced the further depletion of the reservoir of old ice remaining in the Beaufort Gyre, but the moderately high AO conditions averaged over these calendar years had the effect of trapping these anomalies within the gyre, thereby compounding the decreases in sea-ice extent each summer (Figure 3d), producing the ice conditions that we see today (Figure 2b). During the 2002 and 2003 summers this anomalously young, thin ice was advected into Alaskan coastal waters (Figure 3d) where extensive melting was observed, even though temperatures were locally colder than normal [Serreze *et al.*, 2003].

[13] In contrast to the above hypothesis, Serreze *et al.* [2003] argued that the sea–ice extent minimum of 2002 resulted from the increased advection of heat onto the Arctic Ocean during spring, and persistent low pressure and high temperatures during summer. While it is plausible that these mechanisms may have contributed to reducing the concentrations of sea ice over the Arctic Ocean, we believe our hypothesis may provide a better explanation for the 2002 and 2003 minima over the coastal areas of the Beaufort and Chukchi seas. Specifically, the observed low in sea level pressure over the Arctic Ocean may have increased the divergence of sea ice and produced large areas of open water over the central Arctic Ocean, but this divergence would have acted to push ice towards the coastal areas and indeed this is observed in the drift of buoys during the summer of 2002. And although the temperatures were slightly above normal over the central Arctic Ocean, as noted earlier, the temperatures were below normal over the Beaufort and Chukchi seas where the largest decreases in sea ice extent were observed [see Serreze *et al.*, 2003, Figure 3]. However, if the recent minima is attributable to the advection of younger, thinner ice into the coastal melt zones of the Arctic Ocean as we have hypothesized, then the anomalies produced by the mechanisms that Serreze *et al.* [2003] proposed, which would have increased the production of younger, thinner ice over the central Arctic Ocean, will act to enhance the anomalies in sea ice extent in future years as this younger, thinner ice drifts into the coastal melt zones of the Arctic Ocean.

[14] To determine the contribution of the AO to the changes in the age of ice and sea-ice extent in the Beaufort and Chukchi seas, we estimated the changes in the age of ice based solely on changes in sea-ice motion related to the AO from 1979–2002. The ice motion related to the AO for each month is estimated by taking the regression coefficient of sea-ice motion on the AO index at each grid-point, multiplying this by the AO index for each month, and adding this to the mean field of sea-ice motion. These simulations based only ice motion related to the AO capture the decrease in the age of ice during 1989 and 1990. They show the reduced circulation of the Beaufort Gyre and the

dramatic decrease in the age of ice in the gyre seen in the simulations based on the total observed ice motion field. Through this chain of events we hypothesize that the recent record low years in Arctic sea-ice extent may be interpreted as a delayed response to the 1989–95 high-index AO event.

4. Conclusions

[15] The AO affects sea-ice on many different times scales. On seasonal time scales, the high index phase of the winter AO index favors the dynamic thinning of sea-ice in the Eurasian Arctic Ocean, and to some extent in the Beaufort and Chukchi seas, and low index phase of the summer AO favors a decrease in ice concentrations through an increase in the advection warm air onto the ice and the advection of ice away from the coast. On interannual time scales low index AO conditions favor the advection of summer ice anomalies away from the Beaufort and Chukchi seas in the larger Beaufort Gyre, and during moderate to high AO conditions, the reduced Beaufort Gyre traps summer sea-ice anomalies in the gyre and recirculates these anomalies back to the coast 3–4 years later, greatly reducing the time that sea-ice has to ridge and thicken before returning for another melt season along the Alaskan coast.

[16] The transition to an Arctic Ocean dominated by “young” ice occurred abruptly in 1989–1990 when the AO-index was over 2 standard deviations above normal. The reverse transition from present day conditions to a state like that which prevailed prior to 1989, with large areal coverage of old, thick ice, would obviously take much longer. When the model is forced with winds observed starting in 1950, the transition requires about 10 years; if winds starting in 1960 are used it requires 15 years or longer.

[17] The winter AO-index explains as much as 64% of the variance in summer sea-ice extent in the Eurasian sector, but the winter and summer AO-indices combined explain less than 20% of the variance along the Alaskan coast, where the age of sea-ice explains over 50% of the year-to-year variability. If this interpretation is correct, low summer

sea-ice extents are likely to persist for at least a few years. However, it is conceivable that, given an extended interval of low-index AO conditions, ice thickness and summertime sea-ice extent could gradually return to the levels characteristic of the 1980’s.

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I. G. Rigor, Polar Science Center, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA. (igr@apl.washington.edu)

J. M. Wallace, Department of Atmospheric Sciences, University of Washington, Box 354235, 4909 25th Avenue, NE, Seattle, WA 98195, USA.