NAO influence on sea ice extent in the Eurasian coastal region

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[1] Influence of winter pre-conditioning of Arctic sea ice due to atmospheric forcing associated with the North Atlantic Oscillation (NAO) on the reduction in summer sea ice extent is studied. It is found that winter sea ice is about 50 cm thinner in high-NAO index years than in low-NAO index years in the Eurasian coastal region mainly due to stronger wind-driven ice export. The thinner wintertime ice combined with strengthened southerlies in spring promotes an earlier break-up of the ice pack in the Eurasian coastal region, resulting in significant sea ice export. The higher ice efflux, in turn, further reduces the ice compactness, thus more solar radiation is absorbed by the oceans which enhances the summer melting process. Thus, winter and spring atmospheric anomalies associated with the positive phase of the NAO may underlie the reduction of summer sea ice extent observed during the 1980s and 1990s. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4255 Oceanography: General: Numerical modeling. **Citation:** Hu, A., C. Rooth, R. Bleck, and C. Deser, NAO influence on sea ice extent in the Eurasian coastal region, *Geophys. Res. Lett.*, *29*(22), 2053, doi:10.1029/2001GL014293, 2002.

1. Introduction

[2] Modulation of Arctic sea ice conditions has been recognized as a potentially significant climate feedback mechanism for two primary reasons, namely, albedo modification and impact on the energy transfer across the air-sea interface [*Manabe et al.*, 1992; *Randall et al.*, 1998]. Indirectly, variability of the mean oceanic buoyancy forcing in the Arctic and adjacent seas induced by anomalous ice formation (salt ejection) and anomalous ice efflux from the Arctic affects the intensity of the Northern North Atlantic deep convection, thus contributing to the forcing of the global-scale oceanic meridional overturning circulation, which plays a key role in the global meridional heat transport. Variability in the winter low-level atmospheric circulation over the Arctic and North Atlantic, as measured by the North Atlantic Oscillation index [*Hurrell*, 1995], has been empirically linked to fluctuations in annual mean sea ice extent over the Arctic, with high NAO conditions associated with reduced ice cover, especially in summer (Figure 1, left; see also *Maslanik et al.* [1996]).

[3] Using observed atmospheric conditions to define the forcing of a coupled sea ice-ocean general circulation model, we investigate the Arctic-wide dynamic and thermodynamic response of sea ice to sustained NAO-related atmospheric anomalies. The results show that wintertime pre-conditioning of the sea ice in high NAO years compared to low NAO years related to stronger wind-induced export plays an important role in reducing summer sea ice extent. Thus, we speculate that winter NAO trends may underlie recent indications of a shrinking summer sea ice cover [*Maslanik et al.*, 1996, and *Deser et al.*, 2000].

2. Model and Experiments

[4] A coupled sea ice-ocean general circulation model - the Miami Isopycnic Coordinate Ocean Model coupled with the Elastic-viscous-plastic dynamic sea ice model of *Hunke and Dukowicz* [1997] and a simple thermodynamic sea ice model of *Semtner* [1976] - is used in this study. The model basin consists of the Arctic Ocean and the North Atlantic. The southern basin boundary is located at 6°N. A buffer zone is used there. As illustrated by *Paiva* [1999], the basin-scale thermohaline circulation is not sensitive to the location of the southern buffer zone. The oceanic initial state is derived from Levitus data modified by *Steele et al.* [2001]. (For details of the model, see *Hu* [2001].)

[5] Two experiments have been carried out to establish the expected differences in sea ice extent in the Eurasian coastal region under sustained NAO-related forcing anomalies, referred to as the high NAO case and the low NAO case. In each case, the model is integrated for 100 years, starting from a 30-year spin-up run forced by a climatological annual cycle based on 51 years of observations. The results reported here are mainly based on the mean state of the two 100-year integrations.

[6] Composite monthly mean atmospheric forcing components - wind stress and speed, air temperature and humidity, radiation fluxes, and precipitation - for high and low NAO conditions and the 51-year climatology were derived from NCEP/NCAR reanalysis data (1948 to 1998). The high NAO index climatology is the mean annual cycle of years 1973, 1981, 1983, 1989, 1990, 1992 to 1995 whose winter NAO index was higher than +2 standard deviations based on the definition of *Hurrell* [1995]. The low NAO index climatology is the mean annual cycle of years 1955, 1962 to 1965, 1969, 1977, 1979 and 1996 (NAO index lower than −2 standard deviations). Note that, while the years are chosen on the basis of wintertime (December to March) NAO conditions, all 12 months of the respective years are used to derive the composite forcing functions.

3. Model Results

[7] The mean annual change of sea ice extent in the Arctic between high and low NAO cases in the model

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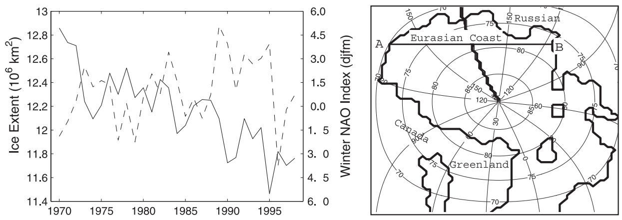

Figure 1. Variations in annual mean sea ice extent in the Northern Hemisphere (left panel), an average over 5 observed time series [solid line, see *Vinnikov et al.*, 1999], and the North Atlantic Oscillation index [dashed line, *Hurrell*, 1995] since 1970. Note the significant negative correlation between the NAO index and the annual mean ice extent, especially from 1989 to 1995. The right panel is the Arctic portion of the model domain. The line AB marks the northern edge of the Eurasian coast basin.

solution is 4.4%, coincidentally almost the same as the estimated loss in sea ice extent from 1978 to 1996 based on satellite observations (4.5% loss in ice extent, *Maslanik et al.* [1996]). In general, the basinwide sea ice extent reaches its winter maximum in April and its summer minimum in early September (Figure 2, left panel). The reduction of the winter maximum sea ice extent is about 1.6% from the high to the low NAO case (Figure 2, right panel); however, the reduction of the summer minimum ice extent is about 17%, much greater than the reduction of the winter maximum.

[8] The focus in this study is on the variation of sea ice extent in the Eurasian coastal basin (see right panel of Figure 1). This represents about 22% of the Arctic basin in the model domain, including the coastal region from west of the Laptev Sea to east of the Chukchi Sea. Compared to variations in sea ice extent in the basin as a whole, about 92% of the reduction in summer sea ice extent in high NAO years in the model occurs in the Eurasian coastal basin, a number which qualitatively agrees well with satellite observations [*Maslanik et al.*, 1996]. The maximum difference between high and low NAO years in sea ice extent in this basin is about 0.9×10^6 km^2 in September (Figure 3).

[9] The changes in sea ice extent in this region can be related to the winter sea ice thickness and compactness. The

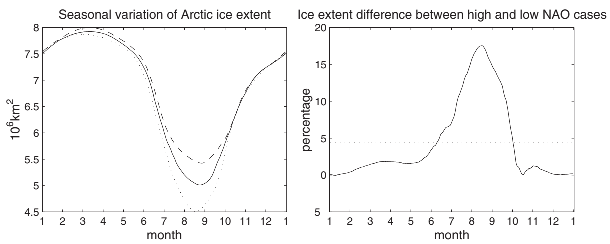

Figure 2. Seasonal variation of the Arctic sea ice extent (left panel) in the climatic case (solid line), the high NAO case (dotted line), and the low NAO case (dashed line) and the percentage difference of ice extent between low NAO and high NAO cases (solid line). The winter maximum sea ice extent appears in late April and the summer minimum sea ice extent appears in early September. The solid (dotted) line in the right panel is the daily (annual) mean percentage difference between the low and high NAO cases.

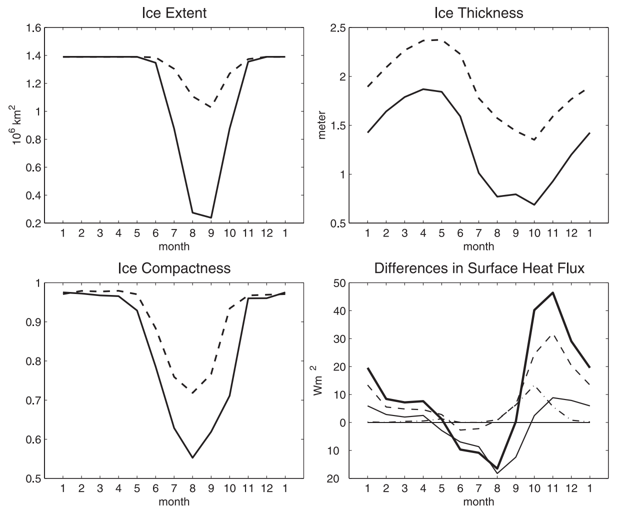

Figure 3. Seasonal variations of sea ice extent (upper left), thickness (upper right), compactness (lower left), and differences of the surface heat flux between high and low NAO index cases (lower right) in the Eurasian coast basin. Solid/dashed ice property curves represent high/low NAO index cases respectively. Heat flux differences are broken down into net surface heat flux (thick solid curve), net radiation flux (thin solid curve), sensible heat flux (dashed), and latent heat flux (dot-dashed). Positive values represent oceanic heat lost.

mean ice thickness in winter is about 50 cm less under high than under low NAO conditions (Figure 3). Ice compactness in winter is slightly lower in the high NAO case. When spring melting starts, the thinner, less compact ice would melt faster than the thicker, more compact ice even under identical atmospheric conditions. In fact, the air is 1 to 2°C warmer in high NAO years than in low NAO years. This further enhances the summer melting process in high NAO years. The faster melting process reduces the ice compactness, resulting in a higher rate of oceanic absorption of solar radiation, which further enhances summer melting. The net radiation flux difference between high and low NAO conditions, the thin solid line in the bottom right panel of Figure 3 shows that the net radiative heat input is higher in high NAO years from late April to September. The maximum difference is 18 W/m^2 in August (a 31% increase from the low NAO case) and the mean difference in this period is 10 W/m^2 (a 5% increase). With the additional radiation absorbed by the ocean, the rate of ice melting in spring and summer increases by 18% in high NAO years.

[10] The formation of thinner, less compact ice in high NAO winters is related to the atmospheric forcing, previous summer sea ice condition, and the oceanic response. In high NAO years, winds blowing from the Eurasian side of the Arctic to the Canadian side are stronger. The stronger wind drives more ice away from the Eurasian coastal region. Except in January, the advection of sea ice from the Eurasian coastal region to the interior Arctic is always higher in high NAO winters than in low NAO winters. The total winter sea ice production in high NAO years is about 3000 km^3, 26% more than the ice volume change between the summer minimum and the winter maximum. In low NAO years, the total ice formation is about 2000 km^3,

slightly lower than the ice volume variation between summer and winter. In other words, the ice influx from the Arctic interior to the Eurasian coastal region in early winter also contributes to the ice volume change in this basin, as shown in Figure 4. From December to March, 20% of the new ice (600 km^3) formed in high NAO years is advected into the interior Arctic from the Eurasian coastal region, a figure that drops to 6.1% (122 km^3) in low NAO years. As a result, the mean sea ice flux difference in this period is about 0.023 Sv (Sv = 10^6 m^3/s) between high and low NAO years.

[11] Further analysis of the model results indicates that by neglecting all of the possible feedbacks, if the export of sea ice were the same in high and low NAO winters, the ice thickness difference between high and low NAO cases would be reduced more than 80% in this basin. Thus, the more efficient sea ice advection results in thinner, less compact ice in high NAO years. This facilitates enhanced winter sea ice formation, as indicated in the previous paragraph.

[12] In high NAO summers, most of the ice in the Eurasian coastal region either melts or is exported into the Arctic interior. The minimum sea ice volume there is only 5% of the winter maximum in high NAO years, but about 38% in low NAO years. As a result, only 17% of the area in this basin is covered by ice in early winter during high NAO years, in contrast to 73% in low NAO years. This may indicate the importance of the effect of summer direct forcing on the reduction of sea ice extent.

[13] Once the open ocean region in this basin is cooled to the freezing point of sea water, the rate of ice formation is higher in high NAO years than in low NAO years. Because of this, the rate of new ice formation in November and December in the high NAO case is more than twice as large as in the low NAO case. The higher rate of heat loss due to lower ice compactness in the high NAO case plays an important role in this higher rate of ice formation. A consequence of these differences is expressed in the net surface heat balance (thick solid line in Figure 3). The graph shows that from October to December, the ocean loses more heat to the atmosphere in high NAO years than in low NAO years. The mean difference in this period is 39 W/m^2 with a maximum of 46 W/m^2 in November. This difference in net surface heat flux represents a 59% increase from low NAO years. The 1 to 2°C warmer air temperature over this region in high NAO climatology might be the atmospheric response to such changes in the net surface heat balance which needs to be studied further.

[14] The most significant difference in heat loss occurs in October. The enhanced oceanic heat loss in the high NAO case relative to the low NAO case is related to the thinner, less compact ice and smaller ice extent in this region. The lower ice compactness and smaller ice extent exposes more ocean directly to the atmosphere which results in an increase in sensible heat flux from ocean to atmosphere (dashed curve in the lower bottom panel of Figure 3) and an increase in outgoing longwave radiation (thin solid curve in the same panel) in winter, especially in early winter (October to December). In early winter, the release of latent heat (dot-dashed curve) due to evaporation is also very important to the higher heat loss in high NAO years.

[15] While the higher rate of heat loss in high NAO winters results in a higher rate of sea ice production, the strong ice export prevents a buildup of sea ice in this basin. The higher net sea ice production causes more salt to be ejected into the ocean. Thus the mixed layer becomes saltier in high NAO years. Our model solutions show that the mixed layer salinity is about 0.5 ppt higher in high NAO winters, consistent with observed surface salinity variation in this basin [*Carmack et al.*, 1997]. Facilitated by salt extrusion in the freezing process, the mixed layer is deepened about 10 m in high NAO winters relative to low NAO winters.

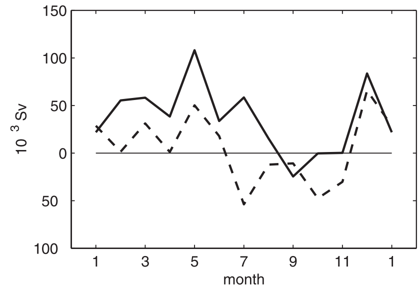

Figure 4. Seasonal variations of sea ice export from the Eurasian coastal region to the interior Arctic for the high (solid curve) and low (dashed curve) NAO cases.

[16] From Figure 4, we also notice that in the spring season (March to May), the sea ice flux from the Eurasian coastal region to the interior Arctic in the high NAO case is about 150% higher than in the low NAO case. This confirms that the increase in spring cyclonic activity in high NAO years relative to low NAO years indeed helps to advect sea ice away from the Eurasian coastal region as argued by *Maslanik et al.* [1996] and *Deser et al.* [2000]. However, as suggested by this study, winter pre-conditioning of the sea ice in high NAO years also plays an important role in the reduction of summer sea ice extent in the Eurasian coastal region.

4. Conclusions

[17] Our model results indicate that variations in Arctic sea ice conditions are directly connected to changes in atmospheric circulation. Specifically, the model solutions suggest that atmospheric circulation and temperature anomalies associated with the NAO may be the major factor influencing the recent observed shrinking of sea ice in the Eurasian coastal region. The importance of wind-driven ice motion to the ice mass redistribution and thickness variations addressed here is consistent with other model studies [*Zhang et al.*, 2000 and *Holloway and Sou*, 2002]. However, these studies did not focus on how NAO-related atmospheric anomalies influence summer sea ice extent along the Eurasian coastal region.

[18] Some specific implications of our work are:

1. The thinner, less compact ice in high NAO winters plays an important role in the reduction of summer sea ice extent in high NAO years. The thinner wintertime ice accompanied by strengthened southerlies in spring promotes an earlier break-up of the ice pack in the Eurasian coastal region, resulting in significant sea ice export.

2. The higher ice efflux, in turn, further reduces the ice compactness, thus more solar radiation is absorbed by the ocean which enhances the summer melting process.

3. In winter, the stronger wind in high NAO years drives more ice away from the Eurasian coastal region, suppressing sea ice buildup there. As a result, the ice is thinner and less compact, which reduces its insulating effect and allows more heat loss from the ocean to the atmosphere, ultimately resulting in enhanced net sea ice production.

4. The higher net sea ice production in the Eurasian coastal basin in high NAO years causes more salt to be injected into the ocean. The resulting buoyancy flux leads to mixed layer deepening.

5. The estimated surface heat flux variability in our model solutions may be potentially important to the regional air-ice-sea interaction. The changes in oceanic stratification induced by the variability of net sea ice production in the Eurasian coastal region may also affect the shelf-basin interaction in the Arctic, and may further modify the water mass exchange between the Arctic and the North Atlantic marginal seas.

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