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Arctic Ocean sea ice response to Northern Annular Mode-like wind forcing

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[1] The response of the Arctic Ocean sea ice system to Northern Annular Mode-like wind forcing has been investigated using an ocean/sea ice general circulation model coupled to an atmospheric boundary layer model. A series of idealized experiments was performed to investigate the Arctic Ocean's response to idealized winter wind anomalies on interannual to multi-decadal time scales. The sea ice response of the model consists of a rapid change of ice movements leading to widespread variation in sea ice thickness and concentration. In most areas the response is largely independent of the forcing frequency with only a slight increase towards longer periods. Only the Greenland Sea exhibited a change in sign of sea ice concentration anomalies at about 20 years period which appears to be caused by slow adjustment of the oceanic circulation. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4255 Oceanography: General: Numerical modeling. **Citation:** Krahmann, G., and M. Visbeck, Arctic Ocean sea ice response to Northern Annular Mode-like wind forcing, *Geophys. Res. Lett.*, *30*(15), 1793, doi:10.1029/2003GL017354, 2003.

1. Introduction

[2] Observations of Arctic sea ice extent over the past century have revealed significant variability from year to year as well as on longer time scales [see e.g. *Maslanik et al.*, 1996; *Deser et al.*, 2000; *Vigne*, 2001]. Much of this variability has been connected to changes in the atmospheric circulation identified as the Northern Annular Mode (NAM; also called Arctic Oscillation, AO) or the closely related North Atlantic Oscillation (NAO) [*Deser et al.*, 2000; *Dickson et al.*, 2000; *Hurrell et al.,* 2003].

[3] Numerical modeling of Arctic sea ice has mostly concentrated on accurately reproducing the observations. When forced with NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] winds such models are, to a varying degree, able to reproduce changes in the sea ice over the past 50 years [e.g. *Hilmer et al.*, 1998; *Häkkinen and Geiger*, 2000]. Model experiments of this kind are useful and can give some insight in whether physics and numerics are sufficiently well represented in the model. It is, however, difficult to analyze them for single processes/phenomena as various forcing mechanisms act on different time scales all at once to create the total observed variability. Experiments using a more controlled setup can be quite useful to isolate the workings of a specific mechanism. We have successfully used a setup in which we applied idealized NAO-like forcing anomalies to an ocean-only model of the North Atlantic to study processes and their variations in the response to NAO [*Visbeck et al.*, 1998; *Krahmann et al.*, 2001].

[4] Here we examine the response of the Arctic Ocean to NAM related wind changes in a similar manner. We describe the results from a first experiment that focused on variations in the response when applying the same idealized NAM forcing pattern with different time modulation.

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2. Numerical Experiments

2.1. The Model

[5] We use an ocean general circulation model which spans the Arctic and Atlantic Oceans from Bering Strait to 10°S with a horizontal resolution between 30 and 200 km. The model has 22 vertical levels with increasing thickness from 12 to 500 m with a variable lowest layer thickness. Basin geometry and bathymetry are resolved on the model grid with only small adjustments.

[6] The model solves the primitive equations on an A-grid and is forced by climatological monthly mean winds [see *Krahmann et al.*, 2001, for more details]. Temperature and salinity are restored to climatological values over a few grid points near solid walls on the Pacific side of Bering Strait and at the boundary in the South Atlantic. Evaporation and precipitation rates are obtained through bulk formulae from the current state of ocean and atmospheric boundary layer and from the NCEP/NCAR reanalysis, respectively. In addition sea surface salinity is restored to monthly climatological data with a 30 day relaxation time scale. Sensible and latent surface heat fluxes are determined by a prognostic atmospheric boundary layer model coupled to the ocean model's SST [*Seager et al.*, 1995]. The atmospheric boundary layer temperature and humidity are specified over land but vary over the ocean according to an advective-diffusive balance subject to air-sea fluxes. Other boundary conditions such as the shortwave and downwelling longwave radiation, cloud cover, wind speed, and wind vector are specified at each grid point with monthly resolution.

[7] Small scale ocean mixing processes are parameterized by a bulk wind driven mixed layer model, convective adjustment, Richardson number dependent vertical mixing and isopycnal thickness diffusion. Monthly wind vector, wind speed, and wind stress forcing fields are derived from daily 925 mb NCEP/NCAR reanalysis winds in order to avoid the exceedingly strong winds east of Greenland which are related to the orography in the reanalysis model. To the 925 mb winds a constant scaling factor of about 0.775 as

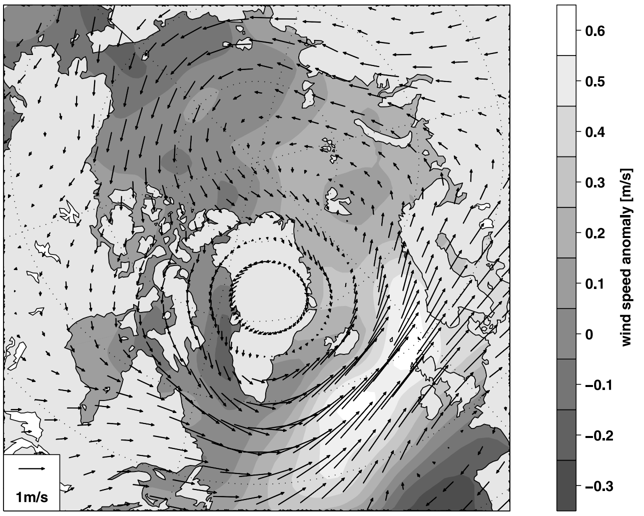

Figure 1. Winter NAM-related wind vector and wind speed anomaly fields used for the idealized NAM-like forcing. The fields were derived from the NCEP/NCAR reanalysis data by regressing winter wind data onto the winter NAM-index derived by *Thompson and Wallace* [1998].

well as a latitude dependent rotation angle of 0 to 25° was applied to obtain winds at 10 m height. In addition a constant drag coefficient of 1.3×10^{-3} and an air density of 1.22 kg/m^3 was used to obtain the surface wind stress. The resulting forcing fields are somewhat weaker and have a less pronounced zone of strong northerly winds east of Greenland when compared to the NCEP/NCAR reanalysis fields.

[8] The sea ice model is based on an elastic viscous plastic sea ice rheology [*Hunke and Dukowicz*, 1997] with a single ice category. The thermodynamics include a single layer of ice with finite heat capacity and a variable thickness snow layer of zero heat capacity. Heat fluxes within the ice are calculated by solving for the snow temperature assuming a balance between heat conduction through the ice and heat flux across the air-snow-ice interface. The radiation budget of the snow layer and heat exchange with the atmospheric boundary layer are calculated through bulk formulae and a snow temperature dependent ice albedo.

[9] After the spin up of 160 years NAM-like wind anomaly patterns were added to the climatological forcing with idealized sinusoidal modulations of 4, 8, 12, 16, 20, 24, 32, and 48 year period. The wind anomalies, consisting of changes in wind vector, wind speed, and wind stress, were applied only from November to April, when the NAM explains most of the sea level pressure variance. Each experiment was run over several forcing cycles to obtain a quasi-equilibrium sea ice and upper ocean model response.

2.2. The Idealized NAM Wind Forcing Pattern

[10] Using a winter (NDJFMA) mean NAM index [*Thompson and Wallace*, 1998], we constructed NAM related anomaly fields by linearly regressing the index against the November through April NCEP/NCAR Reanalysis (1950–1998) wind speed, wind vector and wind stress fields.

[11] The resulting wind vector (see Figure 1) and wind stress anomalies associated with a positive NAM show an increased cyclonic circulation over the Arctic, stronger northerly winds both east and west of Greenland, and enhanced westerlies which extend northward into the Norwegian and Barents Seas. Except for the northeastern Atlantic and the Norwegian Sea where wind speeds are higher by up to 20%, the wind speed anomalies are relatively small. Please note that a change in the location of the northern center of the NAO has been reported by *Hilmer and Jung* [2000] for the periods before and after 1975. The experiments described here use wind variations calculated over both periods. In future experiments we intend to differentiate between the periods.

3. Results

[12] After 160 years of integration the model has settled into a quasi steady state. The climatological winter sea ice thickness distribution and movement is not shown but is close to the mean of the high and low NAM states of Figure 2a and b. Both sea ice thickness and movement agree reasonably well with the limited available observations and with other models [e.g. *Proshutinsky and Johnson*, 1997]. Winter sea ice thickness varies from about 5 m in the Canadian Arctic to about 1.5 m on the Siberian side. Sea-ice drift within the Beaufort gyre shows speeds of 1–2 cm/s and partially feeds into a transpolar drift of 3–4 cm/s magnitude. A substantial fraction of the transpolar drift ice exits the Arctic through Fram Strait at a rate of about 1800 km^3 per year. The summer sea ice area of the model ($6.3 \times 10^6 km^2$) seems somewhat low when compared with longterm averaged observations but is in line with the smallest observed ice extent.

[13] The variable NAM forcing experiments show distinct differences between the positive and negative index phases of the NAM. We first describe the results from the 12 year period NAM experiment. During a positive state of the NAM more cyclonic winds cause the Beaufort gyre to basically vanish (see Figure 2a). At the same time the transpolar drift is strengthened. The overall annual export of sea ice through Fram Strait is increased by 15% due to stronger local northerly winds that increase the local ice velocity as well as due to the presence of thicker ice as a consequence of the adjusted large scale ice circulation. Stronger transpolar drift and the weakened Beaufort gyre lead to thicker sea ice on the Canadian side of the Arctic while it gets thinner on the Siberian side. During the

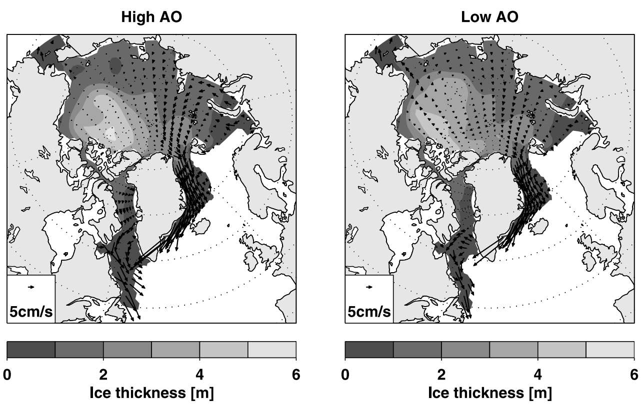

Figure 2. Winter (JFM) sea ice thickness and movement for the high and low states of the idealized NAM-like forcing.

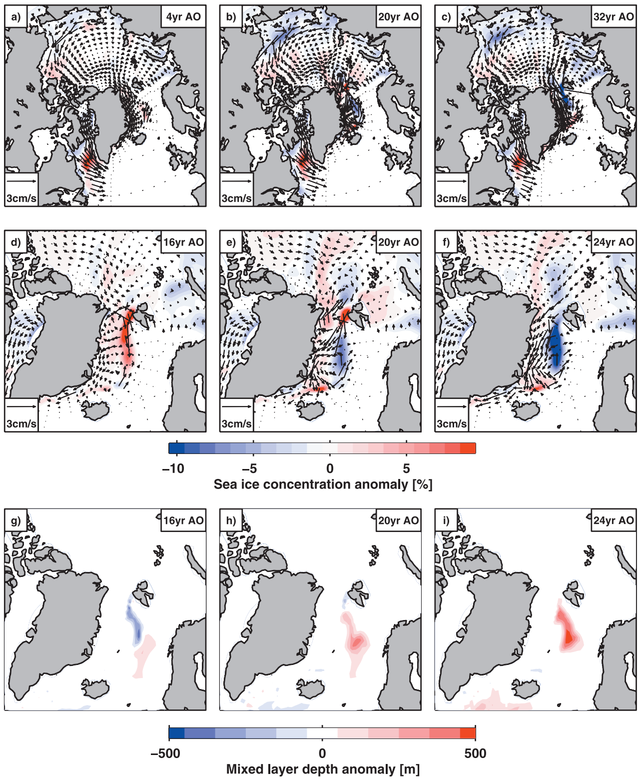

Figure 3. Harmonic amplitudes of sea ice concentration anomalies in phase with the NAM forcing. Graphs a to c exhibit the basic response pattern in the Arctic and its marginal seas. Graphs d to f zoom in on the Greenland Sea region where the only significant NAM frequency dependent response variation is found. Graphs g to i show the mixed layer depth anomalies corresponding to graphs d to f. A deepening and northwestward relocation of deep convection appear to be responsible for the variation in sea ice concentration response.

negative NAM state we find the opposite with an enhanced Beaufort gyre, a weakened transpolar drift, and a smaller ice export through Fram Strait. In summary we find that the positive and negative NAM index states are reminiscent of the cyclonic and anticyclonic wind driven regimes identified by *Proshutinsky and Johnson* [1997].

[14] In the surrounding marginal seas the response to the 12 year period NAM behaves as one might expect from the wind forcing anomalies (Figure 1). During a positive NAM state the Labrador Sea has a larger ice extent caused mostly by the stronger advection of ice from Baffin Bay and the Newfoundland coast. The Barents Sea shows a lower ice concentration as stronger relatively warm winds push the ice further to the northeast. In the Greenland Sea both the influence of the higher ice export from the Arctic and the stronger winds cause higher sea ice concentrations and a larger extent. This is mostly due to sea ice recirculating northward in the central Greenland Sea after having followed the East Greenland current to the south.

[15] To investigate the dependence of the model response on the period of the NAM forcing we calculated the harmonic amplitudes of the monthly mean values of relevant model variables at the periodicity of the NAM forcing. To ensure a stable estimate of the harmonics we used the last two or three of the forcing cycles from each model run. A reference run without forcing anomalies and a second order polynomial fit were subtracted so as to remove any remaining model drift or internal low frequency variability. As an example of the frequency dependent response we show in Figure 3 the harmonic amplitudes of sea ice concentration in phase with the positive NAM index.

[16] The spatial pattern of the response is largely the same for all forcing periods with a slight strengthening towards longer periods. Distinct variations in the response are located in the eastern part of the Greenland Sea and in the Fram Strait region. For periods shorter than 20 years higher sea ice concentrations are found during a positive NAM index. For longer periods the response changes sign with a reduced sea ice concentration during the positive NAM phase. This variation in the response is similar to that found by *Krahmann and Visbeck* [2003] in observational data. They analysed the response of the Nordic Seas' sea ice concentrations to band pass filtered NAM indices and report a response independent of NAM periodicity in the Labrador and Barents seas and variations in the response in the Greenland Sea.

[17] In our model the source of the variation is a relocation and deepening of the deep water formation in the Norwegian and Greenland Seas likely caused by changes of the oceanic heat transport into the region. For periods shorter than 20 years the response to the NAM consists of a deepening of the winter mixed layer in the Norwegian Sea while it is slightly shallower in the Greenland Sea. For sustained NAM forcing deep winter mixed layers spread further northwestward into the Greenland Sea. There it reverses the trend toward shallower mixed layers found for shorter NAM periods. As the winter mixed layer gets deeper more warm water of Atlantic origin is brought

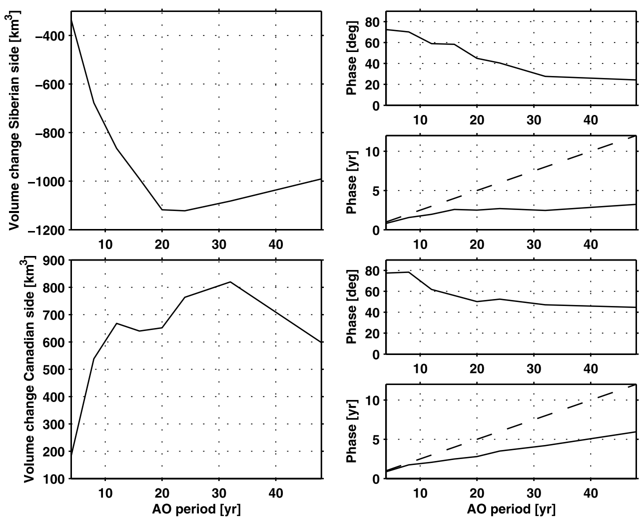

Figure 4. Amplitudes and phases of sea ice volume response to NAM-like forcing anomalies calculated for the Siberian and Canadian sides of the Arctic. Please note that the Siberian side amplitude is shown negative to better indicate its relation to the phase of a positive NAM. The phase of the peak response for both areas changes from mostly in quadrature at short AO periods to more in phase at longer NAM periods.

in contact with the surface which can be seen in the harmonic response of the SST (not shown). Such higher SSTs were also found in the observational data [*Krahmann and Visbeck*, 2003]. An enhanced heat transport from the Atlantic into the Norwegian Sea likely caused by positive temperature anomalies only after longer period phases of the NAO/NAM [*Krahmann et al.*, 2001] further supports this warming. The additional heat melts the sea ice along the ice edge in the Greenland sea, the ice edge recedes, and the open water where the deep convection takes place moves further to the northwest. At the same time the additional melting of sea ice provides a restratifying feedback, thus limiting the growth of the convective area.

[18] In the preceding two paragraphs we described the variations in response to different NAM periodicities. While this variation is the most obvious when looking at the graphs in Figure 3, a more subtle variation is found in the inner Arctic. The strength of the response in phase with the NAM forcing increases somewhat with the length of the NAM periodicity. It appears to level off at periods longer than about 15 years. To further investigate this, we have computed the sea ice volume on the Canadian and Siberian side of the Arctic. Figure 4 shows the amplitude and phase of the respective sea ice volume anomalies. The amplitudes show that the redistribution of the sea ice not only stops to increase towards longer NAM periods but starts to decrease for periods longer than about 20 years. The phases of the sea ice volume anomalies also reveal an interesting variation. For short NAM periods the response is nearly in quadrature with the forcing. This changes with longer NAM periods to a response which is, though still lagging, more in phase with the forcing. Thus the coupled ice-ocean system behaves somewhat like a forced damped oscillator with an internal frequency of about 15–30 years.

4. Summary

[19] We have investigated the Arctic Ocean's response to idealized NAM-like forcing as a function of frequency and found three main results:

[20] The spatial sea ice concentration and thickness response patterns in the Arctic ocean as well as in the Labrador and Barents Seas are largely independent of the frequency of the NAM-like forcing. The amplitude does, however, increase with longer forcing periodicity until it levels off and even slightly decreases again at periods longer than about 20 years.

[21] A more complex variation in the sea ice response is found only in the Greenland and Norwegian Seas where a relocation and deepening of the deep convection modifies the fast wind related sea ice reponse.

[22] In the inner Arctic the strongest response in sea ice concentration and thickness is not coincidental with the peak of the idealized forcing but can lag by several years. For short NAM periods it is nearly in quadrature with the forcing. This changes for longer NAM periods when the response is more in phase.

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