The Arctic Ocean's response to the NAM

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Abstract
The sea ice response of the Arctic Ocean to the Northern Annular Mode (NAM) is studied both in observations and in a numerical ocean general circulation model. The analysis of the observed sea ice concentrations shows the well known seesaw in response between the Labrador Sea and the Greenland and Barents Seas. After band pass filtering the data, it reveals a variation in response in the Greenland Sea between interannual and multidecadal NAM periodicity.
In the numerical model experiments idealized NAM-like wind and windstress forcing anomalies of varying periodicity are applied to the model. This setup allows us to investigate variations in the response to the NAM in a controlled environment. The analysis of the numerical experiments reveals a similar change in response in the Greenland Sea as we found in the observational data. The changes in response appear to be caused by a slow oceanic response component which on interannual timescales does not get strong enough to modify the quicker windstress driven response of the sea ice.

Introduction
The Northern Annular Mode (NAM) is, like the closely related North Atlantic Oscillation (NAO, Visbeck et al., 2003), a large scale pattern of atmospheric variability in the northern hemisphere (Thompson and Wallace, 1998). It represents substantial variations of the northern hemisphere mid- and high latitude atmospheric circulation on a broad range of times scales from weeks to multiple decades. As the winds change they exhibit influence on many parts of the climate system such as ocean currents, surface heat fluxes, and precipitation. A further component of the system that is strongly influenced by the NAM/NAO is the sea ice in the Arctic. Between high and low states of the NAM/NAO, thickness, concentration, extent, and advection of the Arctic sea ice vary substantially (e.g. Deser et al., 2000). Observations revealed that the atmospheric circulation pattern over the Arctic changed substantially over the past decades (Walsh et al., 1996). This change is tightly linked to a shift in the preferred state of the NAM/NAO over the same period (Thompson and Wallace, 1998) and has been named as the cause for the observed long term decrease in summer sea ice extent in the Arctic (Chapman and Walsh, 1993; Parkinson et al., 1999; Deser et al., 2000). In contrast to the summer ice extent, the winter sea ice extent has not changed significantly (Deser et al., 2000). It exhibits, however, significant year to year variability.
Numerical modeling of Arctic sea ice has so far 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; Haekkinen and Geiger, 2000). Model experiments of this kind are useful and can give some insight 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).
In this study we analyze observations of the sea ice concentration in the Arctic Ocean and its marginal seas for their response to the NAM and compare the findings to results from numerical experiments in which we applied idealized NAM forcing.

Observations

The observational basis of our analyses is the updated version of the sea ice concentration data set of Chapman and Walsh (1993). We have calculated the response of winter (January through March) averages of sea ice concentration at each grid point of the the data set to a typical positive NAM (defined as one standard deviation of its index). For the calculation we regressed the NAM index onto the sea ice concentration and multiplied the regression coefficients by one standard deviation of the index. To separate the frequency dependency of the response we used both filtered and unfiltered NAM indices. The bands we used to filter the data are: periods shorter than 5 years, which we denote as high-pass, 5 to 15 years, which we denote as band pass, and longer than 15 years which we denote as low pass. We have performed the same calculations with the NAO index but we found no significant difference in the sea ice response to the calculations with the NAM index. We thus present only the results from the calculations in which the NAM index was used. The analysis has been restricted to the period after 1950 since sea ice concentration data are more reliable for this time interval.

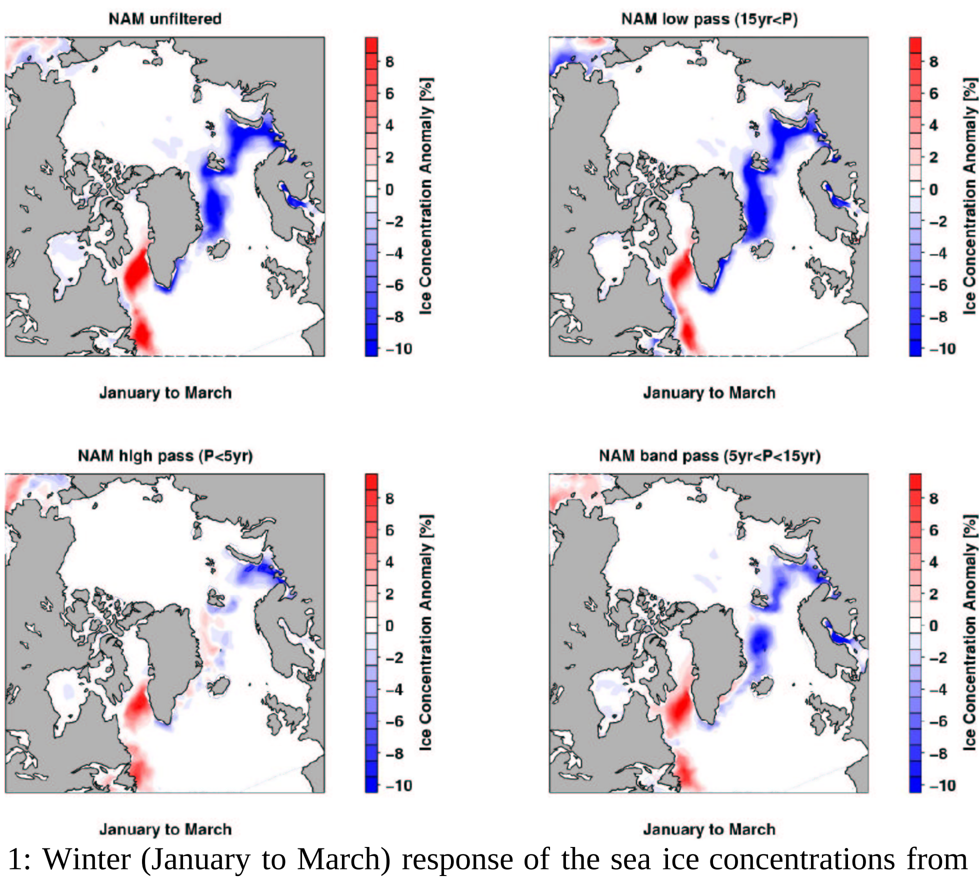

Figure 1: Winter (January to March) response of the sea ice concentrations from the Walsh and Chapman (1996) data set to a positive one standard deviation Northern Annular Mode index (Thompson and Wallace, 1998). The four panels show the response for the full time series as well as the response obtained with high-, band-, and lowpass filtered NAM time series.

In Figure 1 we show the sea ice concentration response to the different NAM-indices. The title of the single graphs indicates the filter band that was used. As has been shown by previous studies (e.g. Deser et al., 2000) the dominant signal in the response of the winter sea ice concentration to the NAM is a seesaw in the sea ice extent between the Labrador Sea and the Greenland and Barents Seas (upper left graph in Figure 1). When comparing the four graphs in Figure 1 we find that the response in the Labrador and Barents Seas varies only little with the periodicity of the NAM. In the Greenland Sea we do, however, find a significant variation. At short periodicities the sea ice concentration response is weak to positive (i.e. higher concentrations during a positive NAM). This changes to a strongly negative response at longer periodicities.

Numerical Experiments

We use an ocean general circulation model which spans the Arctic and Atlantic Oceans from Bering Strait to 10°S with a horizontal resolution ranging from about 200 km near the equator to about 30 km near Greenland where the model grid's pole is located. The model has 22 fixed vertical levels with increasing thickness from 12 to 500 m. Evaporation and precipitation rates are obtained through bulk formula from the current state of ocean and atmospheric boundary layer and from the NCEP/NCAR reanalysis, respectively. 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 net shortwave and downwelling longwave radiation, cloud cover, wind speed, and wind vector are specified at each grid point with monthly resolution (see Visbeck et al., 1998 and Krahmann et al., 2001 for more information on the general experiment setup).

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-ice interface. The radiation budget of the snow layer and heat exchange with the atmospheric boundary layer are calculated through bulk formulae and a temperature dependent ice albedo.

After the spin up an AO-like wind anomaly pattern was added to the climatological forcing with idealized sinusoidal modulations of 4, 8, 12, 16, 20, 24, 32, and 48 year period. The wind anomalies were only applied between November and April, when the NAM explains most of the sea level pressure variance. The anomaly pattern was obtained using a winter (NDJFMA) mean AO index (Wallace and Thompson, 1998), by linearly regressing the index against the November through April NCEP/NCAR Reanalysis (1950--1998) wind speed, wind vector and wind stress fields.

In Figure 2 we show the winter sea ice concentration response found in the numerical model experiments. The periodicity of the idealized NAM is shown in the titles of the single graphs. As in the observations the basic sea ice concentration response to the NAM consists of a seesaw of concentrations in the Labrador Sea and in the Barents Sea. Similar to the observations we also find a variation in the response in the Greenland Sea. For short NAM periodicities a weak or slightly positive response is found whereas for long periodicities the response changes to mostly negative. First analyses of the hydrographic response in the model experiments indicate that a variation in the inflow of warm Atlantic water into the Norwegian Sea is responsible.

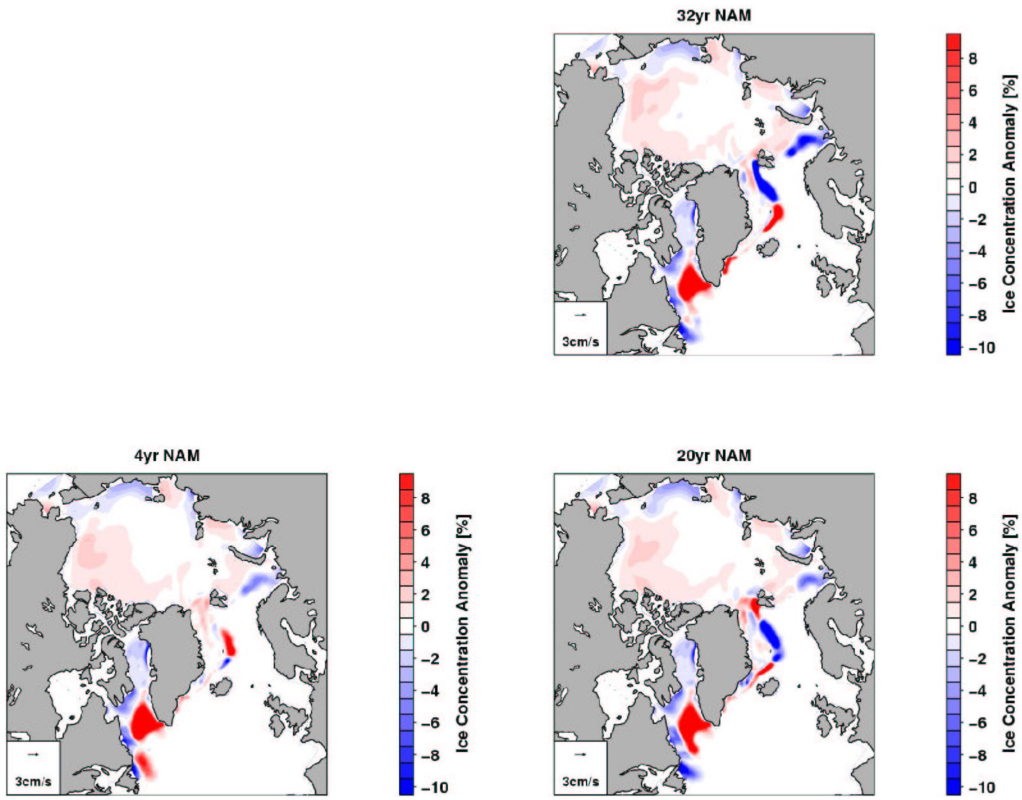

Figure 2: Winter (January to March) response of the sea ice concentrations in the numerical experiments. Shown are the idealized NAM periodicities 4, 20, and 32 years.

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