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Two wind-driven modes of winter sea ice variability in the Barents Sea

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A B S T R A C T

The interannual variability of the winter sea ice area in the Barents Sea is investigated using SMMR-SSM/I data and a coupled ocean–sea ice model over the period 1979–2012. Our analysis reveals that the sea ice area in the northern and eastern parts of the Barents Sea do not covary. This contrast in behavior allows us to associate two distinct modes of variability with these two regions, with the variability of the overall Barents Sea ice cover being predominantly captured by the northern mode. Both modes show a dominant, near in-phase response to the surface wind, both being associated with different spatial patterns. The northern mode emerges in response to northwesterly wind anomalies which favor the export of ice and surface polar water from the Arctic between Svalbard and Franz Josef Land. Atlantic Water temperature anomalies, formed concomitantly with northerly wind anomalies in the vicinity of the Barents Sea Opening, also influence the northern mode in the following winter. These temperature anomalies are linked to local convergence of the oceanic heat transport. The delayed influence of the ocean on the sea ice is found primarily in the northeastern Barents Sea and occurs through the re-emergence of the Atlantic water temperature anomalies at the surface in the following fall and winter. An ocean-to-atmosphere feedback initiated by October SST anomalies in the central Barents Sea is further identified. This feedback is hypothesized to enhance the sea ice response in the northern Barents Sea by promoting the formation of meridional wind anomalies. In contrast, the eastern mode of variability of the Barents Sea ice mainly responds to wind anomalies with a strong zonal component, and is less influenced by the Atlantic Water temperature variability than the northern mode. While our results clearly highlight a role of the ocean in the Barents Sea ice variability, this role appears to be more spatially restricted following the sudden northward retreat of the ice margin in 2004. In particular, the sudden drop in the sea ice area in 2004 could not be linked to earlier Atlantic water changes in the Barents Sea Opening.

1. Introduction

The summer Arctic sea ice cover has exhibited significant decline over recent decades, marked by the extreme events of September 2007 and 2012 (e.g Stroeve et al., 2012; Zhang et al., 2013). This retreat has been hypothesized to drive changes in the winter atmospheric circulation, especially by favoring the emergence of specific phases of the North Atlantic Oscillation (NAO) (e.g., Deser et al., 2007; Francis et al., 2009; Strong et al., 2009; Jaiser et al., 2012). In winter, the negative trend in the sea ice extent is smaller and more recent (Comiso, 2006); nevertheless changes in winter sea ice concentration have been shown to exert some influence on the atmospheric conditions (Alexander et al., 2004, Strong et al., 2009). The ice cover of the Barents Sea is, however, an exception to the seasonality in ice loss trends noted above. With the largest winter decrease among all the Arctic seas, the Barents Sea ice cover shows almost as strong a negative trend in winter as in the other seasons (Kern et al., 2010; Cavalieri and Parkinson, 2012). This remarkable retreat is thought to have favored cold winter conditions (Petoukhov and Semenov, 2010) or cold extremes (Gerber et al., 2014) over Europe, a link which may be enhanced in the future (Yang and Christensen, 2012). Winter sea ice concentration (SIC) anomalies in the Barents Sea also have the potential to generate large scale SLP anomalies (Liptak and Strong, 2014), with possible implications for coupled atmosphere–sea ice interactions (Yang and Yuan, 2014)

The first mode of variability of the Northern Hemisphere winter sea ice concentration is characterized by two dipoles in the marginal ice zones of the Atlantic and Pacific sectors (Deser et al., 2000; Ukita et al., 2007), which, at least in the last decades of the 20th century, was partly driven by the NAO (Deser et al., 2000; Rigor et al., 2002). Superimposed upon this large-scale pattern of variability, regional contrasts exist between the different Arctic seas. In particular, in the Barents Sea (see Fig. 1 for the geography of the region), the interannual variability of the winter sea ice extent can be related to a simultaneous pattern of SLP anomalies centered over the Greenland–Barents Seas (Sorteberg and

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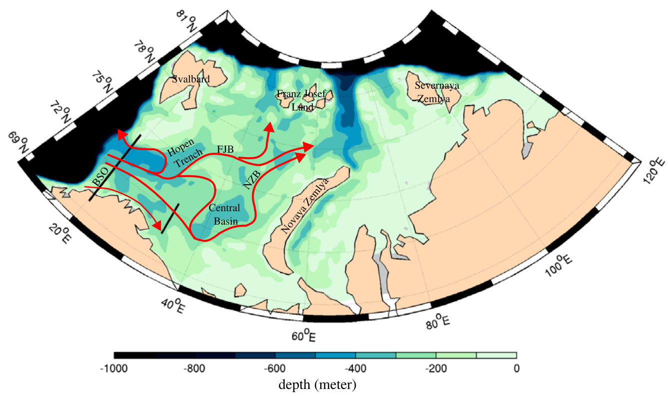

Fig. 1. Schematic of the circulation of Atlantic Water, showing the Novaya Zemlya Branch (NZB) and the Franz Josef Branch (FJB), and the bathymetry (in meters) in the Barents Sea. The black lines define the Barents Sea Opening (BSO) section (western line) and the Kola section (eastern line).

Kvingedal, 2006). In April, at the time of its maximum, the sea ice extent was found to be linked to an SLP dipole having one center of action over the Norwegian Sea and another over western Siberia (Pavlova et al., 2014). In both cases, these SLP anomalies generated northerly wind anomalies. While such anomalies were assumed to enhance the ice transport from the Arctic into the northern Barents Sea and favor ice production through cold air advection, their actual impact was not evaluated. However, several studies have highlighted the lagged effect of the surface wind on the interannual variability of the sea ice cover in the Barents Sea. According to Årthun et al. (2012) and Schlichtholz (2011), the highest correlation between the sea ice area and the surface wind occurs when the wind leads the sea ice by about a year. The lag suggests some implication of the ocean circulation and the associated heat transport in this relationship, and, in further support of this notion, at interannual to decadal time scales, Sorteberg and Kvingedal (2006) suggest that the storm activity in the western Nordic Seas could force a delayed response of the Barents Sea ice edge by driving changes in the Atlantic Water (AW) inflow through the Barents Sea opening (BSO). In all cases, however, the exact mechanisms and time scales involved in the response of the sea ice to the wind are not explicitly detailed.

The most natural link between the ocean and the sea ice in the Barents Sea is to be found in the AW flow entering the Barents Sea from the west and carrying along a large heat reservoir. While this AW loses most of its heat to the atmosphere upon crossing the Barents Sea, some of this heat is brought eastward and northward to the ice edge and can potentially affect sea ice through melting. Indeed, using a sea ice–ocean simulation, Årthun et al. (2012) found a robust anticorrelation (-0.63) between the annual mean heat transport at BSO and the Barents Sea ice cover when the transport led by 1 year. A similar result was found by Sandø et al. (2014) in a coupled model in which a reduction in sea ice growth was accompanied by increased heat transport to the western Barents Sea. These variations in heat transport, which are mainly due to changes in volume transport (Skagseth et al., 2008; Årthun et al., 2012), were hypothesized to drive the variability of the heat content in the southern Barents Sea; in contrast the ocean–atmosphere heat flux has been suggested to contribute only a small fraction to the heat content changes (Smedsrud et al., 2010). The link between the AW temperature and the sea ice cover in the Barents Sea was initially suggested, albeit qualitatively, by Loeng (1991). More recently, a seasonal analysis by Schlichtholz (2011) highlighted the prominent role of the Atlantic Water heat content in the BSO region on the Barents Sea ice cover, suggesting that the most influential changes in the AW occur in early summer, with these anomalies being able to explain 75% of the variance of the sea ice variability in the following winter. In contrast to Årthun et al., (2012), Nakamura et al. (2014) suggested that the temperature anomalies could be advected from the Atlantic Ocean by the mean circulation. It remains, however, unclear what processes actually drive the AW heat content in the Barents Sea and control the time lag of the sea ice response in different regions of the Barents Sea.

The aim of this study is to better understand the variability of the winter sea ice concentration in the Barents Sea and its links to the ocean and the atmosphere at the interannual time scale. We show that the variability in the northern Barents Sea can be distinguished from that in the southeastern Barents Sea. For each of the two modes, we first analyze the influence of the atmospheric forcing. In particular, we try to estimate the relative importance of the in-phase and lagged sea ice responses, as well as the relative contributions of the sea ice convergence and growth to these responses. In a second step, we analyze the impact of the ocean on the Barents Sea ice cover variability. To clarify the link with the heat transport through BSO, the influence of both the inflow and outflow branches of the transport is considered, as well as their link to the evolution of the sea ice and heat content in the interior Barents Sea. The paper is organized as follows: the observations and the model simulation are introduced in Section 2. In Section 3, the performance of the model in the Barents Sea is briefly evaluated. Results are presented in Section 4 and discussed in Section 5. Some conclusions are provided in Section 6

2. Data and methods

2.1. Observations

Monthly SIC estimated from passive microwave radiometer (SSM/I and SMMR) observations, gridded on a 25×25 km grid (National Snow and Ice Data Center; Comiso, 2000), are analyzed over the period 1979–2012. Surface atmosphere temperatures (SAT) and winds extracted from the ERA-I reanalysis (Dee et al., 2011) are used to characterize the atmospheric variability. The hydrographic conditions at the BSO are characterized using CTD data from the Oceanographic Database of the International Council for Exploration of the Sea (http://www.ices.dk). A time series of seasonal (winter is attributed to the JFM average and other seasons are then assigned accordingly) temperatures of the Atlantic Water core (Fig. 4) at the BSO (see Fig. 1 for the location of the section) is constructed by averaging the temperatures higher than 3 °C at depths below 50 m over a domain extending in latitude from 71.5°N to 73.5°N along the 19°E meridian and over one degree in longitude. In order to describe the oceanic variability farther east, seasonal temperature observations collected at the Kola section by PINRO (http://www.pinro.ru/) are used to form a time series of AW characteristics averaged between 50 and 200 m and 70.5° and 72.5°N. Finally, sea surface temperatures (SST) from the ERA-I reanalysis are used to characterize the ocean surface conditions associated with the Barents Sea ice distribution.

2.2. Model simulation

The outputs of a simulation with a regional coupled sea ice–ocean model are used to analyze the relationship between the SIC variability and both the sea ice growth and convergence and the AW properties and circulation. The sea ice–ocean model is based on NEMO (Nucleus for European Modelling of the Ocean) version 3.2 (Madec, 2008) coupled to the LIM2 (Fichefet and Morales Maqueda, 1997) sea ice model. The equations are discretized on 46 vertical levels with thickness varying from 6 m in the top layer to roughly 250 m at the deepest model level. Partial steps are used to