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Sea ice retreat and its impact on cyclone activity in the Nordic Seas: insights from coupled regional climate model simulations

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Abstract. The impact of sea ice concentration (SIC) changes in the Nordic Seas on the winter cyclone activity in the Nordic Seas is analyzed in 10-member ensemble simulations with the coupled Arctic atmosphere-ocean-sea ice model HIRHAM-NAOSIM for the 1979–2016 period. The analysis reveals that anomalously low SIC in the Nordic Seas leads to decrease in vertical atmospheric static stability, and thus may result in favorable conditions for cyclogenesis in the Nordic Seas. Our analysis also shows a statistically significant increase of cyclone frequency over the Nordic Seas under conditions of the low SIC regime.

1. Introduction

The beginning of the 21st century is characterized by increased frequency of extreme weather events both in the middle and high latitudes of the Northern Hemisphere, leading to negative economic, environmental and social consequences. Recent studies show that a rapid retreat of the sea ice in the Arctic, especially over the Barents-Kara Seas can lead to a change in atmospheric circulation both in the mid-latitudes [1,2] and at high latitudes of the Northern Hemisphere e.g., [3,4].

As a result, this may lead to an increase in the frequency of extreme weather events in the Arctic and Northern Eurasia e.g., [5,6] including intense cyclones/anticyclones and polar lows [7]. The study analyzes the changes in winter cyclone activity in the Nordic Seas, which is associated with the variability of sea ice concentration (SIC) in the Barents Sea. Particularly, we examine the role of anomalously low SIC in the Nordic Seas for changes of the cyclone activity characteristics and their related atmospheric conditions in the Nordic Seas with the use of 10-member ensemble simulations with the coupled Arctic atmosphere-ocean-sea ice model HIRHAM-NAOSIM. The study focuses on the winter (December-February) for the 1979–2016 period.

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2. Data and Methods

Our study region is the Nordic Seas including Barents and Kara Seas $(60-80^{\circ} \text{ N}, 20^{\circ} \text{W}-90^{\circ} \text{ E})$. Analyses are performed for the winter (here defined as the period from December to February) 1979-2016.

2.1 Model and reanalysis data

Here we use data from simulations with the most recent version of the coupled Arctic regional climate model (RCM) HIRHAM-NAOSIM [8]. This version consists of the atmosphere component HIRHAM5, which is set up for a domain that covers the whole Arctic north of about 60°N using a rotated spherical coordinate system with horizontal resolution of 0.25° (approximately 27 km). In the vertical, HIRHAM5 comprises 40 levels from about 10 m above the surface up to a pressure level of 10 hPa, with the highest vertical resolution in the lower troposphere. The ocean-sea ice component NAOSIM (North Atlantic/Arctic Ocean Sea-Ice Model) is based on the Geophysical Fluid Dynamics Laboratory Modular Ocean Model MOM-2 [9] and the dynamic-thermodynamic sea ice model described by [10] with substantial modifications of the ice thermodynamics introduced by [11]. NAOSIM is set up for a domain that encloses the entire Arctic Ocean, the Nordic seas, and the northern North Atlantic (with the southern model boundary at approximately 50°N) using a rotated spherical coordinate system with horizontal resolution of 1/12° (approximately 9 km). NAOSIM comprises 50 vertical levels at the maximum (depending on the ocean depth) with vertical resolution of 10 m in the upper ocean.

An ensemble of 10 hindcast simulations was carried out for the period 1979-2016. The RCM simulations were driven by ERA-Interim reanalysis data [12] at the lateral atmospheric boundaries and all surface boundaries outside the coupling domain. A detailed description of both the model and the ensemble simulations is given by [8].

2.2 Cyclone identification

An algorithm of cyclone identification [13,14,15] is applied on 6-hourly mean sea level pressure (MSLP) data from the ensemble simulations and ERA-Interim reanalysis. The algorithm is based on minima in the MSLP fields and has been applied in several other studies that investigated changes in cyclone activity in extratropical and high latitudes [16,17,18,19] including polar mesocyclones [20]. Cyclone frequency, depth (intensity) and size (radius) is analyzed. The cyclone frequency is defined as the number of cyclone events per season. The cyclone depth (intensity) is determined as the difference between the minimum central pressure in the cyclone and the outermost closed isobar. The cyclone size (radius) is determined as the average distance from the geometric center to the outermost closed isobar. To map spatial patterns of cyclone characteristics we use a grid with circular cells of a 2.5° latitude radius. We use 6-hourly MSLP for cyclone identification.

2.3 Composite analysis

To assess atmospheric effects on SIC anomalies in the Nordic Seas, cases with SIC lower or higher of one standard deviation of the ensemble average SIC in the Nordic Seas were selected. In total, the composite analysis comprises 37 cases for low and high SIC. For the difference between the corresponding composites ("Low minus high SIC"), the monthly average fields of near-surface air temperature, MSLP and atmospheric static stability were calculated for the period 1979–2016.

3. Results

3.1 Climatology and variability of the cyclone activity in the Nordic Seas

Before investigating the response of cyclone activity in the Nordic Seas to sea ice variability, it is informative to assess and describe the ability of the RCM to represent the climatology and variability of the cyclone activity in the Nordic Seas.

The HIRHAM-NAOSIM ensemble simulations well capture the mean and interannual variability

of cyclone characteristics in the Nordic Seas derived from their forcing dataset, the ERA-Interim reanalysis (Table 1; Fig. 1). The winter mean frequency of cyclones in HIRHAM–NAOSIM is lower than that in the ERA-Interim reanalysis, which could be related to the poor representation of the polar mesocyclones in the model [20]. Therefore, along with the cyclone activity analysis, we also apply static-stability criterion for polar lows (section 3.2), given by a difference between the sea-surface temperature (SST) and the overlying atmospheric temperature (500 hPa) [21].

Table 1 Cyclone mean characteristics (and standard deviation across the 10 model simulations) from model ensemble mean and ERA-Interim reanalysis for the Nordic Seas for the winter 1979-2016.

Data	Frequency, per season	Depth, hPa	Size (radius), km
HIRHAM-NAOSIM	139.8±1.1	7.1±0.1	364±2.3
ERA-Interim	163.6	9.1	458.1



Figure 1. The cyclone frequency variability from ensemble mean (mean across 10 simulations from HIRHAM-NAOSIM with standard deviations; black line) and ERA-Interim reanalysis (red dashed line) for winter over the Nordic seas.

Detailed statistical analysis of the cyclone characteristics in the Nordic Seas is presented in Table 1 for both HIRHAM–NAOSIM simulations and the ERA-Interim reanalysis. The RCM shows lower mean depth and size relative to the reanalysis, which could be associated with a higher spatial resolution in the simulations.

3.2 Changes in atmospheric conditions in the Nordic Seas

SIC changes are strongly linked with the interannual variability of the near-surface air temperature over the Nordic Seas. In order to assess the contribution of variations of SIC in the Nordic Seas to changes in atmospheric conditions over the Nordic Seas, composite differences between low and high SIC regimes in winter for near-surface air temperature and MSLP over the Nordic Seas including Barents and Kara Seas are presented in Fig. 2.





Figure 2. Differences of the composites analysis of the (a) sea ice concentration, (b) near-surface temperature (K), (c) MSLP (hPa) and (d) static stability (K) between the anomalously high and low SIC ("low minus high SIC") over the Nordic Seas. Black dots indicate statistical significance (p < 0.05)

The figure indicates that decreased SIC in the Nordic Seas leads to increased oceanic heat release into the atmosphere (Fig. 2) and this increases the near-surface air temperature of up to 4 K and reduces the MSLP of up to -2 hPa, indicating more cyclonic/less anticyclonic atmospheric circulation over the Nordic Seas. Thus, the model simulations show the important role SIC changes in the Nordic Seas in the formation of regional variability in the near-surface air temperature and mean sea level pressure in winter.

3.3 Changes in vertical atmospheric static stability in the Nordic Seas

We calculated the vertical temperature difference between SST and T500 as an indicator for the evolution of vertical atmospheric static stability [21]. According to Fig. 2, the decrease of SIC in the Nordic Seas lead to near-surface warming and an increase in the turbulent heat exchange between the ocean and the atmosphere. This lead to change in vertical atmospheric static stability. It should be noted that positive differences indicate on decrease of static stability. Indeed, a decrease in the atmospheric static stability is pronounced (about 1 K) in the southern part of the Barents Sea, as well as in the Fram Strait. In contrast, an increase in the static stability of the atmosphere is noted over the northern Barents Sea (Fig. 2d).

A decrease of static stability over the specified regions may create more favorable conditions to form intense cyclones, especially polar mesocyclones (e.g. polar lows) [22, 23] and also may impact the cyclone size and intensity [24]. In next section, we analyze changes in cyclone activity induced by SIC variability.

3.4 Changes in cyclone activity in the Nordic Seas

Fig. 3 shows the impact of anomalously low SIC on cyclone frequency. We find a significant increase in the cyclone frequency over the Barents Sea and Fram Strait, and insignificant decrease over the Kara Sea. Increase of the cyclone frequency is also observed over the Greenland Sea, especially in its north part. Wherein the areas of cyclone frequency increase is associated with areas of decrease of atmospheric static stability. Therefore, we can conclude that a decrease of static stability may create more favorable conditions to form cyclones, especially polar mesocyclones.



Figure 3. Differences of the composites analysis of the cyclone frequency between the anomalously high and low SIC ("low minus high SIC") over the Nordic Seas. Black dots indicate statistical significance (p < 0.05)

4. Summary and conclusion

We analyzed the impact of the variations of the sea ice concentration on winter cyclone activity in the Nordic Seas using 10-member ensemble hindcast simulations from the coupled regional climate model HIRHAM-NAOSIM performed for the 1979–2016 period. Sea ice retreat in the Barents Sea may lead to increased near-surface air temperature and, therefore, decreased regional static stability. Decrease in static stability is associated with changes of cyclone activity characteristics, especially polar

mesocyclones [23]. We note a decrease of MSLP over the Nordic Seas and increasing cyclone frequency over the Barents Sea and Fram Strait.

Our results are in accordance with others: In [3], a significant relationship was found between changes in the regime of sea ice and cyclone activity over the Barents Sea during the cold season. The studies [3, 25] showed that a decrease of Arctic sea ice area contributes to a decreased static stability of the atmosphere, creating conditions for cyclogenesis and the development of activity of Arctic mesocyclones [21]. The results are consistent with the conclusions from studies of the effect of sea ice changes in the Barents Sea on atmospheric circulation at high Northern Hemisphere latitudes [25, 26, 27].

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