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Can preferred atmospheric circulation patterns over the North-Atlantic-Eurasian region be associated with arctic sea ice loss?

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A B S T R A C T

In the framework of atmospheric circulation regimes, we study whether the recent Arctic sea ice loss and Arctic Amplification are associated with changes in the frequency of occurrence of preferred atmospheric circulation patterns during the extended winter season from December to March. To determine regimes we applied a cluster analysis to sea-level pressure fields from reanalysis data and output from an atmospheric general circulation model. The specific set up of the two analyzed model simulations for low and high ice conditions allows for attributing differences between the simulations to the prescribed sea ice changes only. The reanalysis data revealed two circulation patterns that occur more frequently for low Arctic sea ice conditions: a Scandinavian blocking in December and January and a negative North Atlantic Oscillation pattern in February and March. An analysis of related patterns of synoptic-scale activity and 2 m temperatures provides a synoptic interpretation of the corresponding large-scale regimes. The regimes that occur more frequently for low sea ice conditions are resembled reasonably well by the model simulations. Based on those results we conclude that the detected changes in the frequency of occurrence of large-scale circulation patterns can be associated with changes in Arctic sea ice conditions.

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1. Introduction

Over the last decades, the Arctic sea ice has declined throughout the year, but most strongly in late summer (see e.g. http://www.meereisportal.de/en/seaicetrends/monthly-mean-arctic). In September, the Arctic sea ice has declined by 12% per decade since the beginning of satellite measurements in 1979 (Stroeve et al., 2011). In the same period, the winter temperatures in the Arctic have risen by 1.6K/decade, which is stronger than anywhere else on the Northern Hemisphere (Screen and Simmonds, 2010). The sea ice decline exerts a strong impact on the atmospheric circulation. Low sea ice conditions in autumn often result in cold Eurasian winters, extreme snowfall, strong blockings and a negative phase of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) in late winter (e.g. Jaiser et al., 2012; Cohen et al., 2012; Nakamura et al., 2015).

Many studies analyzed the impact of autumn sea ice conditions on the winter circulation. Francis et al. (2009) investigated the dynamical response to the Arctic sea ice loss, which becomes detectable in terms of modifications of Rossby waves and the jet stream. They showed that the reduced sea ice leads to a weakening of the polar jet stream. Rossby waves get higher amplitudes and move slower which favors the development of blockings and extreme weather such as cold air outbreaks at the Eastern Continents (Francis and Vavrus, 2012). Honda et al. (2009) described the excitation of an atmospheric Rossby wave due to heating anomalies over the Barents/Kara Seas (BKS) in November, which strengthens the development of the Siberian high. Studies by Petoukhov and Semenov (2010), Inoue et al. (2012), Mori et al. (2014), and Overland (2016) showed that low sea ice conditions in autumn are linked to a strong Siberian high and cold Eurasian winters. Additional moisture provided from more opened Arctic Ocean leads to increased snow fall over Eurasia in autumn and winter as pointed out by Cohen et al. (2012), Liu et al. (2012), and Wegmann et al. (2015). Vihma (2014) summarized the interrelation between Arctic sea ice and large-scale circulation anomalies, which includes a high over Eurasia, a high over Western and a low over Eastern North America in winter. Overland and Wang (2010) showed that

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the frequency of the Arctic Dipole, a more meridional pattern, appears more often in the 21st century compared to the 20th century which can be linked to the Arctic sea ice reduction.

Among others, Jaiser et al. (2012) pointed out that sea ice changes can impact the dominant pattern of the large-scale extra-tropical circulation, namely the AO. Thereby, low sea ice conditions foster a shift towards the negative phase of the AO. Kim et al. (2014), Nakamura et al. (2015, 2016), and Jaiser et al. (2016) also focused on the modulation of the AO and NAO following Arctic sea ice loss. They confirmed that low sea ice conditions favor a negative AO/NAO phase through coupling with the stratospheric polar vortex.

Most studies analyze the seasonal winter response to low sea ice conditions. The dynamical response, however, varies greatly from month to month (Deser and Phillips, 2009; García-Serrano et al., 2016). Recent studies by e.g. Cohen et al. (2014), Jaiser et al. (2016), Nakamura et al. (2015) propose a temporal evolution of pathways for Arctic-midlatitude linkages from autumn to winter, which requires studying the related processes with higher temporal resolution.

It has long been recognized that the concept of atmospheric circulation regimes is useful in understanding main aspects of the low-frequency variability of the extra-tropical atmospheric circulation. Today it is common to describe this low-frequency variability in terms of a few preferred and recurrent circulation patterns called circulation regimes (see review by Hannachi et al., 2017). Within this conceptual framework, low-frequency variability could arise owing to transitions between distinct atmospheric circulation regimes.

Furthermore, the frequency of occurrence of preferred atmospheric circulation regimes is influenced by the external forcing factors such as other components of the climate system (e.g., the forcing of large-scale waves by anomalies of the sea surface temperature in the tropics; see Hoskins and Karoly, 1981) or anthropogenic forcing. Palmer (1993, 1999) introduced a dynamical paradigm for climate change. According to this paradigm, a weak external forcing does not change the structure and number of atmospheric regimes, but instead changes the frequency of occurrence of the regimes. This determines, at least partly, the time-mean response of the atmospheric flow to the external forcing. On the other hand, strong external forcing factors can lead to changes in the number and structure of circulation regimes as proven in several studies, e.g. by Kageyama et al. (1999) and Handorf et al. (2009).

Stephenson et al. (2004) and Hannachi et al. (2017) reviewed many studies that have shown the division of the Northern Hemispheric boreal winter flow into two to six preferred circulation regimes under present-day conditions based on daily and monthly data. Using the paradigm of circulation regimes, we are going to study whether the strong Arctic sea ice loss in the last decades can act as an additional external forcing to the atmosphere, which influences the frequency of occurrence of the preferred circulation regimes and leads to a more frequent occurrence of particular patterns.

We determine preferred atmospheric circulation patterns based on sea-level pressure (SLP) fields over the North-Atlantic-Eurasian region of the Northern Hemisphere (30° − 90°N, 90°W-90° E) for winter (DJFM) and analyze changes in the frequency of occurrence in association with different Arctic sea ice conditions. The North-Atlantic-Eurasian region was chosen because of the evidence from observational and modelling studies for dynamical pathways and a monthly progression of processes connecting Arctic sea ice anomalies over the BKS in late summer and autumn to cold Eurasia temperatures in mid-to late winter (e.g. Honda et al., 2009; Cohen et al., 2014; Overland et al., 2015). We analyze the related patterns of synoptic-scale activity and 2 m temperatures to characterize the circulation regimes with respect to synoptic-scale processes. We argue for the association with Arctic sea ice changes is reasoned by the comparison of results from reanalysis data with the output from the two atmospheric general circulation model (AGCM) simulations which differ only in terms of the Arctic sea ice conditions. The paper is organized as follows: Section 2 describes the used data sets and model simulations and the regime analysis method. Section 3 explains the results of the regime analysis for reanalysis and model data, whereas Section 4 provides the discussion of the results and completes with conclusion and outlook.

2. Methods

2.1. Data

We make a use of the recent ERA-Interim reanalysis data provided by the ECMWF (Dee et al., 2011). The data is computed at the T255 spectral resolution (approximately 0.75°), while we use interpolated daily output at the 2° horizontal resolution from 1979 to 2014. Based on the Arctic sea ice concentration and the Arctic sea ice index, provided by the National Snow and Ice Data Center (Fetterer and Knowles, 2004), it is possible to divide the ERA-Interim data into high and low sea ice concentration periods as in Jaiser et al. (2016). The high ice period starts in 1979 and ends in winter 1999/2000, whereas the low ice period continues from winter 2000/2001 until 2014. An inspection of the sea ice anomaly maps reveals large sea-ice reductions between the low and high ice period, but with regional differences. In September, sea ice is reduced over the Beaufort, East Siberian, Laptev, Kara and northern Barents Sea, whereas sea-ice retreat is located in the Barents-Kara Sea and the Chukchi Sea/Bering Strait in November, and in the Barents Sea, the Nordic Sea, and the Sea of Okhotsk in January (cf. Fig. 1 in Nakamura et al. (2015) and Fig. 1 in Jaiser et al. (2016)).

The model simulations have been run with the atmospheric general circulation model for Earth Simulator (AFES) with a spectral resolution of T79 described by Nakamura et al. (2015). They have performed a sensitivity experiment with two perpetual model runs, each with an integration time of 60 years. The first experiment is labeled CNTL and represents high sea ice conditions by using the

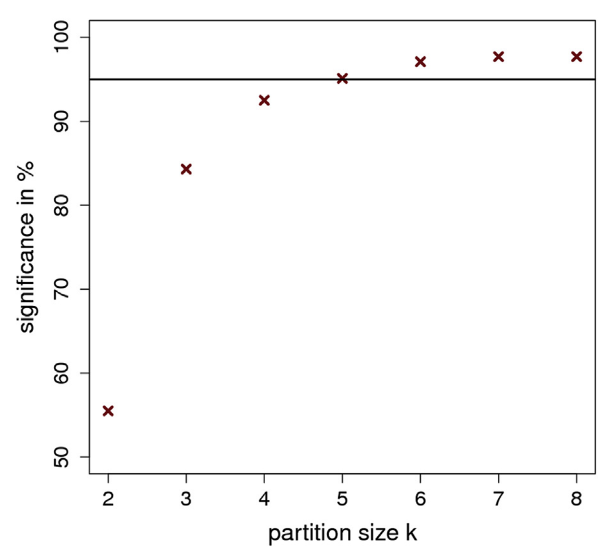

Fig. 1. Significance of the clustering of the ERA-Interim daily SLP fields over the North-Atlantic-Eurasian region for DJFM for k = 2 … 8 clusters. k = 5 is the smallest significant partition size which is significant at the 95% level (black line) and therefore used as cluster size.

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