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EXTREMELY STRONG WINDS AND WEATHER PATTERNS OVER ARCTIC SEAS

ABSTRACT. Strong wind is the main cause of storm sea waves. In order to minimize risks and damages from this phenomenon in the future, precise projections of future climate conditions are necessary. Extremely high wind speed events in the 20th - 21st centuries over Arctic seas were investigated using ERA-Interim reanalysis data (1981-2010) and CMIP5 models ensemble (RCP8.5 scenario, 2005-2100). Two different approaches were applied to investigate extreme wind events. The first one is traditional and involves direct analysis of wind speed data. It was used for the entire area of the Arctic seas. The second approach is based on an assumption that local and mesoscale extreme weather events are connected with large-scale synoptic processes. As it was shown in previous studies for the Black, Caspian and Baltic seas, it is possible to make climate projection of sea storm waves indirectly, studying the heterogeneity of sea level atmospheric pressure (SLP) fields that are the main factors of strong wind speed and wind waves. In this case, it is not necessary to run long-term simulations with a sea wave model to predict storm activity for the future climate. It is possible to analyze projections of storm SLP fields that are predicted by climate models much better than the wind speed required for a wave model. This method was implemented for the high wind speed events over the Barents Sea. Four major types of SLP fields accompanying high wind speed were revealed for the modern climate. It was shown that the frequency of their occurrence is expected to increase by the end of the 21st century.

KEY WORDS: wind speed extremes, global warming, Arctic, weather patterns, ocean-atmosphere interaction

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INTRODUCTION

Extreme value analysis is of the great importance in different fundamental and applied scientific areas. High wind speed is one of environmental extremes influencing wide spectrum of human life and activities both from positive and negative points of view. Extreme winds over the seas are very dangerous not only by themselves but they may be considered as a predictor of

storm waves and shore erosion processes. Wind strength and wave energy should be taken into account in shipping and marine engineering (e.g., structural reliability and strength of materials of ships, sea and coastal constructions etc.). On the other hand, wind and wave power can be used for electricity production.

High wind speeds due to cyclonic activity in the Arctic region, are typically observed

there all year around and especially, in cold season (Climate of Russia 2001). Decrease of sea ice coverage during last decades is resulted in lowering of sea surface roughness, and, thus, in higher wind speed and storm waves. The reports of Intergovernmental Panel on Climate Changes (IPCC 2013) showed the prevailed positive tendency of modern wind speed (both mean and extreme) over the Arctic in the areas situated to the north of 70-75 N latitude.

The severe climate of the Arctic region with high cloud cover makes difficult to use remote sensing data for direct atmosphere and ocean observations. In this case the weather and climate models can help to understand the present atmosphere-ocean interaction processes and there physical mechanisms. Earth system modelling is an important tool for future climate projection of extreme weather events that should help managing the risks of extreme events and disasters to advance climate change adaptation (IPCC 2012).

To derive the present and future climate conditions in our study we used the reanalysis and climate model data. Obtained results can be divided into two parts. One is based on direct evaluation of wind speed extremes for the entire Arctic from reanalysis and modeling data. In the second part the main attention is paid to the Barents Sea area. It is well known, that the significant changes of hydrometeorological parameters over the last decades are characterized by increase of strong wind frequency in the Arctic. In our study we analyzed the weather pattern accompanying strong winds, that was described from analysis of the atmospheric sea level pressure (SLP) to derive the frequency of high wind speed events. Such method is appropriate for regional studies, in which the spatial wind pattern is closely associated with regional synoptic processes and the atmospheric pressure field at sea level. Weather conditions accompanying strong winds over the Barents sea are investigated in our study both for the present climate and projected future climate conditions in the 21st century.

MATERIALS AND METHODS

For the first part of our study we used 6-hour wind vector components: u (zonal) and v (meridional). The ERA-Interim reanalysis database (Dee et al. 2014) for period of 1981-2010 with grid spacing 0.75x0.75 degree of latitude and longitude was used to derive the present-day weather conditions. As it was shown by Lindsay et al. (2014), this reanalysis provides rather realistic prediction of the wind regime within the Arctic region. It is obvious, that some short-term wind speed extremes cannot be captured with 6-hour time step, but it is completely sufficient to analyze the persistent and constant strong winds causing large-scale sea storms.

For the modern climate the data set of numerical experiments named *Historical* was taken. To derive the future climate conditions we used the results obtained within the Climate Modeling Intercomparison Project CMIP5 (Taylor et al. 2012). The RCP8.5 emission scenario (Moss et al., 2008) supposing the strongest radiation influence of anthropogenic greenhouse gases in comparing to other scenarios for period 2005-2100 was used.

To analyze the spatial wins pattern over whole Arctic we used the results of 14 climate models having data with 6-hours time resolution available in open access (ACCESS1-0, ACCESS1-3, bcc-csm1-1, BNU-ESM, CMCC-CESM, CMCC-CMS, CanESM2, HadGEM2-CC, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MPI-ESM-LR, MPI-ESM-MR).

To derive the spatial wind distribution over the Barents Sea, mean daily values of wind speed and atmospheric sea level pressure were used: they were taken from ERA-Interim reanalysis (0.75x0.75 degrees) and modeling results of CMIP5 (*Historical* and RCP8.5 experiments). For daily mean values there are more data in CMIP5 data base. That's why we analyzed the simulation results of 27 climate models (ACCESS1.0, bcc-csm1-1, BNU-ESM, CanESM2, CCSM4, CESM1-

BGC, CESM1-CAM5, CMCC-CESM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3.6.0, GFDL-CM3, GFDL-ESM2G, GISS-E2-H, GISS-E2-R, INMCM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, MRI-ESM1, NorESM1-M). All model results were interpolated on the grid with the same size of grid cells as reanalysis data had.

Projections of extreme wind speed over the Barents Sea are based on the connection between large-scale circulation and environmental variables and relied upon the “environment to circulation” method (Huth et al. 2008). Unlike the alternative the “circulation to environment” method – which is based on classification of all circulation types with particular attention on calculation of the frequency of extreme events, we focused on investigation and classification of those weather patterns that are associated with extreme events. Nowadays, both approaches are widely used in various fields of the atmospheric sciences. An extensive review of existing classification methods was performed by Huth et al. (2008). For example, there are numerous studies based on the “environment – to circulation” approach (Demuzere et al. 2011; Surkova et al. 2013, Cannon et al. 2002; Yarnal 1993; Brisson et al. 2010; Corte-Real et al. 1998, 1999; Santos et al. 2005; Cassou et al. 2010; Stahl et al. 2006; Philipp et al. 2010; Solman, Menendez 2003). The alternative “circulation – to environment” method is successfully implemented within the framework of the COST733 action (<http://cost733.met.no>) entitled “The harmonization and application of weather types classifications for European regions”.

Atmospheric circulation types for extreme wind episodes over the Barents Sea were obtained by cluster analysis preprocessed by the Empirical Orthogonal Function (EOF) analysis to reveal leading modes that determine their spatial variability. For each case a dataset was prepared which consists of 30 daily SLP grids including the storm day and the 15 days prior and

14 days after. After EOF decomposition of daily SLP grids, the first three eigenvectors explaining more than 70% of the variance were retained, thus filtering any high-frequency perturbations (SLP_{EOF}). SLP_{EOF} fields for storm days were used as input variables to classify circulation patterns.

Weather regimes are traditionally characterized using cluster analysis or classification methods (Wilks 1995). Those organize pressure maps into nested sequences of clusters forming a growing tree association (hierarchical method, (e.g. Cheng, Wallace 1993), or iteratively perform the classification from predefined initial states randomly selected from the total sample, according to a given number of cluster k (partition method, e.g. the k -means approach (e.g. Michelangeli et al. 1995)). More complex approaches, e.g. the Self-Organizing Map method arising from the field of artificial neural network (Johnson et al. 2008) have been also recently proposed. From statistical or technical point of view, weather regime types are thus classes of atmospheric circulation patterns gathered together from a similarity criterion. Those classes are defined by their mean conditions, or centroids, by their variance and by their frequency of occurrence.

Definition of circulation types was provided using the k -mean cluster analysis. When choosing this method, we followed the experience of the previous studies, successfully applied for classification of pressure fields (Cassou 2010). The k -means algorithm starts with a preset number of clusters k and then moves objects between clusters with the goal of, first, minimizing the variance within clusters and, second, maximizing the variance between clusters. Cluster centroids (ensemble means of cluster members) were constructed for each circulation type by averaging the SLP grids of all days that belonged to the same circulation type. It was assumed that four clusters will be sufficient for our study.

Projection of the frequency of extreme wind episodes was provided from

correlation analysis of individual “extreme” SLP fields and daily SLP for each climate model. The day is classified as “extreme” wind day if the correlation coefficient was more than threshold value. The threshold value was estimated individually for each model by comparing the frequency of modeled extreme days in *Historical* experiment and reanalysis data for the present climate.

To compare mean SLP-fields simulated by each model during warm and cold seasons (1981-2010) with a reference field derived from ERA-Interim reanalysis data the Taylor diagram was used (Taylor 2001). The diagram showed relatively good correlation between all considered fields.

RESULTS AND DISCUSSION

An analysis of extreme wind speeds for the RCP8.5 scenario showed that for the large part of Arctic seas there is a positive response to the global warming of the 21st century (Fig.1). Opposite trends were detected in the north Atlantic regions and in some parts of the Barents Sea. Similar trends for the modern climate were discussed in the IPCC report (IPCC 2013) in respect of the mean wind speeds in high latitudes of the Arctic. It can be expected

that these trends can be prolonged and intensified in case of further global warming. As it was shown in our previous study (Surkova, Krylov 2017), based on the results of future climate simulations made in the framework of CMIP5, this region is rather vulnerable to the global warming and their response is differed significantly from other Arctic regions. Due to complex nonlinear connections in the ocean-atmosphere system it is not easy to explain such specific response of different climate characteristics in the Atlantic part of Arctic (Norwegian and Barents seas). One of possible reason can be related to the expected weakening of meridional water transfer from tropical to high latitudes (Volodin et al. 2013). Another reason may be related to the change in cyclonic activity in this region. But at the present time there is no common opinion about the direction and intensity of these changes as well as about their consequences.

Another outcome of the study is that the positive mean and extreme wind speed anomalies provided by most models are confined to the sea boundaries. The exceptions to this are the North Atlantic and adjacent seas where there is an active heat transport from low latitudes.

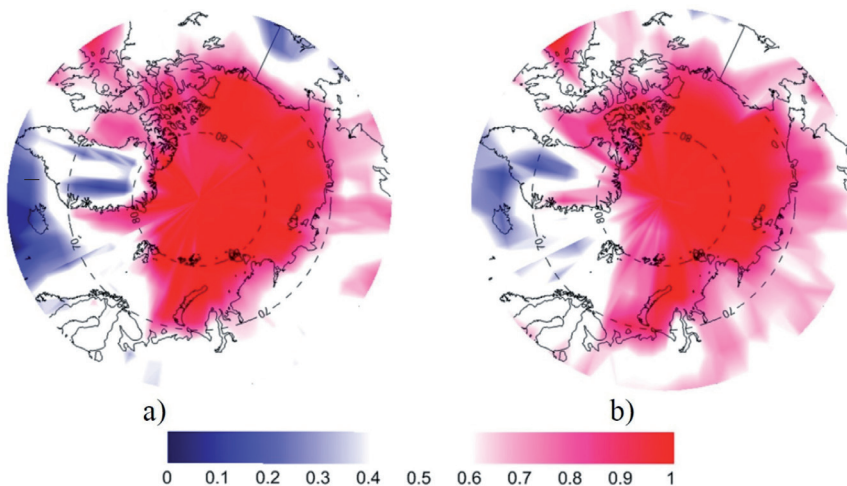


Fig. 1. The tendency of the anomalies of wind speed quantiles (2081-2100 minus 1981-2010): V_{50} (left panel), V_{99} (right panel) according to CMIP5 model ensemble (scenario, RCP8.5). Red-colored values (0.5 – 1) correspond to increased quantiles (V_{50} , V_{99}), and blue-colored range (0 – 0.5) - to decreased quantiles (V_{50} , V_{99}) for the majority of the models, respectively

The same pattern for the Arctic is also observed at the present time – a decrease in the wind speed over the land and a certain increase to the north of 70–75 N. Among the possible reasons for this pattern there is an estimated decrease in the area of sea ice in the Arctic. Following the RCP8.5 scenario, in the warmest months of the year Arctic sea ice can completely disappear for some time (IPCC 2013). Other reasons may be related to the changes of atmospheric baroclinity, restructuring of atmospheric circulation, the displacement of cyclone tracks, etc.

Considering that the values of both the medians and 99th quantiles tend to grow (as well as the 75th and 95th quantiles), we can assume that under RCP8.5 scenario, the entire distribution function of SLP is shifted to eastern Arctic seas. At the same time, the decrease of both currently observed wind speed over land and the wind speed projected by climate models under global warming scenarios have to be pointed out.

Classification of the SLP data for the days with extreme wind speed allows us to create composite maps for each of the four distinguished types (Fig. 2).

Type I is characterized by the most uniform field of the anomalies of atmospheric pressure in comparison with other types (deviation from the mean pressure field does not exceed 12 hPa). The negative anomaly occupies almost the entire territory of the Barents Sea and is most pronounced in the Spitsbergen area, while over the continent the pressure is above the mean values. In this type of synoptic situation, storm wind is usually observed at the southern periphery of cyclones rapidly moving to the east from the North Atlantic (Greenland region) in the direction of the Franz Josef Land. This is one of the most common types of synoptic situations (as well as type 2), causing high values of wind speed in the Barents Sea as it was shown also in the previous studies (Hydrometeorology 1990; Myslenkov et al. 2015).

Type II is distinguished by large anomalies of the pressure field comparing with type I. Two distinct baric formations are clearly visible on the map: the cyclone that emerges into the Barents Sea from the North Atlantic and a powerful anticyclone whose center is located above the Novaya Zemlya archipelago and the eastern part of the Kara Sea. The isolines are oriented almost meridionally. This situation is most consistent with cases when high wind speeds are associated with the southern wind direction, as indicated, for example, by Surkova et al. (2015), where it is noted that the Barents Sea has two priority wind direction sectors, where wind speed reached maximum values – the western and southern ones.

A distinctive feature of type III is a deep cyclone (the pressure gradient from the periphery to the center is about 30 hPa), shifting eastward from Iceland to Scandinavia. Strong east and north-east winds are observed on the eastern periphery of this baric formation. The frequency of this type recurrence is slightly lower than for the first or second types of synoptic situations.

Type IV is characterized by the presence of a particularly deep cyclone (the pressure at the center of the cyclone is 35 hPa below the average). The center of the cyclone is shifted eastward than in type III, and there is no positive anomaly in the pressure field above the north of the European territory of Russia. The frequency of this type is much lower than of the other types. Such circulation can be formed due to the regeneration of the cyclone on the Arctic front.

The right panel of Fig. 2 shows the change in the frequency trend for each type of circulation according to the climate projection based on the RCP8.5 scenario until the end of the 21st century. The results show that the frequency of extreme wind speed events will be increased. The main contribution to this growth will be made by the I and III types of SLP distribution (Fig. 3).

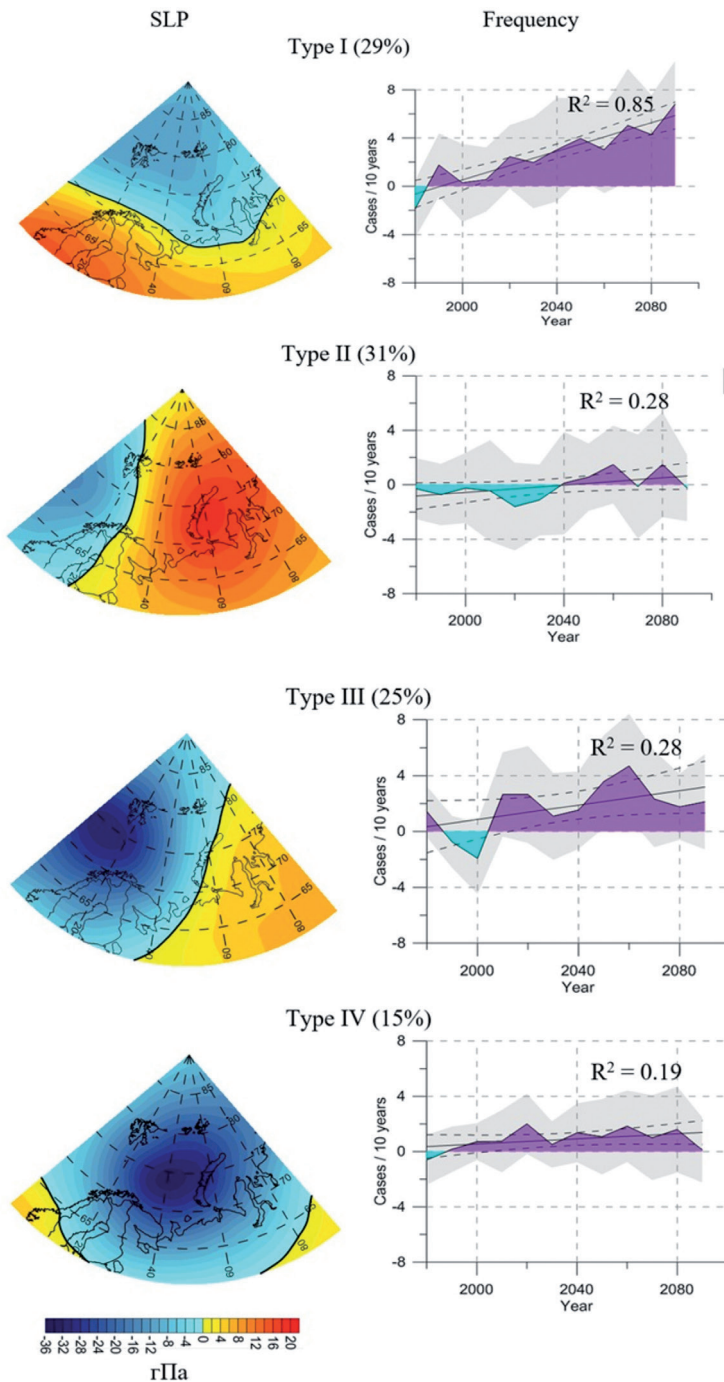


Fig. 2. Weather patterns accompanying strong winds over the Barents Sea (60–90 N, 0–90 E). Left panel – composite maps of SLP pattern types as deviations from climate means, the frequency of different types of weather patterns are given in brackets. Blue-colored areas correspond to negative anomalies (contour lines are drawn for each 2 hPa). Right panel shows temporal variability of decadal frequency of extreme wind speed events as deviation from the long-term mean (1981–2005). Light grey shows the differences between models

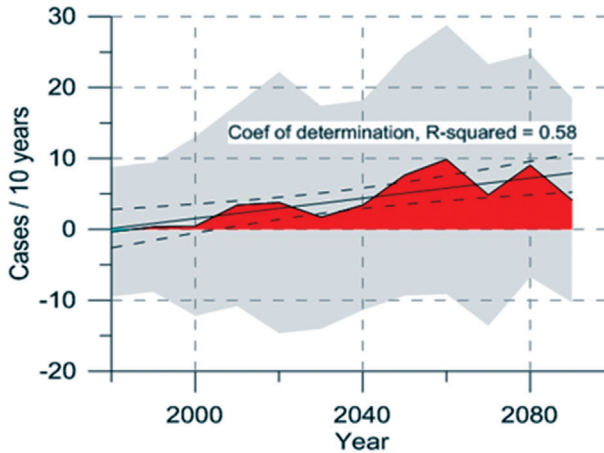


Fig. 3. Interannual variability of synoptic patterns characterized by extremely high wind speed over the Barents seas calculated by model ensemble for all clusters (1-4)

CONCLUSIONS

In this study we present the possible trends of extreme wind speed changes during the 21st century over Arctic using the results of climate model simulations. Very high temporal resolution (6 hours) allowed us to make consistent comparisons across the Arctic. It was shown that the wind speed extremes can shift towards higher values almost everywhere in the Arctic region. Analysis of daily mean wind speed extremes and the corresponding weather patterns allowed to conclude that the global warming projected by global climate models under scenario RCP8.5 will result in increase of both average and extremely high wind speeds by the end of the 21st century over the entire Arctic area. In addition, we show that the frequency of weather patterns over the Barents Sea initiating and accompanying extreme daily mean winds for selected scenario will be higher than under present climate conditions. This study improves our understanding about the spatial patterns of projected warming and its possible influence on changes of extreme winds. Nevertheless,

the problems to explain the mechanisms of the climate system functioning still remain. Because of the complexity and nonlinearity of interaction between the atmosphere and the ocean, as well as teleconnections within the atmosphere itself, it is not easy to explain the reasons of increase of extreme wind speeds and the frequency of such episodes by the end of the 21st century in the Arctic.

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