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Wind Energy Potential in the Arctic and Subarctic Regions and Its Projected Change in the 21st Century Based on Regional Climate Model Simulations

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Abstract—Quantitative estimates of changes in wind energy resources in the Arctic were obtained using the RCA4 regional climate model under the RCP4.5 and RCP8.5 climate change scenarios for 2006–2099. The wind power density proportional to cubic wind speed was analyzed. The procedure for the model near-surface wind speed bias correction using ERA5 data as a reference with subsequent extrapolation of wind speed to the turbine height was applied to estimate the wind power density (WPD). According to the RCA4 simulations for the 21st century under both anthropogenic forcing scenarios, a noticeable increase in the WPD was noted, in particular, over the Barents, Kara, and Chukchi seas in winter. In summer, a general increase in the WPD is manifested over the Arctic Ocean. The changes are more significant under the RCP8.5 scenario with high anthropogenic forcing for the 21st century. According to model projections, an increase in the interdaily WPD variations does not generally lead to the deviations of wind speed to the values at which the operation of wind generators is unfeasible.

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Keywords: Wind energy resources, near-surface wind speed, sea ice, Arctic, climate change, climate modeling, reanalysis

INTRODUCTION

An accelerated warming in the Arctic is accompanied by the unprecedented sea ice loss [1, 2, 8, 26]. Climate change makes the Arctic more accessable for the economic development: navigation, mining, and other kinds of activities, in particular, the energy production from renewable sources are becoming easier in the Arctic regions [4, 12]. One of the most available and demanded sources of energy is wind energy. Wind energy is referred to so called "pure" or "green" energy, since it is characterized by almost zero greenhouse gas emissions of the electricity generation. This creates potential for the active development and use of wind energy resources in the Arctic. Along the Arctic coast, wind farms are actively constructed, and related infrastructure is developed [5, 11].

Studying the spatiotemporal variability of near-surface wind characteristics is of special importance for assessing the wind energy potential of the Arctic and its possible changes under conditions of ongoing climate warming [9, 13, 25, 27, 30]. The changes in the atmospheric circulation as a result of climate change, including the cyclone activity [7, 15], as well as regional conditions, such as the atmospheric stratification [6, 16], affect the spatial and temporal variability of near-surface wind [3, 21]. Thus, the quantification of wind variability at the operating height of turbines is particularly important for planning the construction of wind farms and related infrastructure.

One of the key factors affecting changes in near-surface wind in the Arctic is sea ice retreat, which affects the surface drag, heat and moisture exchange, and atmospheric stratification, which, in its turn, affects the near-surface wind regime. At the same time, the contribution of sea ice changes to the regional variability of near-surface wind speed depends on the season.

The low density of the weather station network in the coastal zones of the Arctic, and even more so their absence, in particular, on the shelf, raises a problem of adequate assessment of regional wind energy resources. Regional climate models (RCMs) can be used to evaluate the impact of climate change on the Arctic wind energy resources under conditions of limited climatic information. As compared to global climate models, RCMs are characterized by higher spatial and temporal resolution and, consequently, describe regional processes and their changes in more detail. This is especially important for the Arctic region [14, 29].

In the present paper, based on the results of simulations with the RCA4 regional climate model (Rossby Centre Regional Atmospheric Model, Swedish Meteorological and Hydrological Institute) [22], quantitative estimates were obtained of the impact of climate change in the Arctic expected in the 21st century on the power of wind potential, which is one of the main climatic indicators of reasonability of developing wind energy infrastructure.

INITIAL DATA AND METHODS FOR ANALYSIS

The fields of near-surface wind speed with a three-hour resolution according to the RCA4 simulations and ERA5 reanalysis data for the Arctic region (Fig. 1) for the cold (December–February) and warm (June–August) seasons were analyzed. The results of model simulations with the RCA4 with different boundary conditions from CMIP5 (Coupled Model Intercomparison Project, Phase 5) global climate models were taken: MPI-ESM-LR, EC-EARTH2.3, CanESM2, NorESM1-M. The choice of the RCA4 regional model was based on an adequate simulation of climate and its variability in the Arctic region with it as compared to observations and other RCMs in the framework of the Arctic-CORDEX project [22]. Hereinafter, unless otherwise stated, the results are given only for the mean estimates according to numerical simulations based on four variants of boundary conditions. The present study utilizes the estimates based on data with daily averaging.

The results of the analysis are presented for two periods (1950–2005 and 2006–2099) under the scenarios of moderate and high anthropogenic forcing for the 21st century: RCP4.5 and RCP8.5, respectively [31].

The wind power density (WPD, W/m^2) was calculated to estimate the wind energy potential [10]:

$$\mathrm{WPD} \quad \frac{1}{2} \quad U^3$$

where U is wind speed (m/s) at a given height (the traditional operating height of wind generators is ~100 m);   is sea-level air density (~1.23 kg/m^3).

To estimate the WPD at different heights, in particular, at the typical height of wind generators (~100 m), the special extrapolation procedure using the ERA5 reanalysis data was applied to the model projections of 10-m near-surface wind speed. The extrapolation was carried out using the power law of changes in the wind speed modulus with the index   = 0.14 for the ocean and   = 0.2 for the continents in accordance to the recommendations of the International Electrotechnical Commission [25]:

$$\frac{u_2}{u_1} \quad \frac{z_2}{z_1}$$

where u_1 is near-surface wind speed at the height of measurement z_1; u_2 is wind speed at the height of extrapolation z_2 (the traditional operating height of wind generators is 100 m).

For calculating the WPD in accordance to the model scenarios, the corresponding correction of near-surface wind values was performed to use the model simulations: using the quantile transformation method

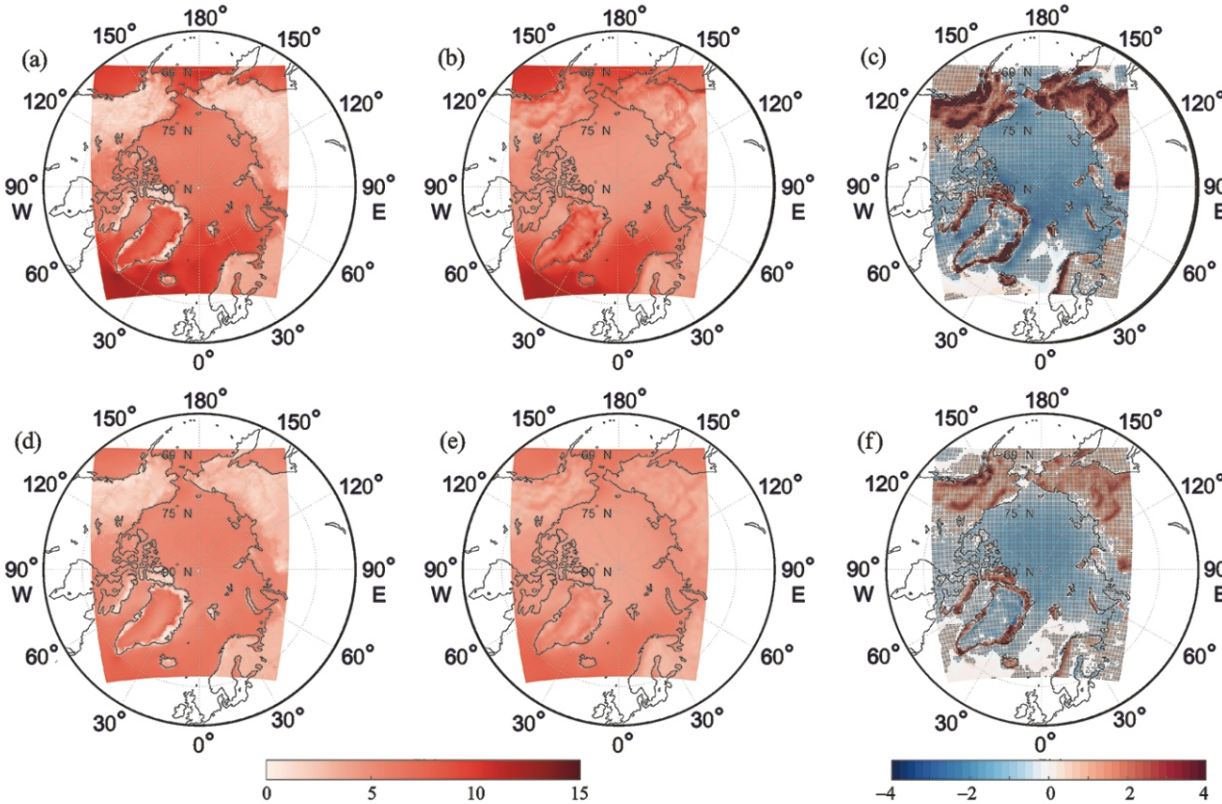

Fig. 1. The spatial distribution of the near-surface wind speed modulus (m/s) in the Arctic according to (a, d) ERA5 data and (b, e) RCA4 model simulations, as well as (c, f) their difference for (a–c) winter and (d–f) summer for 1980–2005. Here and in Figs. 3, 4, and 5, statistically significant differences at the level of 95% are marked with the dots.

based on the Weibull distribution [18, 23, 25]. The Weibull distribution for near-surface wind based on the model simulations is compared to the distribution based on the ERA5 data. Then, the scale parameter and shape parameter of the cumulative Weibull distribution are determined for the past period based on the RCM simulations and ERA5 data. These parameters are used to correct the results of WPD model simulations at the necessary height.

The expression for the corrected near-surface wind speed is:

$$u_{cor} = c_{ERA5}\left[-\ln\left(1-\left(1-e^{-\left(\frac{u_{mod}}{c_{hist}}\right)^{k_{hist}}}\right)\right)\right]^{1/k_{ERA5}}$$

where u_{cor} is near-surface wind speed corrected for the required level for the RCA4; u_{mod} is near-surface wind speed simulated with the RCA4; c and k are the scale parameter and shape parameter, respectively, of the cumulative Weibull distribution for wind speeds according to the ERA5 data and RCA4 simulations for the past (hist) or future (rcp) periods.

It should also be noted that the quantile transformation method based on the Weibull distribution demonstrates the best results in case of the near-surface wind correction as compared to other widely used correction methods [23].

The monthly mean values of sea ice concentration in the Arctic obtained from model simulations with the CMIP5 ensemble models (MPI-ESM-LR, EC-EARTH2.3, CanESM2, NorESM1-M) under the RCP4.5 and RCP8.5 scenarios were also used in the present study. The results of the same model simulations as for obtaining boundary conditions for the RCM calculations were taken for sea ice in the Arctic Ocean.

The estimates provided in the present paper were obtained under the condition that the operation of wind generators is impossible at a wind speed of less than 3 m/s or more than 20 m/s [17].

All data used in the present paper were interpolated to the RCA4 grid (0.44).

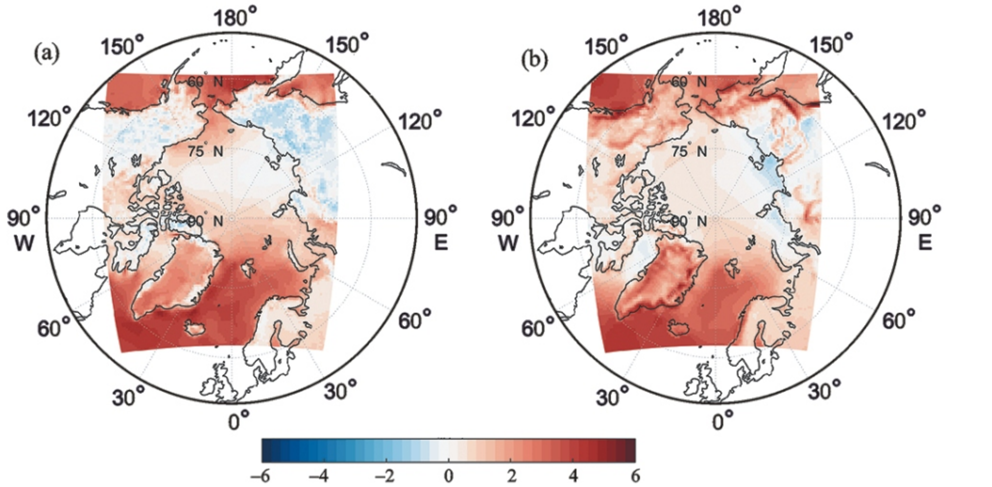

Fig. 2. The intraannual changes in near-surface wind (the difference in near-surface wind speed in winter and summer, m/s) in the Arctic according to (a) ERA5 data and (b) RCA4 model simulations for 1980–2005.

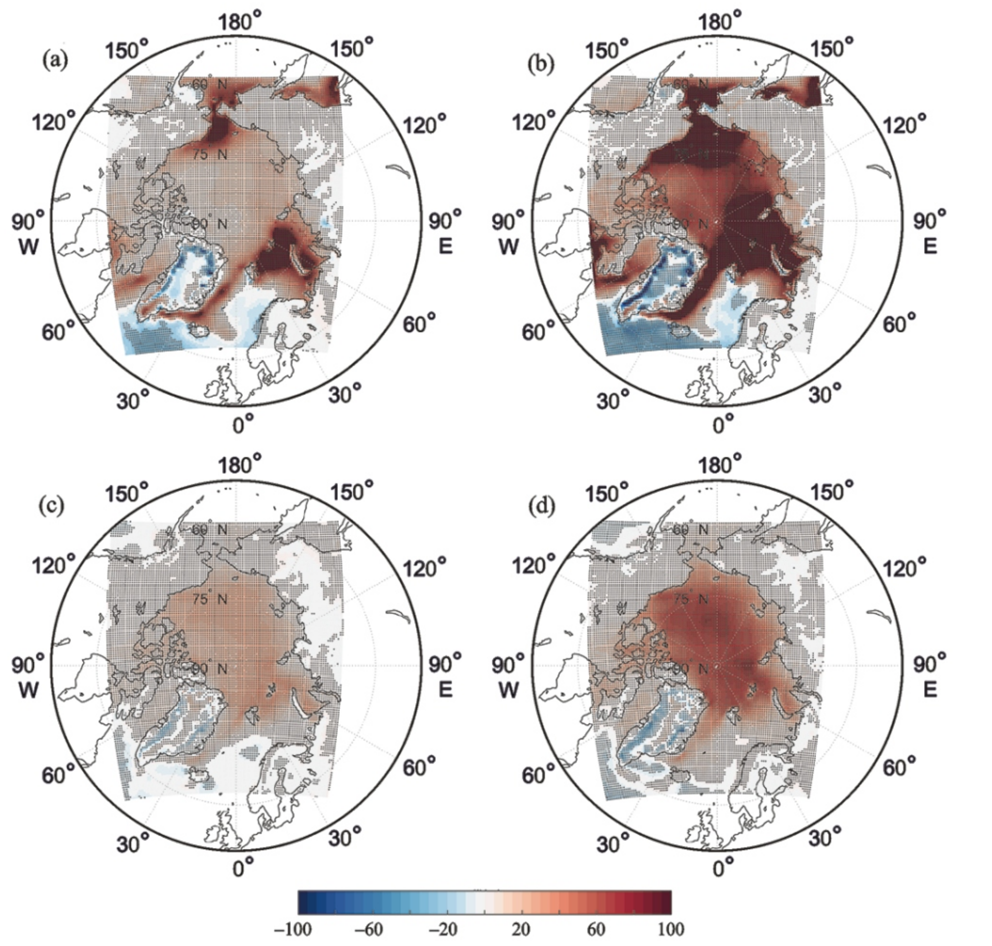

Fig. 3. The changes in the seasonal values of the WPD (W/m^2 per decade) in 2006–2100 in (a, b) winter and (c, d) summer explained by the linear trend according to the RCA4 model simulations under the (a, c) RCP4.5 and (b, d) RCP8.5 atmospheric forcing scenarios.

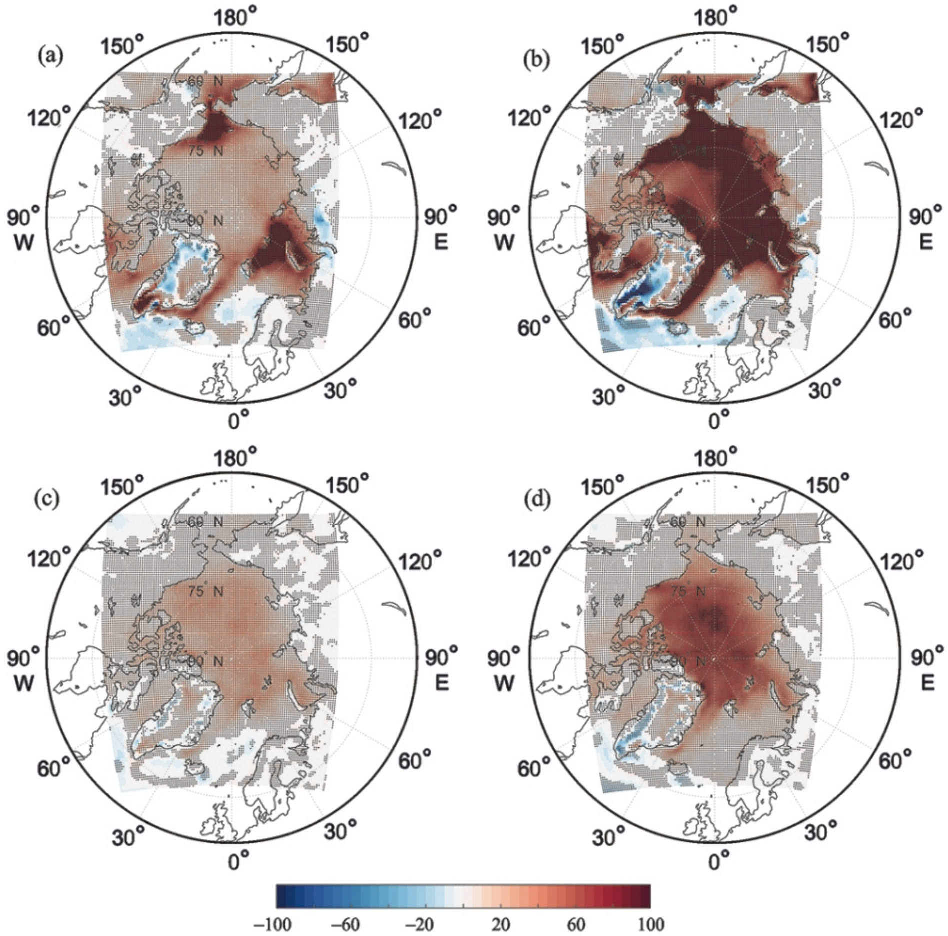

Fig. 4. The changes in the seasonal interdaily values of standard deviations of the WPD (W/m^2 per decade) in 2006–2100 in (a, b) winter and (c, d) summer explained by the linear trend under the (a, c) RCP4.5 and (b, d) RCP8.5 atmospheric forcing scenarios.

RESULTS

Figure 1 presents the spatial distribution of the near-surface wind speed modulus according to the ERA5 data [19] and RCA4 simulations, as well as their differences for the winter and summer in the Arctic during 1980–2005. The choice of the ERA5 reanalysis was caused by the fact that its data on near-surface wind speed are the best (as compared to other reanalysis systems) consistent with observational data both for the multiyear means and for the variability characteristics [24, 28]. In general, the RCA4 simulates rather well the spatial distribution of near-surface wind speed over the Arctic with the maximum wind speed over the Euro-Atlantic sector of the Arctic (the region with the highest cyclone activity) and the minimum one over the continents for all seasons. At the same time, the regional model also reproduces well the intraannual variability, although it slightly overestimates near-surface wind speed over the continents and underestimates it over the Arctic Ocean. The model intraannual variability was evaluated using the difference in near-surface wind speed in winter and summer as compared to the ERA5 data (Fig. 2). To assess efficiency of the extrapolation method for correcting the results of RCA4 near-surface wind speed simulations, the coefficients of spatial correlation were used for the multiyear means of near-surface wind speed in winter and summer (Fig. 2). The coefficients of spatial correlation R for near-surface wind speed between individual (when selecting one of the variants of boundary conditions) simulations using the RCA4 and ERA5 range from 0.71 to 0.75 for the winter and from 0.65 to 0.74 for the summer.

Model	RCA4-CanESM2	RCA4-EC-EARTH	RCA4-MPI	RCA4-NorESM1
Winter	0.71/0.99	0.74/0.99	0.75/0.99	0.71/0.99
Summer	0.74/0.99	0.68/0.99	0.65/0.99	0.65/0.99

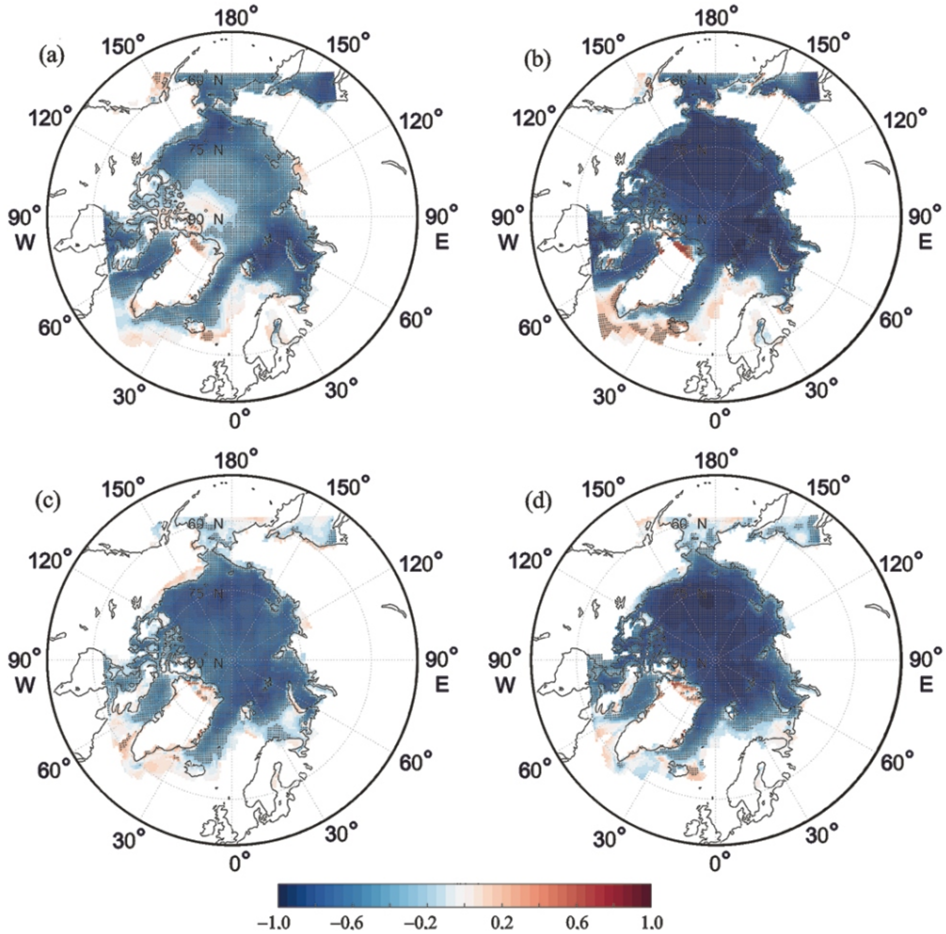

Fig. 5. The coefficients of correlation between near-surface wind speed according to the RCA4 model data and sea ice concentration according to the CMIP5 data (intermodel mean) in (a, b) winter and (c, d) summer in 2006–2100 under the (a, c) RCP4.5 and (b, d) RCP8.5 atmospheric forcing scenarios.

The numerator indicates the correlation coefficients before the correction of the systematic error, in the denominator, after it. The correction procedure for near-surface wind speed, which significantly increases the respective correlation coefficients, is reasonable for deriving possible changes in the wind power.

Figure 3 presents projected changes in the seasonal WPD simulated with the RCA4 under the RCP4.5 and RCP8.5 scenarios for 2006–2099. In winter, the areas of the significant WPD growth are manifested over the Barents, Kara, and Chukchi seas under the RCP4.5 scenario. These changes are still more significant for the RCP8.5 scenario with higher anthropogenic forcing in the 21st century. In summer, the WPD generally increases over the Arctic Ocean under the RCP4.5, and these changes are still more pronounced under the RCP8.5. An increase in the interdaily standard deviations was noted for the WPD (Fig. 4), and the zones of their most significant changes correspond to the areas of changes in the seasonal mean WPD. The noted WPD variations rather highly correlate with the projected sea ice extent decline in the Arctic (Fig. 5). The Arctic sea ice reduction affects the surface drag, heat and moisture exchange, and atmospheric stratification and, thus, has a noticeable effect on near-surface wind speed [20].

Wind speed required for the optimum operation of wind turbines at the height of 100 m is estimated to range from 10 to 20 m/s. These values of wind speed correspond to the WPD range of 600–1900 W/m^2. Against a background of the simulated increase in interdaily standard deviations of WPD, a slight increase is manifested in the number of days with wind when the wind generator operation is unfeasible (Fig. 6). At the same time, the possibility of wind generator operation is not generally disturbed. The Arctic regions where, according to Fig. 3, the WPD changes by 100 W/m^2 per decade are projected, are rather promising for the wind energy development.

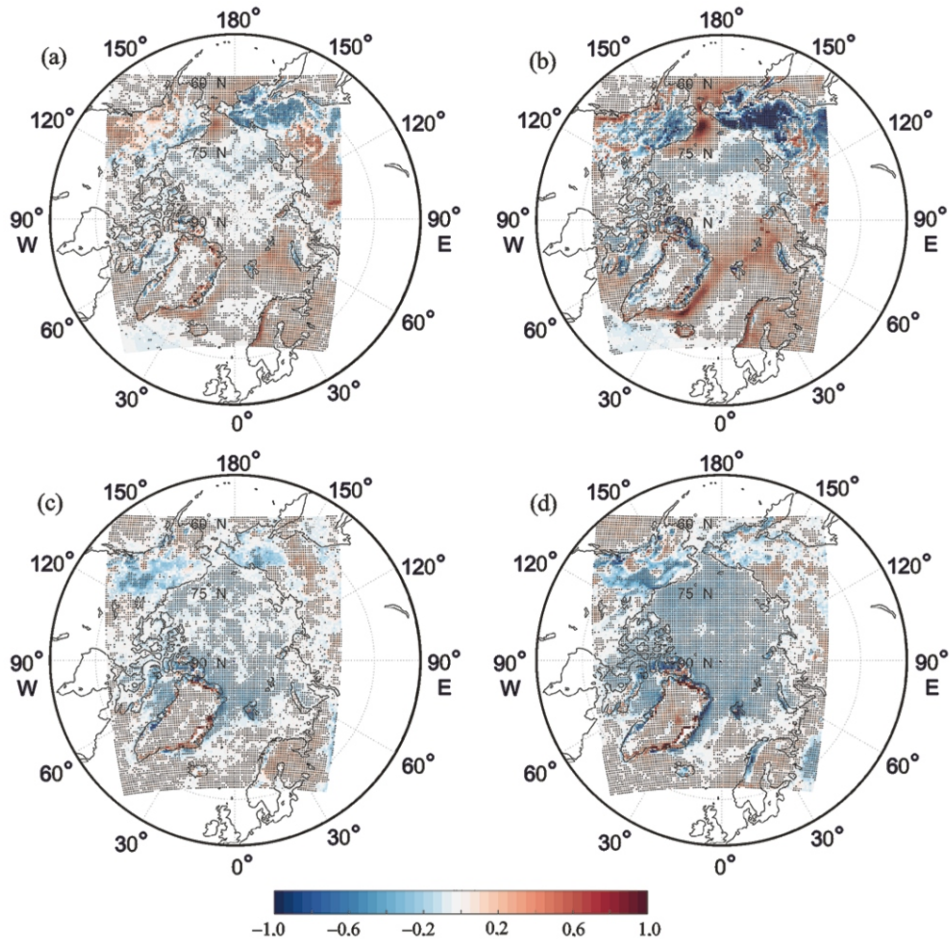

Fig. 6. The changes (explained by the linear trend) in the number of days (per decade) with wind speeds (below 3 m/s or above 20 m/s) at which the operation of wind turbines is unfeasible for (a, b) the winter and (c, d) summer under the (a, c) RCP4.5 and (b, d) RCP8.5 atmospheric forcing scenarios.

CONCLUSIONS

The comparative analysis of the results of near-surface wind speed simulations based on the RCA4 RCM with the ERA5 reanalysis data was carried out. In general, the spatial distribution of near-surface wind speed over the Arctic is adequately simulated using the RCA4. It was noted that the regional model also rather well simulates the intraannual variability, although with some general overestimation of near-surface wind speed over the continents and its underestimation over the Arctic Ocean.

The model projections of the WPD in the Arctic were performed. The procedure for correcting the bias of model near-surface wind speed as compared to the ERA5 data as a reference with the subsequent extrapolation of wind speed to the height of the turbine was applied to analyze the WPD at different heights, in particular, at the typical height of wind generators.

The model projections of changes in the power of wind energy potential were obtained for the Arctic region under the RCP4.5 and RCP8.5 anthropogenic forcing scenarios for the 21st century. The results demonstrate a noticeable increase in the WPD over the Barents, Kara, and Chukchi seas in winter and a general WPD increase over the Arctic Ocean in summer. More significant changes are manifested under the RCP8.5 scenario with high anthropogenic forcing for the 21st century. At the same time, the noted increase in interdaily standard deviations of the WPD does not generally lead to the deviations of wind speed to the values at which the wind turbine operation is unfeasible.

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