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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Wind Energy Potential of High Latitudes of the Northern Hemisphere under Modern Climate Changes

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Abstract—Changes in wind energy resources in high latitudes of the Northern Hemisphere are quantitatively assessed based on ERA5 reanalysis data for 1979–2021. The wind energy potential (WEP) is estimated during the analysis. According to the ERA5 reanalysis data, the WEP noticeably increases over the Greenland, Norwegian, Barents, Kara, and Chukchi Seas and European Russia in winter and over the Kara and Norwegian Seas in spring under the modern climate regime. A general increase in the WEP is observed along the Arctic coast, in particular, over its Russian sector in summer and autumn. These changes in the WEP correlate quite well with the retreat of sea ice in the Arctic and with the leaf area index, which characterizes the roughness of the underlying surface, in high latitudes of the Northern Hemisphere. An increase in the part of the year when wind generators are capable of operating in the Russian Arctic makes the region quite promising for the use and development of wind power under current climate change.

Keywords: wind energy resources, sea ice, leaf area index, Arctic, climate change, reanalysis

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INTRODUCTION

Global warming in recent decades has been accompanied by an unprecedented reduction of the sea ice area in the Arctic [1–4], which makes the Arctic more accessible for development. The sea ice loss in the Arctic gives impetus to the development of shipping, fishing, mining, and other activities in the region, in particular, electrical energy generation from renewable sources [5, 6]. Wind is among most promising energy sources. Wind energy is classified as "clean," or "green," since it is characterized by a very low level of greenhouse gas emissions during its generation. This creates prerequisites for the active development and use of wind energy resources in high latitudes of the Northern Hemisphere.

The spatiotemporal variability of wind characteristics in high latitudes of the Northern Hemisphere depends on changes in the atmospheric circulation due to climate change, including eddy activity [7–9], and on regional conditions, such as atmospheric stratification [10–12]. Sea ice loss is one of key factors of variations in wind parameters over the Arctic Ocean. This factor affects the aerodynamic roughness of the surface, heat and moisture exchange, and atmospheric stratification, which, in turn, influence the wind regime. The contribution of changes in the sea ice regime to the regional variability of the surface wind speed depends on the season. Another equally important factor which affects the aerodynamic roughness of the underlying surface is the vegetation cover. Thus, the quantitative assessment of wind variability at the turbine height and its relationship with changes in the sea ice and vegetation cover areas are of particular importance when designing wind farms and related infrastructure [13, 14].

The aim of this work is to quantitatively assess the wind power in high latitudes of the Northern Hemisphere in recent decades (1970–2021).

DATA AND METHODS

We analyze hourly wind speed fields at the turbine height (100 m) and monthly sea ice concentration fields in high latitudes of the Northern Hemisphere (>60° N) (Fig. 1) in winter (December–February), spring (March–May), summer (June–August), and autumn (September–November) on the basis of the ERA5 reanalysis data [15].

As an assessment of the wind energy potential, we calculate the wind power, W/m^2, [16]:

$$\mathrm{WP} = \frac{1}{2}\rho U^3,$$

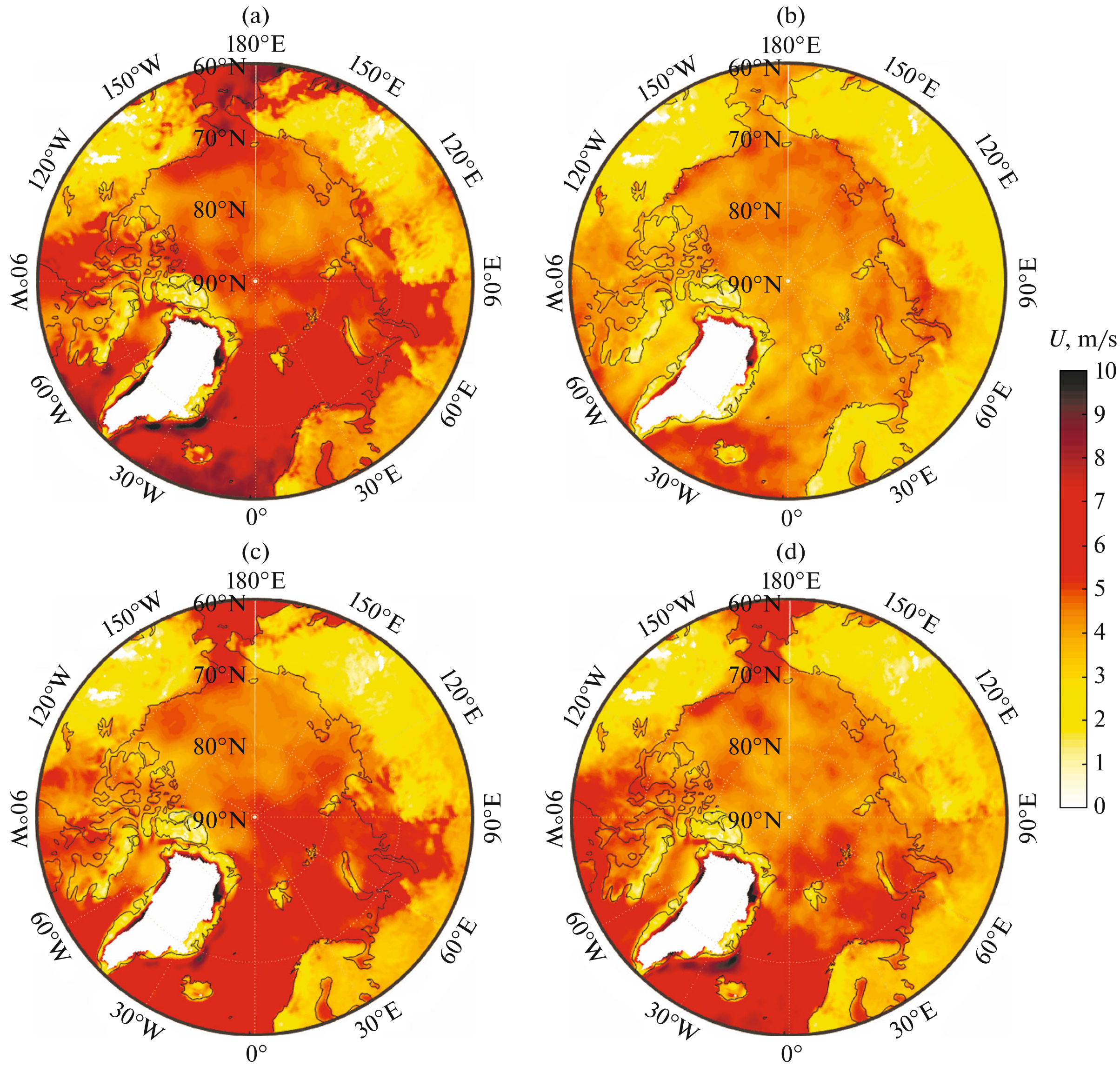

Fig. 1. Spatial distribution of the wind speed modulus at an altitude of 100 m in high latitudes of the Northern Hemisphere according to ERA5 reanalysis data in different seasons of 1979–2021: (a) winter; (b) summer; (c) spring; (d) autumn.

where U is the wind speed at an altitude of 100 m, m/s; $\rho = 1.23$ kg/m^3 is the air density at sea level.

The assessments in this work are made under the assumption that wind generators are incapable of operating at wind speeds of less than 3 or more than 20 m/s [17].

The total leaf area index (LAI), m^2/m^2, which characterize the variability of roughness of the underlying surface, is calculated as

$$\mathrm{LAI} = c_{\mathrm{u}}\mathrm{LAI}_{\mathrm{o}} + c_{\mathrm{u}}\mathrm{LAI}_{\mathrm{o}},$$

where $\mathrm{LAI}_{\mathrm{u}}$ ($\mathrm{LAI}_{\mathrm{o}}$) is the index for grass (tree) cover, m^2/m^2; c_{u} (c_{o}) is the fraction of the area of a grid cell with grass (tree) cover.

RESULTS AND DISCUSSION

Figure 1 shows the spatial distribution of the long-term average wind speed modulus at an altitude of 100 m according to the ERA5 reanalysis data [15] in high latitudes of the Northern Hemisphere in 1979–2021. The ERA5 reanalysis has been chosen because its data on the wind speed are in the best agreement (as compared to other reanalysis systems) with observations of both long-term averages and characteristics of the variability [18, 19]. The wind speed at an altitude of 100 m in the high latitudes of the Northern Hemisphere is maximal over the Euro-Atlantic sector of the Arctic (the region of the highest cyclonic activity) and minimal over the continents in all seasons. Figure 2 shows its annual standard deviation. In general, the

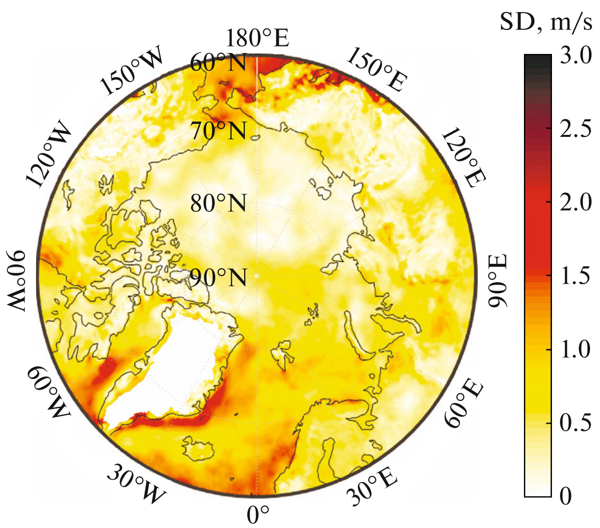

Fig. 2. Annual standard deviation of wind speed (m/s) at an altitude of 100 m at high latitudes of the Northern Hemisphere according to ERA5 reanalysis data for 1979–2021.

strongest variability is observed over the Euro-Atlantic sector of the Arctic and the region of the Chukchi Sea.

Figure 3 gives an idea of the trends in seasonal changes in the WEP according to the ERA5 reanalysis for 1979–2021. In winter, the WEP significantly increases over the Greenland, Norwegian, Barents, Kara, and Chukchi Seas and over European Russia. A weak decrease in the WEP is observed over the continents. In spring, the WEP increases the most over the Kara and Norwegian Seas and over vast continental areas. A noticeable decrease in the WEP can be seen over the Greenland Sea. In summer, the WEP increases along the Arctic coast, in particular, over its Russian sector and the territory of the Russian Federation and Alaska, and weakly decreases over eastern Siberia. In autumn, WEP changes are less regular: its noticeable increase is seen in the region of the Davis Strait, a decrease, in the northern part of the Norwegian Sea, and an increase, along the coast of Arctic seas.

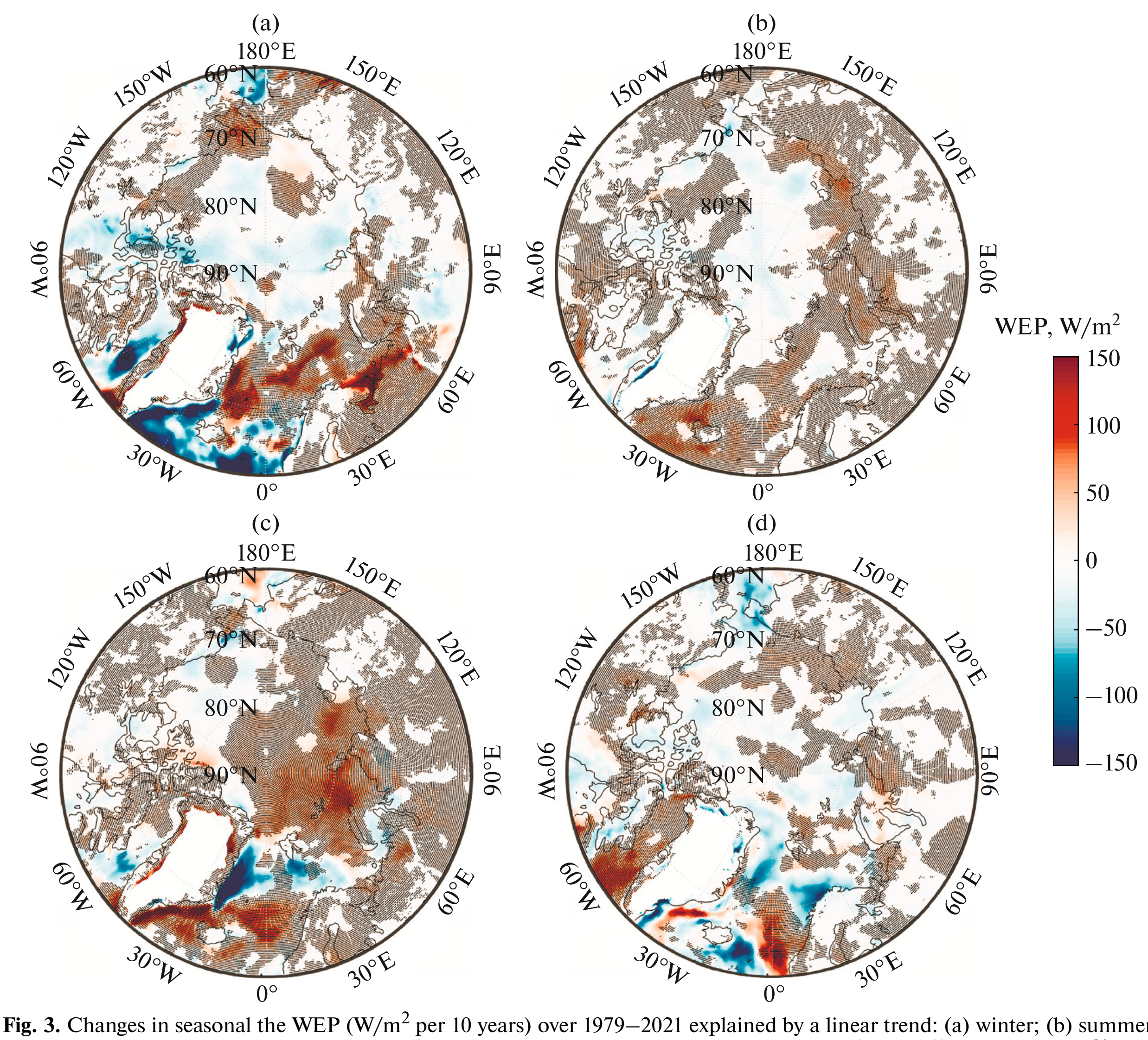

Fig. 3. Changes in seasonal the WEP (W/m^2 per 10 years) over 1979–2021 explained by a linear trend: (a) winter; (b) summer; (c) spring; (d) autumn. Here and below in the figures, gray areas correspond to statistically significant differences at the 95% level.

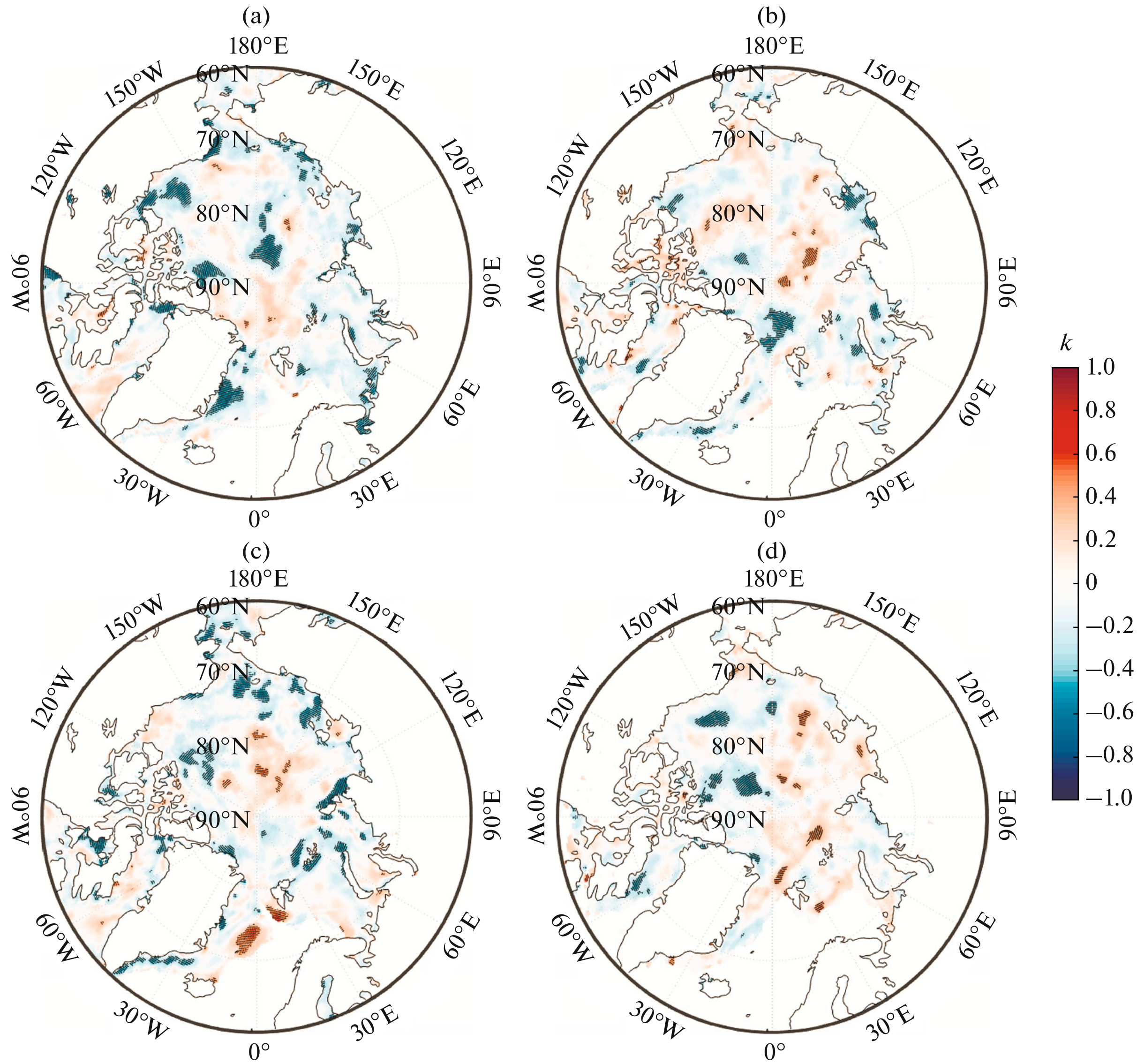

Fig. 4. Coefficients of correlation between the wind speed at an altitude of 100 m and the sea ice concentration according to ERA5 reanalysis data for 1979–2021: (a) winter; (b) summer; (c) spring; (d) autumn.

These changes in the WEP correlate quite well with the predicted retreat of sea ice in the Arctic (Fig. 4). A reduction in sea ice area influences the aerodynamic roughness of the surface, heat and moisture exchange, and atmospheric stratification [20], which, it turn, significantly affect the WEP [21].

Changes in the continental vegetation cover in high latitudes of the Northern Hemisphere can also affect wind speed through changes in the roughness of the surface [22]. One of the parameters characterizing the vegetation cover is the leaf area index, which is the ratio of the total area of one-sided green leaves on a site to the site area. The LAI is characterized by high variability in winter as compared to other seasons. Therefore, we analyze the correlation between the wind at an altitude of 100 m and the LAI only for winter.

A positive and statistically significant trend in the LAI and a positive correlation between it and the wind speed are observed (Fig. 5) in the north of the European Russia, in Scandinavia, and in the north of North America. This can be due to the effect of an increase in the productivity of terrestrial vegetation on the height of roughness. Thus, extension of the growing season under climate warming in these regions [23, 24] and fertilization of terrestrial vegetation by atmospheric CO_2 [23, 25] intensify the biological production with a corresponding increase in biomass in terrestrial vegetation. With allowance for the allometric relationships between the height of shrubs and the LAI [26] (it should borne in mind that the annual variations in the LAI are negligible for taiga species typical for these regions), the accumulation of biomass leads to an

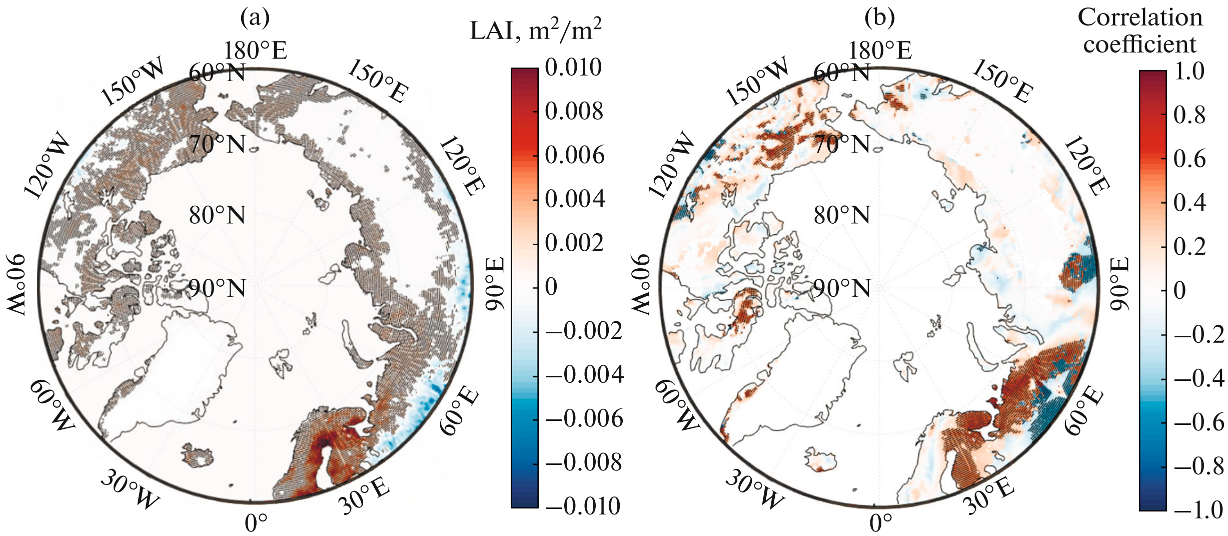

Fig. 5. Coefficient of (a) decadal LAI trend and (b) of its correlation with the wind speed at an altitude of 100 m according to ERA5 reanalysis data for winters 1979–2021.

increase in stand height with the corresponding increase in the height of roughness.

Note that the corresponding trend coefficient and correlation coefficient are negative in Europe south of ~65° N. There, the height of roughness apparently has a weaker effect on the wind speed modulus as compared to other factors (for example, the horizontal pressure gradient).

The wind speed at an altitude of 100 m should be from 10 to 20 m/s for optimal operation of wind turbines. This range approximately corresponds to the WEP range from 600 to 1900 W/m^2. According to the ERA5 reanalysis data the number of days with the wind speeds at an altitude of 100 m below 3 m/s and higher 25 m/s, under which the operation of wind turbines is impossible (unfavorable days), decreases in winter above the Scandinavian Peninsula and increases over Siberia. In spring, the frequency of unfavorable days generally decreases everywhere, including the Arctic coast of Russia. In summer, the number of unfavorable days increases. The corresponding coefficient of the linear trend is up to 4 m/s per decade (10 years) over the continents. In autumn, the number of unfavorable days slightly increases except for the Far East, where it decreases.

Thus, we can conclude that the use and development of wind energy in the coastal regions of the Russian Arctic and more southern regions is promising taking into account climate change.

CONCLUSIONS

We have assessed the wind energy potential in high latitudes of the Northern Hemisphere based on ERA5 reanalysis data for 1979–2021. According to the results, the WEP noticeably increases in winter over the Greenland, Norwegian, Barents, Kara, and Chukchi Seas and over European Russia and in spring over the Kara and Norwegian Seas. In summer and autumn, the WEP generally increases along the coast of the Arctic, in particular, its Russian sector. These changes in the WEP correlate quite well with the regions of sea ice loss in the Arctic, in particular, in the Russian Arctic seas. This is due to a decrease in the roughness of the ocean surface caused by the change from ice cover to open water, as well as a decrease in the stability of the atmosphere, which leads to a decrease in the wind speed in the Arctic.

Wind speed is also affected by changes in the continental vegetation cover in high latitudes of the Northern Hemisphere via changes in the roughness of the surface. In the north of European Russia, in Scandinavia, and in the north of North America, a significant positive trend in the leaf area index and a positive correlation between the index and wind speed are observed. They can be due to the effect of the increase in the productivity of terrestrial vegetation on the roughness height, including due to the extension of the growing season under climate warming and fertilization of terrestrial vegetation by atmospheric CO_2.

The noted increase in the part of the year when wind turbines are capable of operating in the Russian Arctic makes the region quite promising for the use and development of wind energy under the conditions of current climate change.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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