Wind projections for the territory of Russia considering the development of wind power

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Abstract. The aim of the present work is to obtain surface wind speed projections which could be used as guidelines for long-term planning of wind power construction in Russia. A classical multi-model ensemble approach is implemented by using CMIP5 simulation results. The reliability of the ensemble estimation is assessed by a comparison of three different ensemble versions, which are validated against reanalysis data for the whole 20th century and have been found to give consistent results since 1950. Agreement between the results of all the assembling approaches has been found to be quite good for the mid-twenty-first century. All ensembles being considered agree that a considerable decrease in wind resources should be expected in the European part of Russia and in the south of Western Siberia towards 2050. Another robust output of the analysis is an increase in annual wind speed in the Southern Russian Far East. The wind change during the considered 40-year period is in the range from -6 to +6%, which means a -18 to +18% change in potential wind generation. The main output of the present work is that climate change by no means can be seen to be an obstacle to the development of renewable power in Russia. However, the climate change associated alteration of wind regime should be necessarily taken into account when establishing long-term plans for wind farm construction in Russia.

1. Introduction
The energy systems are in transition around the world. One of the largest drivers of this transformation process are the renewable electricity generation technologies that seemed to be of a purely academic interest only twenty years ago. Nowadays the development of wind generators is one of the most impressive examples of rapid development of renewable technology. Wind generators have operated since the first decades of the twentieth century, but have played a minor role in the energy systems for many decades. Today wind power all over the world has become one of the leading generation technologies as a part of real industrial power systems. The total wind power output is approaching the nuclear power plants.

The wind generation is directly linked with the wind speed fluctuations, which mean that the wind power economics is greatly influenced by the climatic conditions. Integration of an increasing wind power share into the energy systems is possible only if the wind regime in a particular area is well understood [1]-[3]. Multi-annual wind speed monitoring has become a common step of wind farm procurement.

Wind energy in Russia is currently at the very early stage of development. The overall installed wind power across the country is currently approaching 1 GW. Several new wind farms should be launched across the country during the next decades, multiplying the installed capacity value.
Assessment of the long-term wind speed dynamics across the country is becoming crucially important for the support of this development process.

2. Related research
The long-term wind speed dynamics for different regions of the world is being intensively studied during the last decade. A recent paper [4] has demonstrated that the modern climate models tend to heavily underestimate the decreasing wind trends observed in the Northern Hemisphere during the twentieth century. This makes evident the importance of careful consideration of the models selection used to project the wind speed in a given world area.

2.1. Meteorological observations
A continuously decreasing wind speed trend in the surface has been observed in Russia since the 1970s [5]. A comprehensive meteorological analysis performed by Roshydromet experts has allowed one to conclude that the reduction of the average wind speed is typical for all seasons and occurs almost everywhere [6]. This effect is especially pronounced in the European territory of Russia, where most wind farms to introduce to construction during the next decades should be located. The authors of [6] definitely attribute the observed tendency to the modern climate change.

2.2. Projections
 Comprehensive work on climate projections for the Russian territory was performed at the Voeikov Main Geophysical Observatory [7] about five years ago. These calculations utilized the CMIP5 (Coupled Model Intercomparison Project) Phase5. The authors have made validation of the available global climate circulation models to select sixteen models which reproduce seasonal variations of the temperature, precipitation, and pressure in a way that is most consistent with the observations. The authors have stated that the wind speed changes up to +/- 1 m/s are projected but do not provide any robustness assessment of the projected wind speed fields. The authors of the Roshydromet Assessment Report [5] make reference to the ensemble calculations of the surface wind speed for the rcp 8.5 scenario, but the results of these calculations are not presented. The authors mention that the wind speed change obtained with this assessment is in the range of +/-1 m/s, and believe this change to be insignificant not to discuss any further details.

Recently, paper [8] has presented a detailed analysis of the CMIP5 results for the Russian Arctic territories with a careful consideration of the validation issues for the used models. However, the focus of the authors was only on the Arctic seas. In addition, calculations have been made for the catastrophic climatic scenario of rcp 8.5 which, fortunately, should be treated as a very likely one. This does not allow us to utilize the results obtained in [8] even for the most preliminary conclusions about the real wind conditions which will impact the operation of wind parks in Russia during the next decades.

2.3. Technology status
It is difficult to agree with the conclusion about the insignificance of the observed wind speed changes. The wind turbines are quite sensitive to the wind speed variations due to the fact that wind turbine power generation depends on the kinetic energy of the wind flow \( P_{\text{wind}} \), which is proportional to the cube of the wind speed \( w \):

\[
P_{\text{wind}} = \frac{1}{2} \rho w^3,
\]

where \( \rho \) is the air density. Wind speed changes of about 1 m/s mean a change in the wind turbine output by two to three times at a typical surface wind speed of 3...5 m/s, which is usual on the Russian territory. Thus, the climate change seems to inevitably affect the development of the wind energy in Russia. Nowadays, at the
very beginning of this development process, there is an urgent need to obtain at least some robust projections of the surface wind speed in Russia under realistic climate scenarios.

3. Motivation
The presented work is intended for obtaining projections of the surface wind speed, which could be used as a guideline for long-term planning of the wind power construction in Russia, particularly when assessing the future energy system options and control strategies. We will use a classical ensemble approach considering different ensembling approaches.

4. Methods
The moderate climate scenario rcp 4.5 was taken for further calculations, as the closest one to the likely real climate changes during the 21st century. The soft scenario rcp 2.6 and the dramatic 8.5 were considered to estimate the robustness of the calculated projections. The historic climate experiments were used in the validation procedure. Our calculations used the results of the CMIP5 project that up to date provides access to the most comprehensive set of the global climate models simulation results. We used the monthly output of 27 CMIP5 models available for the near-surface wind speed [9].

Table 1. List of CMIP5 models used for ensemble estimations.

| Model Name   | Institute                                                                 |
|--------------|---------------------------------------------------------------------------|
| ACCESS 1.0   | Commonwealth Scientific and Industrial Research                           |
| ACCESS 1.3   | Organization/Bureau of Meteorology, Australia (CSIRO-BOM)                 |
| bcc-csm1-1-m | Beijing Climate Center, China (BCC)                                       |
| bcc-csm1-1   | Beijing Normal University, China(BNU)                                     |
| CanESM2      | Canadian Centre for Climate Modelling and Analysis, Canada (CCCma)        |
| CMCC-CESM    | Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy (CMCC)          |
| CMCC-CMS     |                                                                          |
| CMCC-CM      |                                                                          |
| CNRM-CM5     | Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France (CNRM-CERFACS) |
| CSIRO-Mk 3.6.0 | Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia (CSIRO-QCCCE) |
| GFDL-CM3     | Geophysical Fluid Dynamics Laboratory, USA (NOAA GFDL)                     |
| GFDL-ESM2G   |                                                                          |
| Model Name       | Institute                                                                 |
|------------------|---------------------------------------------------------------------------|
| GFDL-ESM2M       |                                                                           |
| HadGEM2-CC       | Met Office Hadley Centre, UK (MOHC)                                       |
| HadGEM2-ES       |                                                                           |
| inmcm4           | Russian Academy of Sciences, Institute of Numerical Mathematics, Russia (INM) |
| IPSL-CM5A-LR     | Institut Pierre Simon Laplace, France (IPSL)                              |
| IPSL-CM5A-MR     |                                                                           |
| IPSL-CM5B-LR     |                                                                           |
| MIROC-ESM        | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan (MIROC) |
| MIROC-ESM-CHEM   |                                                                           |
| MIROC5           |                                                                           |
| MPI-ESM-LR       | Max Planck Institute for Meteorology, Germany (MPI-M)                     |
| MPI-ESM-MR       |                                                                           |
| MRI-CGCM3        | Meteorological Research Institute, Japan (MRI)                           |
| MRI-ESM1         |                                                                           |

4.1. Ensemble strategy

The used ensemble strategies accounted for [10] CMIP5 validation results on the high-resolution reanalysis data. The essence of this validation procedure was the reproducibility testing of the daily wind speed distributions in each computational grid cell by each of the CMIP5 models in the European domain. The model quality metric was defined as a cell number where the Kolmogorov-Smirnov test gave a positive result.

In our calculations we have considered three ensembles:
1) the ensemble recommended in [10] consisted of eight models which model the distribution of wind speeds corresponding to the reanalysis data for 75% of the model cells in a considered area;
2) an ensemble of nine models which give 70% of the cells share with a correctly reproduced daily wind speed distribution;
3) an ensemble of all available models.

The geographical restriction of [10] seems not to be critical for the considered problem, since most wind farms in Russia planned for construction are located in the European part of the country. Besides,
the global climate models ensemble estimations may be treated for the wind speed only as a quite approximate assessment. Downscaling approaches should be applied to produce wind speed projections suitable for use in the energy systems modeling and planning. What we are focused on is obtaining a general picture of the multidecadal wind speed trends.

4.2. Validation
A simplified validation procedure was performed to check the reproducibility of the long-term wind speed dynamics across the country by the considered ensembles. The results of the ensemble estimations for the historic CMIP5 experiment were compared with the 20th Century Reanalysis V2c [11] reanalysis data for the whole twentieth century.
Figure 1. Change in the annual surface wind speed in 1995–2004 compared with 1977–1986: a – according to 20Cv2 reanalysis, b – calculated by the eight-models ensemble, c – calculated by the whole set of all available models.

It was found that the eight-model ensemble performs better as compared with the all-models ensemble (Figure 1). The correspondence is more qualitative than quantitative and is satisfactory for the whole Russian area only since 1940. The discrepancy for the earlier dates may obviously result from the ensemble uncertainties and flaws of the reanalysis data. A more detailed analysis seems to be necessary to clarify the long-term trends of the wind speed during the twentieth century. However, the ensemble estimations seem to be quite consistent with the reanalysis data on fifty-sixty years’ time horizons, which is quite sufficient for the purpose of our work.

5. Results and discussion

The three above-considered ensembles give close results for the relative wind speed change across the country during the twenty-first century. However, they differ significantly in details. The range of changes in the territory is the same for all three cases varying from -6...-4% to +5...+6% (Fig. 2). The ensembles also agree that the most pronounced decrease in wind speed is to be expected in the central and southern parts of the European territory of Russia, as well as in the south of Western Siberia, which is consistent with the observation data of [6].

A second conclusion which follows from this comparison is a likely increase in the average wind speed in Primorye and on the Sakhalin shelf. This effect is apparently linked to the atmospheric circulation shift, in particular, to the weakening of the Siberian High and intensification of the cyclonic activity over the Pacific observed during the last decades and attributed to climate change. This result is remarkably stable for all ensembles considered. Moreover, this output is consistent even with different climate scenarios. A control ensemble calculation run has given us qualitatively the same wind speed increase in the Far East for rcp 2.6 and rcp 8.5 as well.

It should be emphasized again that the present work is intended to obtain robust large-scale projections of long-term forecast changes in the wind potential. The effects of mesoscale atmospheric hydrodynamics combined with local topography have a huge impact on wind farm operation. That is why the application of dynamic or statistical downscaling procedures is a necessary step in using the above-obtained national-scale results in energy system optimization models.
What may be concluded right now is that the Russian Far East will definitely obtain a chance to renovate the local energy systems on a much cleaner basis as compared to the coal power plants in operation there today. Apart from the anticipated increase in wind potential, the Far East is one of the Russian regions where a significant rise in bio-productivity is very likely during the 21st century [12]. Climate change seems to favor the renewable renovation plans whose realization is gradually starting now in the energy systems of the Far East. However, the projections for the wind velocity changes in Kamchatka and Chukotka areas are far less certain and require a more detailed analysis, since wind power there is of highest interest for the regional remote energy systems.

There are some areas where the decrease in wind speed may lead up to a 12% decrease in wind specific energy. Fortunately, it does not mean any serious risks for the development of national wind power, since the areas of noticeable wind speed decrease are located in regions where no extensive wind power development is under discussion. The south of European Russia, the Baltic Sea coast, and the Kola Peninsula, where wind park constructions are planned, are likely to be subjected to relatively low changes in surface wind speed, in the range of +/-2%. Climate change seems to provide more possibilities than threats for the development of renewable power in Russia. It should be kept in mind, however, that the integration of an intermittent wind generation into the energy systems requires careful consideration of wind speed dynamics and a shift in the control paradigm of energy systems.

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