IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 121, No. 2, April – June, 2017, pp. 161–187

Near-surface wind speed changes in the 21st century based on the results of ALADIN-Climate regional climate model

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Abstract—This study presents a methodology to assess the climate change impacts on wind conditions and wind energy potential on multiple levels near the surface over the Carpathian Basin and Hungary. The methodology is based on ALADIN-Climate regional climate model results and ERA-Interim re-analysis data.

Since wind energy estimations require wind data in specific hub (turbine) heights, in addition to the 10-meter standard, we evaluate wind speed on 50, 75, 100, 125, and 150 meters above the surface to cover the range of most frequently used hub heights. The main concept of the method is to compute the wind velocity on these levels directly from data on the neighboring model levels instead of extrapolating from the 10-meter wind speed applying a wind profile. Besides giving more accurate velocity values, the use of multiple levels allows us to examine the changes in the vertical profile of near-surface winds as well.

The model results are validated with ERA-Interim re-analysis for the 1981–2000 period. Despite a systematic negative bias, ALADIN-Climate reproduces the main wind characteristics in the Carpathian Basin reasonably. The future projection was carried out considering the RCP8.5 emission scenario and was evaluated for the 2021–2050 and 2071–2100 periods. The projection results show a mild future increase in the average wind speed over most parts of the integration domain. The changes over Hungary are more prominent in 2021–2050 with a slight but statistically significant 7% annual increase. The mean annual change in potential power has similar characteristics, only with higher, 8–13% growth.

As our aim is the demonstration of a methodology, our investigation is based on the outputs of a single climate model simulation, however, to provide some hints about projection uncertainties, we compared our future estimates with further studies which confirmed our main conclusions.

Key-words: climate change, ALADIN-Climate, ERA-Interim, regional climate model projections, wind speed, vertical profile, wind energy

Paper is based on the presentation delivered at Meteorological Scientific Days held on 19–20 Nov, 2015 entitled „Meteorological aspects of use of renewable energies".

1. Introduction

To reduce anthropogenic greenhouse gas emissions, the use of renewable energy is highly supported and rapidly growing all around the world. The European Renewable Energy Directive aims at fulfilling 20% of total energy need of the European Union (EU) from renewable sources by 2020 (EU directive, 2009). Wind energy is currently the largest contributor to renewables within the EU with a total installed power capacity of 142 GW and by growing further, it is expected to play a major role in replacing fossil fuels. During 2015, more wind power capacity was installed in the EU than any other form of power generation, and by the end of 2020, the total wind capacity is planned to reach 210 GW which would cover 14% of the total electricity need of the European Union (European Wind Energy Association, 2016). However, due to the high spatial and temporal variability of wind speed, special research and planning must precede investments to assess the potential effectiveness of a given location. For effective future planning, the impacts of climate change must be considered, since it may alter large-scale atmospheric circulations, which can have significant effects on local wind climatology. Numerical models provide a tool for that: Earth-system models simulate the physical processes of the whole climate system (atmosphere, oceans, land surface, cryosphere, and biosphere), while regional climate models (RCMs) serve to downscale the results of global climate models (GCMs) over a specific area of interest. Dynamical downscaling is essential for wind power estimations, because wind speed is heavily influenced by local topography and surface characteristics which are described more precisely in high-resolution regional models.

Researches aiming at exploring the wind climatology of Hungary began based on observational data: in the 1950's, the first National Climate Atlas contained some information about the prevailing winds in our region; shortly after, the first wind tower measurements were launched to assess the available wind energy and the possible options to harness it. In the 1990's, the Department of Meteorology at Eötvös Loránd University started a systematic and detailed analysis of wind-climatological characteristics over Hungary. The WAsP software (Wind Atlas Analysis and Application Program, *Mortensen et al.,* 1993) was adapted and used to assess wind speed in different vertical levels above the surface and to determine the modifying effect of the topography and surface roughness to near-surface airflows (*Bartholy* and *Radics*, 2001). After its validation using tower measurements of Hegyhátsál station, the available wind energy was modeled over the area of Hungary (*Radics*, 2004). The vertical profile of wind velocity was studied by *Varga* and *Németh* (2004), conducting field measurements with SODAR in four different locations. The frequency distribution and mean value of wind speed were measured in different height levels and used to calculate the average value and diurnal cycle of the Hellmann coefficient. *Szentimrey* et al. (2006) developed a high-resolution gridded wind dataset of Hungary at 10 m and 75 m height above the surface, using station observations interpolated with the MISH (Meteorological Interpolation based on Surface Homogenized Data Basis, *Szentimrey* and *Bihari,* 2007) software developed specially for meteorological interpolation. In the framework of an international cooperation, CARPATCLIM project (*Lakatos* et al., 2013), a high resolution (0.1° × 0.1° spatial resolution) gridded, homogenized daily observational dataset was produced over the area of the Carpathian Basin including surface wind speed information for 1961–2000. Data from all the available stations were used, the interpolation was performed with MISH and the homogenization was done with MASH (Multiple Analysis of Series for Homogenization, *Szentimrey*, 2008), both methods developed at the Hungarian Meteorological Service (HMS).

Climate re-analyses gave new tools and opportunity to wind power related studies. A 5 km resolution multi-level wind field was produced by *Kertész et al*. (2005) downscaling ERA-40 global re-analyses with ALADIN numerical weather prediction model for the 1957–2002 period. It was performed with three nesting steps, first downscaling the 125 km re-analysis to 45 km, than the 45 km resolution ALADIN fields to a 15 km grid, and finally to the target 5 km spatial resolution. The last step was a short-term model run with a special dynamical adaptation configuration of ALADIN that uses a more detailed topography but simplified parametrization. This method was also applied to refine the results of operational ALADIN wind forecasts to provide more accurate and reliable information required by wind power stations. The results were validated by *Szépszó* and *Horányi* (2010) against tower observations in 78 m height for a 7-month period. They found that the dynamical adaptation successfully improved the operational forecasts reducing their systematic errors, however, it did not cure the deficiencies in their wind diurnal cycle.

Regional climate model experiments were started in 2005 at the Hungarian Meteorological Service and Eötvös Loránd University in order to assess future climate change in the Carpathian region. Surface wind speed results of ALADIN-Climate, REMO, and PRECIS RCMs were validated by *Szépszó et al.* (2007) finding mainly underestimation of mean wind speed in ALADIN-Climate results and overestimation by the other two models. Evaluation of surface wind data of RegCM RCM was performed by *Péliné* (2015) in an extensive research on wind conditions over Hungary using re-analysis and observational data as reference. Validation and bias correction was performed on the model results using the CARPATCLIM-HU observation dataset. Bias adjusted projection results were also presented focusing on wind extremes and different wind indices. RegCM results showed rather subtle but interesting changes: increasing occurrence of both small and high wind speed extremes with a negligible change of the mean (*Péliné*, 2015). *Illy* (2014) examined the climate change impact on wind conditions and potential wind power in 10 and 100 m height above surface, based on ALADIN-Climate and REMO projection results considering A1B emission scenario. The 100 m wind speed was extrapolated from the surface using a special wind profile introduced by *Szentimrey et al.* (2006). The changes in wind power were found to be positive but small, under 5 % during all seasons.

The main objective of our study is to present an improved methodological framework (compared to *Illy*, 2014) for assessing near-surface wind speed and wind energy potential in regional climate model results. The method is based on ALADIN-Climate model simulations and ERA-Interim re-analysis data. It aims at evaluating model data in multiple height levels (10, 50, 75, 100, 125 and 150 m) above the surface with minimizing the effects of vertical interpolations and extrapolations. In Section 2, the utilized model and re-analysis datasets are described in addition to the applied vertical interpolation methods. Section 3 contains the validation and projection results regarding wind speed and wind power production on multiple height levels. A brief comparison of projection results with other recent studies can be found in Section 4, and finally, Section 5 closes the article with a short summary and some ideas and future plans that arose while working on the article.

2. Data and method

2.1. Re-analysis data

Re-analysis datasets contain three-dimensional gridded meteorological information of the atmosphere and the surface, gained from observations and short-term numerical model forecasts. Complex data assimilation methods are used to combine the background model estimation with in-situ and remote sensing observational data, considering the different uncertainties and temporal origins of the different data sources. Re-analyses typically extend over several decades, which makes them a useful tool in climate research and monitoring. Due to the physical consistency of the fields, they are applicable as initial and lateral boundary conditions for limited area numerical models, as well. In our study, ERA-Interim re-analysis was chosen as reference data for the validation of ALADIN-Climate near-surface wind speed results for the period of 1981–2000. ERA-Interim is the current generation of global re-analysis datasets, developed at the European Centre of Medium-Range Weather Forecasts (ECMWF). The observations were compiled with the forecasts of the global model version which was operational in 2006 in ECMWF, applying a 4-dimensional variational data assimilation technique. The temporal coverage of the dataset begins on January 1, 1979, and it is continuously updated in near real-time. Its horizontal resolution is approximately 80 km, and it has 60 vertical levels between 10 m and around 64 km of height above the surface (*Dee et al.,* 2011). In our investigation we applied the following variables:

– *u* and *v* wind components on model levels 56–59 (at 0, 6, 12, and 18 UTC);
– temperature on model levels 56–59 (at 0, 6, 12, and 18 UTC);
– surface pressure (at 0, 6, 12, and 18 UTC).

ERA-Interim model levels are numbered starting from the top of the atmosphere with level 1, and increasing in number towards the surface, which is represented by level 61. The above mentioned levels 56 through 59 are usually located between 220 and 30 meters above the ground with slight temporal variation due to the hybrid vertical levels applied in the forecast model. The use of temperature and surface pressure data was necessary for the interpolation process, by which the wind velocities in given model levels were transformed to specific height levels. The method is presented thoroughly in Section 2.3.1.

2.2. Regional climate model data

ALADIN-Climate regional climate model is developed from the ALADIN numerical weather prediction model (*Horányi* et al., 2006) and the ARPEGE-Climat global climate model (*Déqué*, 2003). The model dynamics is taken from ALADIN, which is complemented with the physical parameterization schemes of ARPEGE, to be optimized for processes on climate timescales. ALADIN-Climate horizontal coordinate system is designed on Lambert conformal conic projection, and its vertical coordinates are defined by a hybrid pressure-sigma coordinate system. The prognostic variables are the horizontal wind components, the temperature, the surface pressure, and the specific humidity. The model applies hydrostatic approximation, therefore, the vertical velocity is determined diagnostically. The horizontal differential operators are calculated with spectral approximation, and the temporal evolution of prognostic variables is computed with the combination of semi-implicit and semi-Lagrangian schemes. The physical parametrization package is based on that of ARPEGE-Climat. RRTM (Rapid Radiation Transfer Model; *Mlawer* et al., 1997) scheme is used for calculating the longwave component, and the *Fouquart-Bonnel* scheme (1980) for the shortwave component of radiation. Large-scale precipitation is described by *Smith* (1990), convective processes and precipitation are parameterized with the *Bougeault* method (1985). The atmosphere-surface interactions are handled by the SURFEX scheme (*Masson* et al., 2013), which is also capable of taking the climatic effects of urban surfaces into account. Anthropogenic greenhouse gas emissions are represented through average yearly concentrations of CO_2, CH_4, N_2O, CFC-11, CFC-12 provided by the RCP8.5 emission scenario in the current simulation. Five types of aerosol particles are considered as well: black carbon, organic carbon, sulphate, desert dust, and sea salt.

ALADIN-Climate was adapted at HMS in 2005 (*Csima* and *Horányi,* 2008). Since its adaptation, numerous simulations were performed with different settings in the framework of various downscaling projects (e.g., CECILIA, EURO-

CORDEX). The model version was recently updated to version 5.2, and a new, significantly larger integration domain was chosen for the current experiments in order to improve model performance, especially precipitation bias and extremes. The domain selection was based on the results of a sensitivity study (*Szépszó et al.*, 2015).

In the present research, we evaluate wind data on multiple levels near the surface from the most recent ALADIN-Climate simulations conducted in HMS. One of the examined experiments is driven by ERA-Interim re-analyses (hereafter referred to as ALADIN-ERAI), and the other experiment got its initial and lateral boundary conditions from the ARPEGE-Climat/OPA atmosphere-ocean coupled general circulation model (referred to as ALADIN-ARP). The main characteristics of the two simulations are summarized in *Table 1.* In the case of ALADIN-ARP, there was an intermediate downscaling step: the global model results were first downscaled to 50 km spatial resolution, and then further downscaled to 10 km resolution. Both dynamical downscaling processes were performed at HMS with ALADIN-Climate version 5.2 considering the RCP8.5 emission scenario. The applied model domain (*Fig. 1*) covers the Carpathian Basin, the Alpine region, and a part of the Mediterranean coast. It also contains the whole drainage basin of the Danube and Tisza rivers, which is relevant regarding the potential applicability of the results for hydrological impact assessments.

Table 1. Characteristics of evaluated model simulations

Name of simulation	**ALADIN-ERAI**	**ALADIN-ARP**
LBC	ERA-Interim	ALADIN-Climate (downscaled from ARPEGE-Climat)
Spatial resolution	10 km	10 km
Vertical levels	31	31
LBC resolution	80 km	50 km
Time period	1980–2010	1950–2100
Scenario	–	RCP8.5

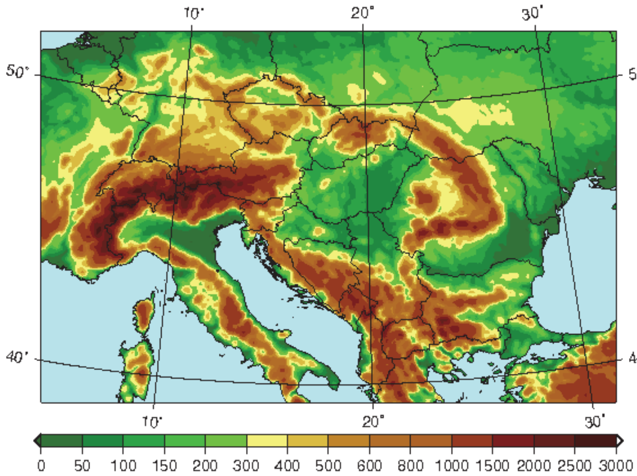


Fig. 1. Integration domain of the analyzed ALADIN-Climate simulations.

The model variables used in the study were the wind components on selected height levels at 0, 6, 12, and 18 UTC. Wind energy estimations require wind data in specific hub (turbine) heights, therefore, besides the 10-meter height, we evaluate the wind speed on 50, 75, 100, 125, and 150 meters above ground level to cover the range of most frequently used hub heights. ALADIN-Climate has a post-processing configuration called FullPos (*Yessad,* 2015) that allows us to retrieve data on any requested height levels above the surface. The interpolation of wind components from model levels to height levels are calculated by the model itself, so no further transformation is needed. The interpolation method applied by FullPos is described in Section 2.3.2.

2.3. Calculation of upper level wind speed

One of the many challenges of wind energy related estimations is the lack of reliable near-surface observational data that can be used to analyze upper level wind climatology and to validate numerical models. Tower measurements exist, but they are rare and scattered in space, therefore, they are not ideal for the validation of gridded model data over a large area. A viable and frequently used way is to extrapolate the observed surface wind velocity to the given height by fitting a wind profile. This method often requires surface parameters (e.g., roughness length) that are difficult to precisely measure and can only be estimated. On the other hand, the impact of surface characteristics on upper level wind conditions diminishes by the height, and they are largely influenced by the atmospheric dynamics. The main goal of our study was to establish a methodology to evaluate the results of ALADIN-Climate model regarding wind speed and wind energy potential on fixed height levels using directly the model level data, thus minimalizing the effects of vertical interpolation. ERA-Interim was chosen as reference because of the availability of upper level wind data. Neither ALADIN-

Climate, nor ERA-Interim uses z-coordinates in vertical direction, therefore, the first step was to transform all the necessary variables from model levels to the chosen height levels in both cases for easy comparison.

2.3.1. Wind speed from ERA-Interim

ERA-Interim vertical coordinates are defined by a hybrid pressure-sigma coordinate system. This consists of pure pressure levels in the upper region (top 24 model levels) of the model atmosphere, with continuous transition into a terrain-following sigma coordinate system at the lower levels. ERA-Interim has 60 hybrid model levels and level 61 represents the surface. The pressure of a given level is the function of surface pressure and two time-independent coefficients that vary in the vertical, but not in the horizontal direction. The pressure of the nth level can be computed by the formula:

$$P_n(\lambda, \phi, t) = a_n + b_n P_s(\lambda, \phi, t), \tag{1}$$

where P_n is the pressure of the nth model level, P_s is the surface pressure, a_n and b_n are the coefficients mentioned above. The actual value of the coefficients for each level can be found in the documentation of ERA-Interim (*Berrisford et al.,* 2011). The method used for transforming the hybrid level wind data to discrete height levels consists of two major steps: (1) first, the height of the model levels is calculated in each gridpoint through all the timesteps; (2) knowing the altitude of model levels in each gridpoint, wind speed is interpolated to the target height by fitting a wind profile to the data at each timestep. For calculating the height of model levels, hydrostatic balance is assumed:

$$P_n = P_s - \rho g h_n, \tag{2}$$

where h_n is the height of the level to be determined, P_n can be computed from Eq. (1) using P_s. ρ is the average air density which is estimated based on the molar form of the ideal gas law:

$$P_n = \rho R_* T_n, \tag{3}$$

where T_n is the temperature on the nth level and $R_* = 287\ \mathrm{Jkg^{-1}K^{-1}}$ is the specific gas constant. With these formulas, the height of each model level can be approximated. After determining these heights in each gridcell, wind speed is calculated using the simple power-law wind profile:

$$v = v_n (h/h_n)^{\alpha}, \tag{4}$$

where v_n is the wind speed on the nth model level, h_n is the height of the model level and h is the target altitude. The Hellmann exponent was chosen to be $\alpha = 0.2$ based on international standards for wind turbine design provided by the International Electrotechnical Commission (*IEC,* 2005).

For every target level (50, 75, 100, 125, and 150 m), this interpolation method was carried out from the two neighboring model levels, resulting in an "upward" and a "downward" fitting of the wind profile (*Fig. 2*). The final velocity was defined as the weighted average of these two values. The weights were specified inversely proportional to the distances between the target level and the two model levels. The average height of the chosen model levels can be seen in *Table 2.* The 75 m target level was an exception, because it is close to the model level 58, therefore, in this case, the wind speed was calculated directly from the level 58 data.

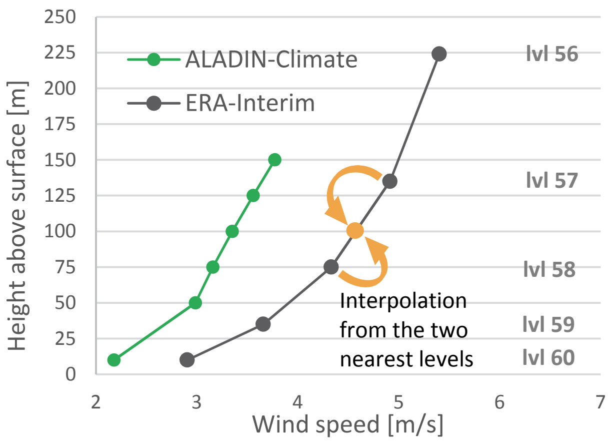


Fig. 2. Interpolation of ERA-Interim wind data to the target (50, 75, 100, 125, 150 m) levels.

Table 2. Average heights of ERA-Interim model levels

Level no.	**Average height above surface**
56	190–220 m
57	130–140 m
58	70–75 m
59	30–35 m

To evaluate the effectiveness of the presented interpolation process, we compare it side by side with a frequently used method, in which the upper level wind speed is extrapolated using only the near-surface values, i.e., the 10-meter wind speed. The comparison was performed on ERA-Interim data. Wind speed on level 58 was chosen as reference for the period of 1981–2000. The 75 m wind speed was calculated in two ways: (1) from data on levels 57 and 59 with the methodology presented above, and (2) with extrapolation from the near-surface wind speed, applying the wind profile of Eq. (4) in both cases. The results show that using data from neighboring model levels, the 75 m wind speed is reproduced with significantly less error: the difference of the calculated and reference wind speeds is less than 3% over all the land surface gridpoints in all seasons and less than 1% over Hungary. When extrapolating from the surface, the departures reach 10–15% over mountain areas and exceed 20% over ocean gridpoints (*Fig. 3*).

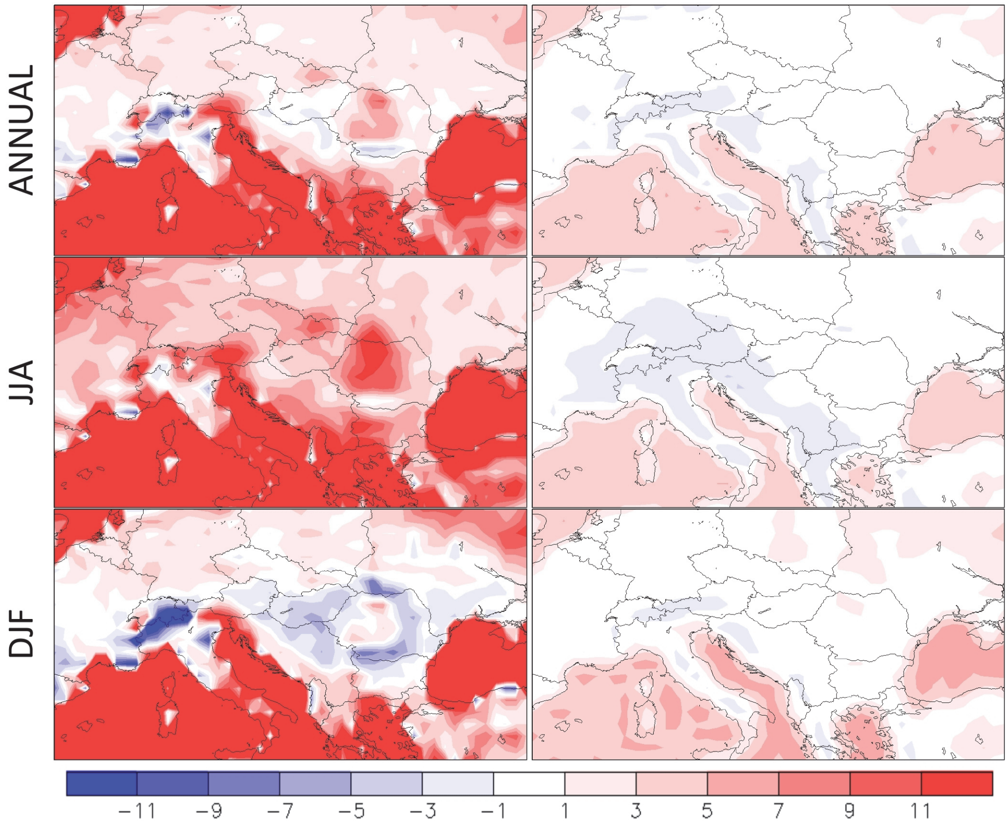


Fig. 3. Comparison of the two applied methods: annual, summer, and winter mean difference (%) between wind speed at level 58 in ERA-Interim and wind speed extrapolated to 75 m using surface data (left) and interpolated using upper level data (right) 1981–2000.

2.3.2. ALADIN-Climate

In case of ALADIN-Climate, the upper level wind components were calculated with the FullPos post-processing package. FullPos contains various options to perform vertical interpolations, making the variables available on any pressure, potential temperature, height, or model level. In the lowest part of the boundary layer, where the wind speed strongly depends on the height above ground level, the vertical profile of wind components is calculated as:

$$v(z) = v_L \cdot C \cdot \ln[1 + \frac{z}{z_L}(e^D - 1) - F], \tag{5}$$

where *C*, *D,* and *F* are coefficients depending on the stability of the atmosphere, the height above surface, and the surface roughness; z_L is the height of the lowest model level, and v_L is the wind component on that level (*Tóth,* 2004). The height of the lowest model level varies in time and space but generally is around 30 m above the surface. Consequently, Eq. (5) is applied to determine wind components on 10 meters. Above this altitude, wind components are calculated with linear interpolation between the neighboring vertical levels (*Yessad*, 2015). The schematic diagram of computation methods used with ALADIN-Climate and ERA-Interim can be seen in *Fig. 4.*

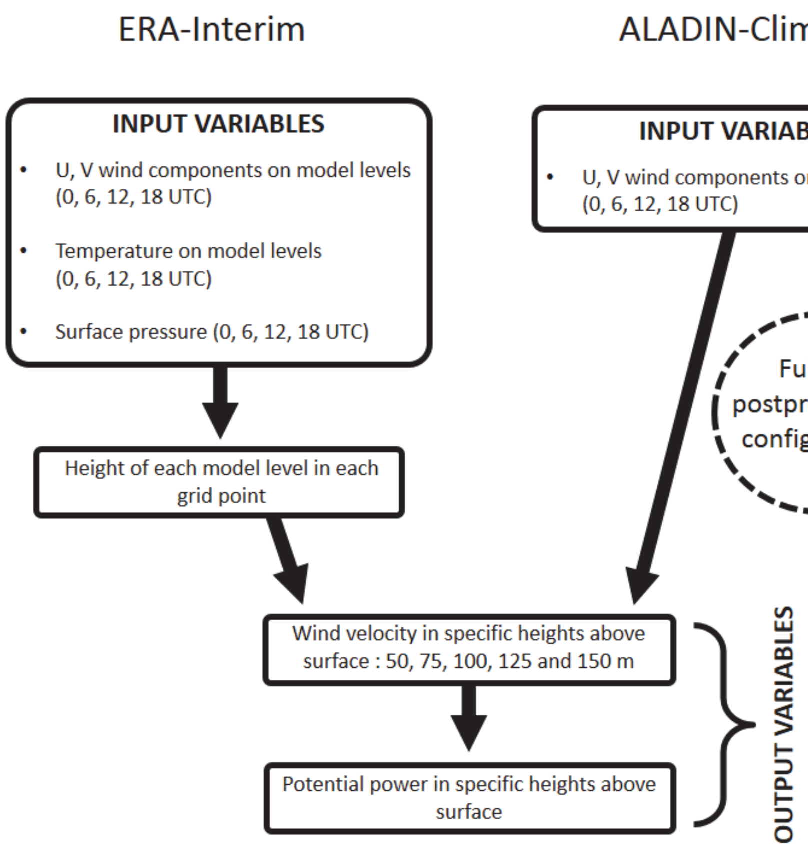


Fig. 4. Schematic overview of the applied interpolation method.

2.4. *Potential wind power production*

In wind power generation, not only the mean wind speed is relevant, but also its distribution. Wind power production was estimated based on the power curve of the Gamesa G90 2 MW rated wind turbine, as it is the most frequently used turbine type in Hungary (*Tóth,* 2012). The power curve defines the power output of the turbine in function of the wind speed in hub height. All wind turbines have a given cut-in wind speed below which power generation is not possible, and a cut-out wind speed above which the turbine is intentionally stopped due to security reasons. The cut-in wind speed of Gamesa G90 2 MW turbine is 3 m/s, and the cut-out speed is 21 m/s.

3. Results

3.1. *Validation*

In this section, validation results of the ALADIN-ERAI and ALADIN-ARP simulations are presented for 1981–2000 using ERA-Interim as reference data. In case of both simulations, the negative bias dominates over the integration domain in all of the chosen height levels. The mean bias of 10-meter wind speed over Hungary is around –15% in ALADIN-ERAI, and it gradually decreases with the altitude reaching an average of -1 % at 150 meters above ground level (*Fig. 5, Table 3*). ALADIN-ARP underestimates wind speed more strongly, and the decreasing trend is less pronounced in this case with a mean annual bias of 22% at 150 m (*Fig. 5, Table 4*). The departure between the ALADIN and ERA-Interim data does not have high spatial variability in either of the simulations. Over Hungary, maximal and minimal errors are found mostly in autumn and summer, respectively (*Table 3*). Despite the systematic underestimation, the interannual variability of the wind speed is well represented in the re-analysis driven ALADIN-ERAI simulation, i.e., the 20-year time series of ALADIN follows the reference values as it can be seen in *Fig. 6*, which also illustrates the altitude dependence of systematic error. The annual distribution of 10-meter wind speed, however, is poorly reproduced by both model simulations. ALADIN-ARP produces the maximum and minimum values in the appropriate months, but the shape of the distribution is too flat compared to the reference datasets. ALADIN-ERAI simulation did not reflect the characteristics of the annual cycle despite its smaller average bias (*Fig. 7*).

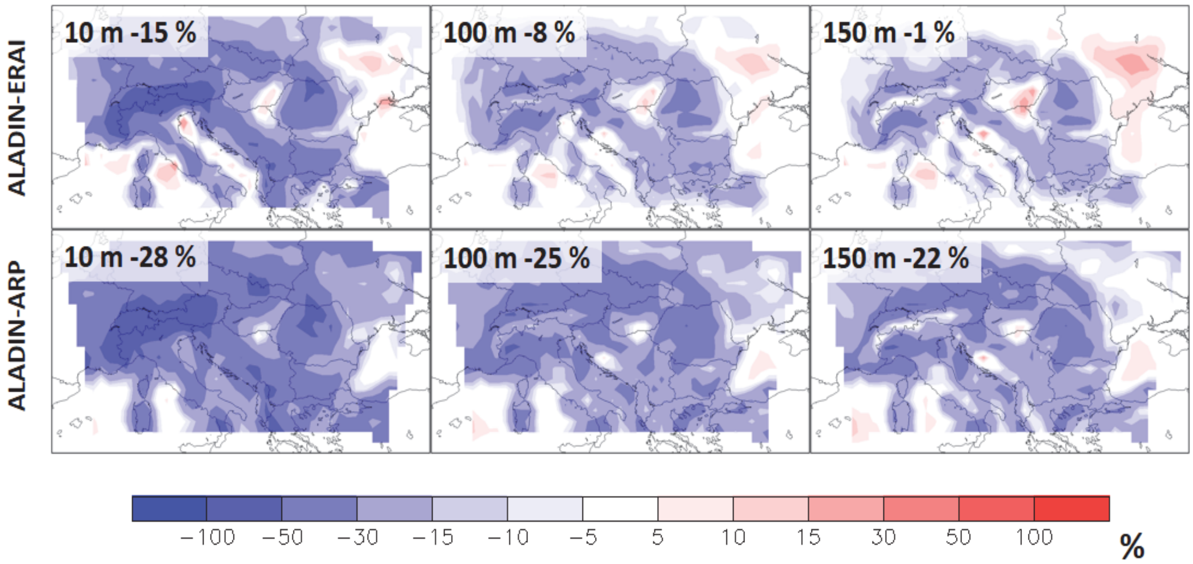


Fig. 5. Annual mean 10 m, 100 m, and 150 m wind speed differences (%) between ALADIN-Climate results and ERA-Interim for 1981–2000. The top left values indicate the average of bias over Hungary.

Table 3. Relative difference (%) between mean wind speeds in ALADIN-ERAI results and ERA-Interim (1981–2000).

Height	Annual	MAM	JJA	SON	DJF
10 m	–15	–18	–8	–21	–13
100 m	–8	–9	3	–14	–10

Table 4. Relative difference (%) between mean wind speeds in ALADIN-ARP results and ERA-Interim (1981–2000)

Height	Annual	MAM	JJA	SON	DJF
10 m	–28	–25	–23	–36	–30
100 m	–25	–20	–16	–34	–30

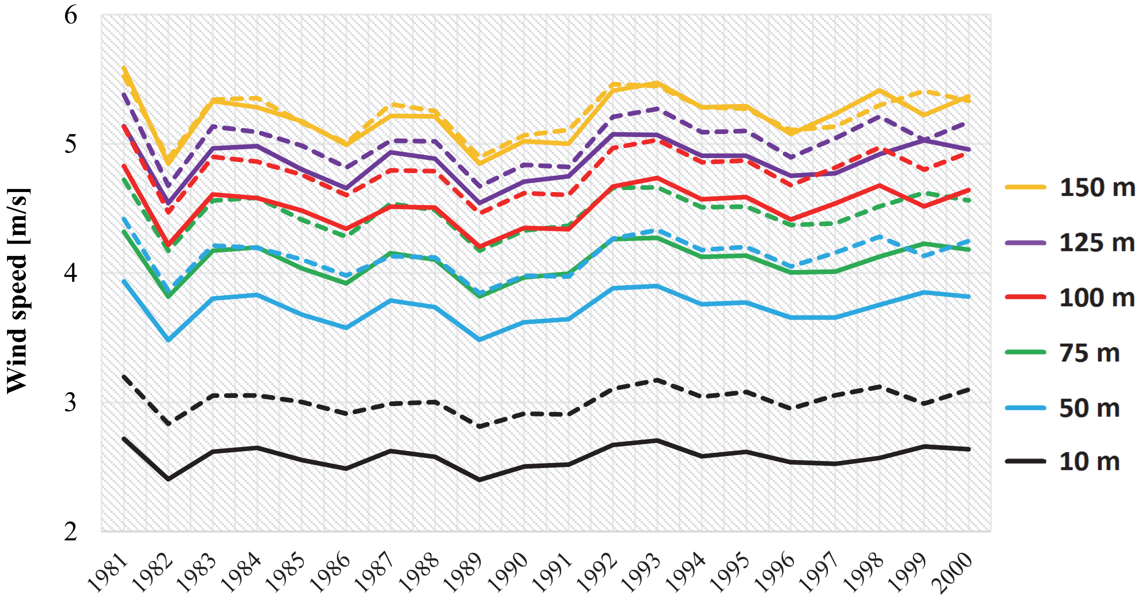


Fig. 6. Annual mean wind speed values (m/s) over Hungary at different heights during 1981–2000. Solid and dashed lines indicate the ALADIN-ERAI simulations and re-analyses, respectively.

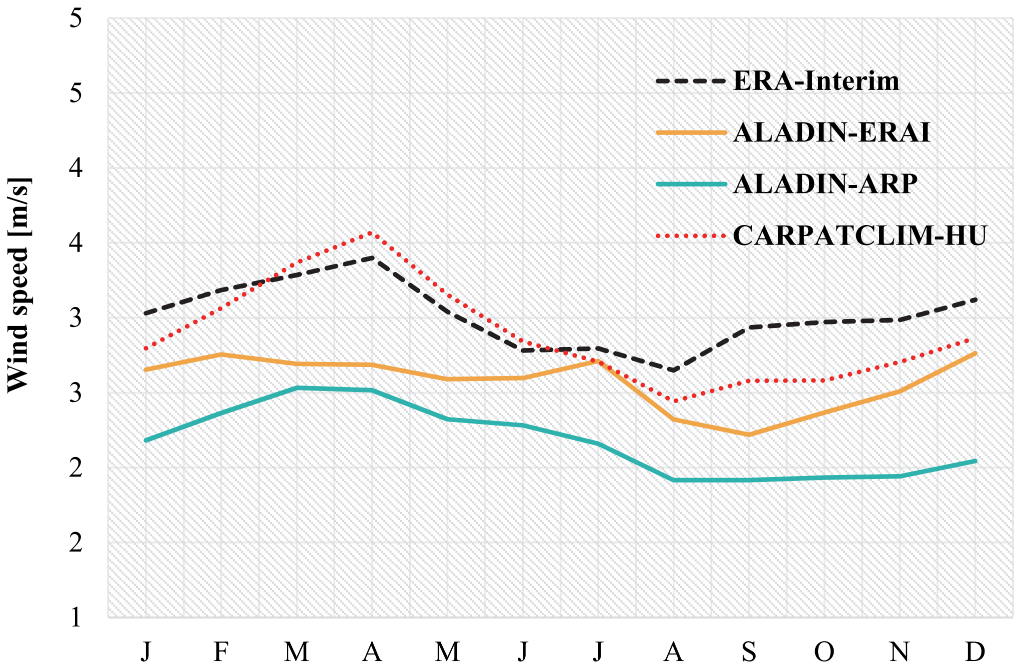


Fig. 7. Monthly mean wind speed (m/s) over Hungary based on CARPATCLIM-HU observational dataset, ERA-Interim re-analysis, and ALADIN-Climate simulation data for 1981–2000.

The vertical wind profile is examined in three gridpoints: two points (A and B) are selected in the territory of Hungary and one (C) over the Mediterranean see (*Fig. 8*). Points A and B represent the locations of the two greatest wind farms in Hungary, and the C point was chosen to investigate a certain model behavior found in projection results over sea gridpoints (further discussed in Section 3.2). The points are selected as the nearest ERA-Interim gridpoints to the targeted locations: A (48° N, 17.25° E); B (47.25° N, 21° E); C (42.75° N, 15° E). In the case of ALADIN-Climate wind fields, an interpolation was performed before extracting the wind profiles. Model outputs were interpolated to the ERA-Interim grid so that the vertical profiles would be comparable with the ones of the re-analysis. *Fig. 8* shows the mean wind profiles at the selected gridpoints. ALADIN-ARP underestimates the wind speed in each location and height level, whereas the sign of ALADIN-ERAI bias depends more on the location and height. The decreasing mean error with altitude is not valid in these selected locations. Wind profile in point C is clearly different from the ones over land: 10-meter values are higher here due to the lower surface roughness of water compared to mainland, which results in a more neutral vertical structure. This aspect is very well reproduced in both model simulations.

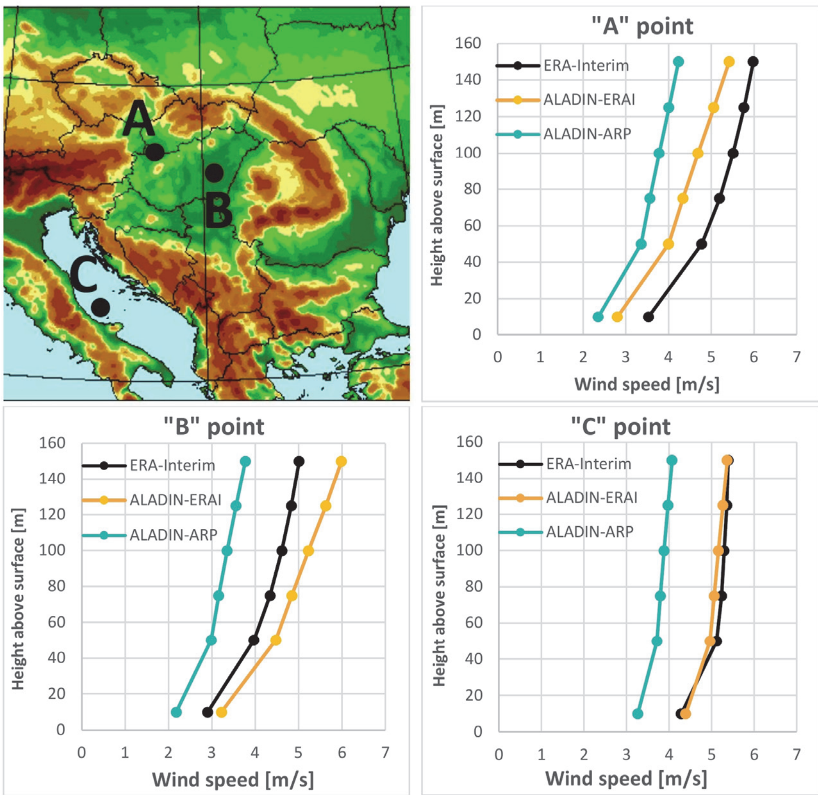


Fig. 8. Average vertical wind speed profiles of ERA-Interim re-analyses (black) and ALADIN-Climate simulations (green and yellow) in three selected gridpoints for 1981–2000. The locations are shown on the map in the top left panel.

Regarding the frequency distribution of 6-hour mean wind speeds at 10 meters, the re-analysis driven simulation overestimates the occurrence of wind speeds smaller than 2 m/s and higher than 9 m/s, while it underestimates the occurrence of wind speeds between 2 and 9 m/s. In the GCM-driven simulation, the frequency of small wind speeds are even more exaggerated, while the values exceeding 2 m/s are underrepresented compared to the reference (*Fig. 9*). With increasing altitude, the difference between the simulated and reference distributions becomes less significant in general, the frequencies of both small and high wind speeds are coming closer to the reference (*Fig. 9*).

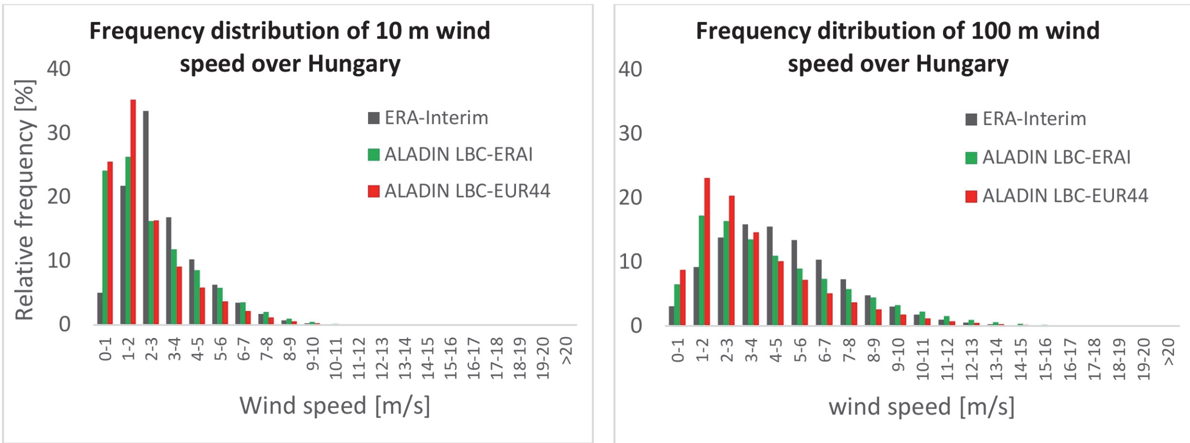


Fig. 9. Frequency (%) of different wind speed categories at 10 m (left) and 100 m (right) based on ERA-Interim data and ALADIN-Climate simulations. Period: 1981–2000.

3.2. Projection results

The changes of future wind conditions are evaluated for two thirty-year periods: 2021–2050 and 2071–2100 with reference to 1971–2000. The projection results are only presented for the near-surface (10 m) and the 100 m height level, although the evaluation was performed for each selected level. The significance of the climate change signals were assessed performing the Welch statistical hypothesis test. The projected changes in near-surface wind speed are mostly below 10% across the whole domain, nonetheless often found to be significant over Hungary during both projection periods. In the mid-century period, the model simulated a slight increase of wind velocity with the exception of the higher mountains and the southwestern part of the domain (*Fig. 10*). The annual mean change over Hungary is around 7 %, and the strongest (9 %) seasonal growth was found in summer and winter (*Table 5*). At the end of the 21st century, the spatial pattern of the climate change signal is similar to that of the first period, but the areas with decreasing wind speed extended. Moving to the 100-meter level, the spatial pattern still remains the same, however, the projected increase of wind speed is smaller (*Table 6*), and the areas with negative change signal are even more pronounced (*Fig. 11*). As mentioned earlier, an interesting model behavior can be observed in summer: there is a relatively strong, 20–30% (0.5–0.8 m/s) local enhancement of wind speed over the Mediterranean Sea in every height level over water gridpoints near the coastlines. Over the land surface, the summer changes are below 15 % in each gridpoint. Similar local maximums were found in the change signal of an RCM ensemble by *Tobin* et al. (2014) over the Baltic and the Aegean Sea. To investigate the cause of this model behavior, the phenomenon needs further research.

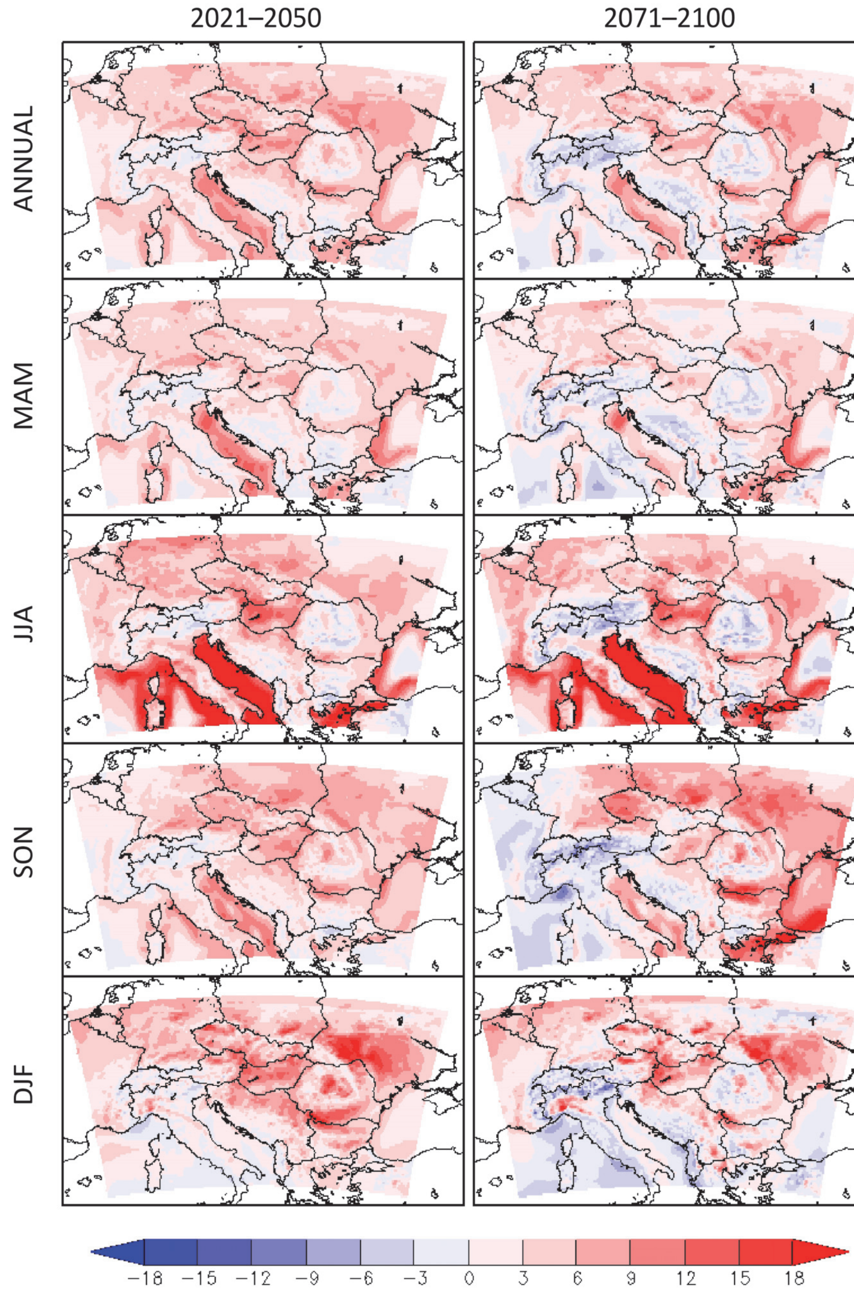


Fig. 10. Annual and seasonal mean changes (%) of 10 m wind speed based on ALADIN-ARP simulation results for 2021–2050 (left) and 2071-2100 (right) with respect to 1971–2000.

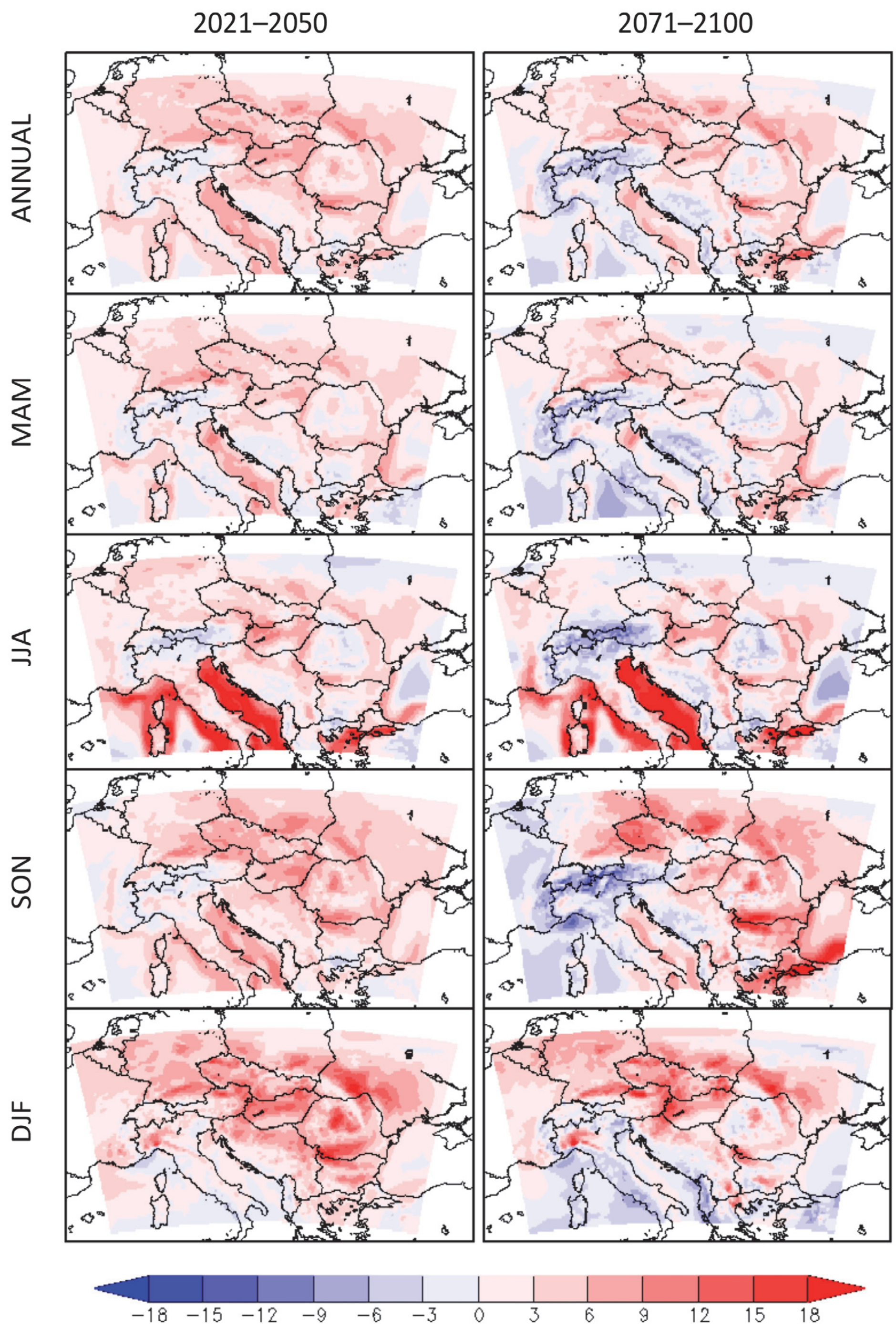


Fig. 11. Annual and seasonal mean changes (%) of 100 m wind speed based on ALADIN-ARP simulation results for 2021–2050 (left) and 2071–2100 (right) with respect to 1971–2000.

Table 5. Annual and seasonal mean change (%) of 10 m wind speeds in ALADIN-ARP simulation results over Hungary with reference to 1971–2000

10 m	**Annual**	**MAM**	**JJA**	**SON**	**DJF**
2021–2050	7	5	9	7	9
2071–2100	5	3	9	4	6

Table 6. Annual and seasonal mean change (%) of 100 m wind speeds in ALADIN-ARP simulation results over Hungary with reference to 1971–2000

100 m	**Annual**	**MAM**	**JJA**	**SON**	**DJF**
2021–2050	6	4	6	7	9
2071–2100	4	2	5	4	7

The frequency distributions of 10 m and 100 m wind speeds are presented in *Fig. 12* for both the projection and reference periods. To highlight the differences between the distributions, the changes corresponding to each interval are also shown. At the near-surface level, the most frequent wind speed category is between 0 and 2 m/s, and this is where the largest change is projected. Wind speeds below 2 m/s will be less frequent, and the occurrence of values between 2 and 8 m/s will slightly increase in both future periods compared to the reference. At the 100 m height, the peak of the histogram is between 1 and 2 m/s with a frequency around 20%. According to the model results, the number of events with wind speeds under 3 m/s is decreasing, while wind speeds above that limit are slightly more likely to happen in both projection periods.

The mean changes of wind power production are presented for the 100 m level. It shows similar pattern to the 100 m wind speed change, but with more contrast due to its cubic relation to wind velocity. Over Hungary, 13% and 8% mean annual increase is projected in 2021–2050 and 2071–2100, respectively (*Table 7*). In the second period, decreasing tendencies become particularly relevant over the Alps and along the coastline of Southern Europe. The effect of summer wind strengthening over certain parts of the Adriatic Sea is clearly visible causing an increase in potential wind power production of more than 30 % over those gridpoints (*Fig. 13*). Focusing on Hungary, the changes of the given categories of potential wind power production values were analyzed in points A and B. The experienced increasing frequency of wind speeds over 3 m/s has a relatively strong positive effect on the potential power distribution, since the Gamesa G90 turbine, which was used as reference, has a cut-in speed of 3 m/s. *Fig. 14* shows that the number of cases where the output power equals to zero is decreasing by 3–6% in both locations through all seasons.

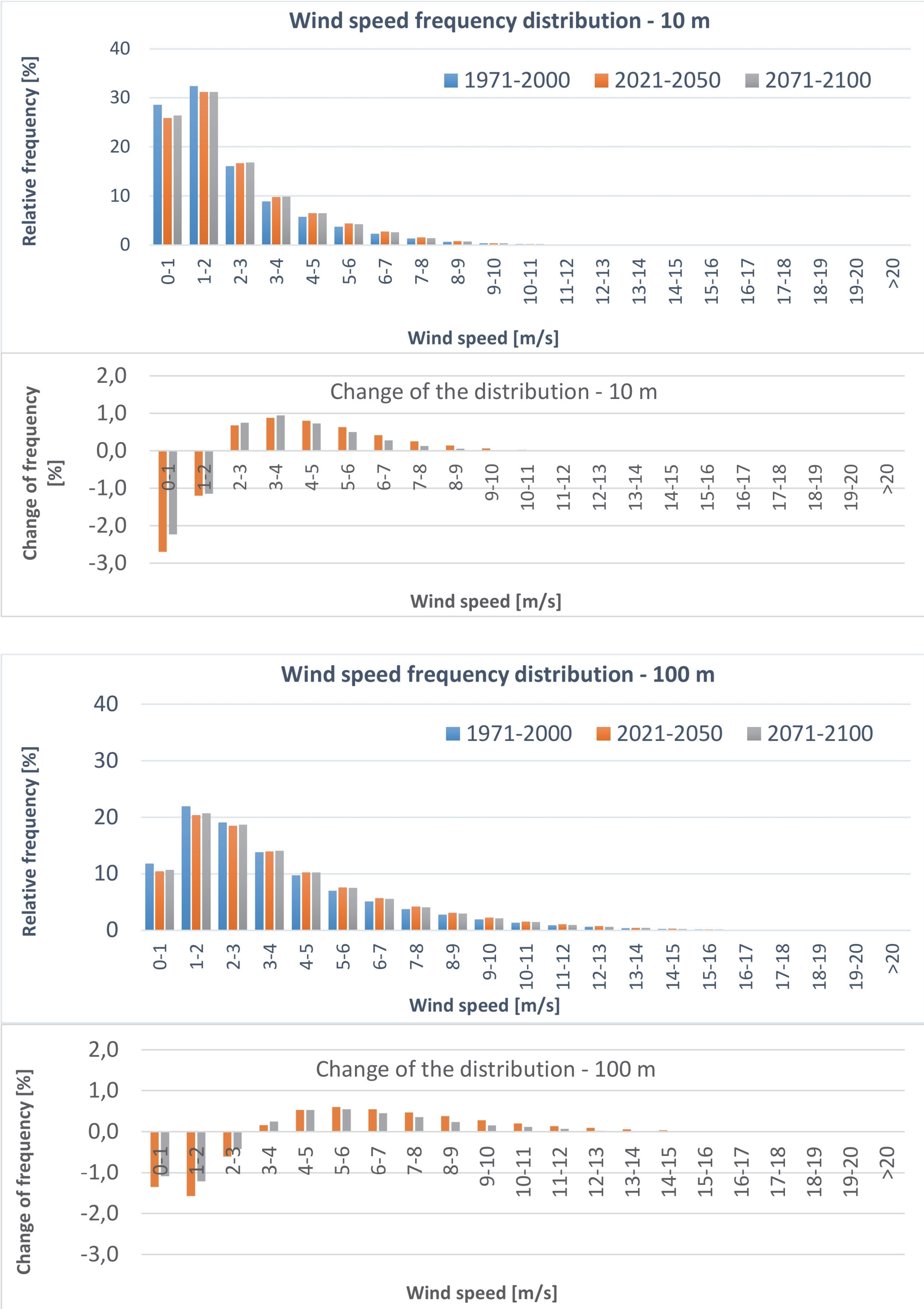


Fig. 12. Average frequency (%) of different 10 m (top) and 100 m (bottom) wind speed categories and projected frequency changes (%) based on ALADIN-ARP simulation results.

Table 7. Annual and seasonal mean change (%) of wind energy production in ALADIN-ARP simulation results over Hungary at 100 m height with reference to 1971–2000

100 m	Annual	MAM	JJA	SON	DJF
2021–2050	13	7	13	13	16
2071–2100	8	3	7	7	14

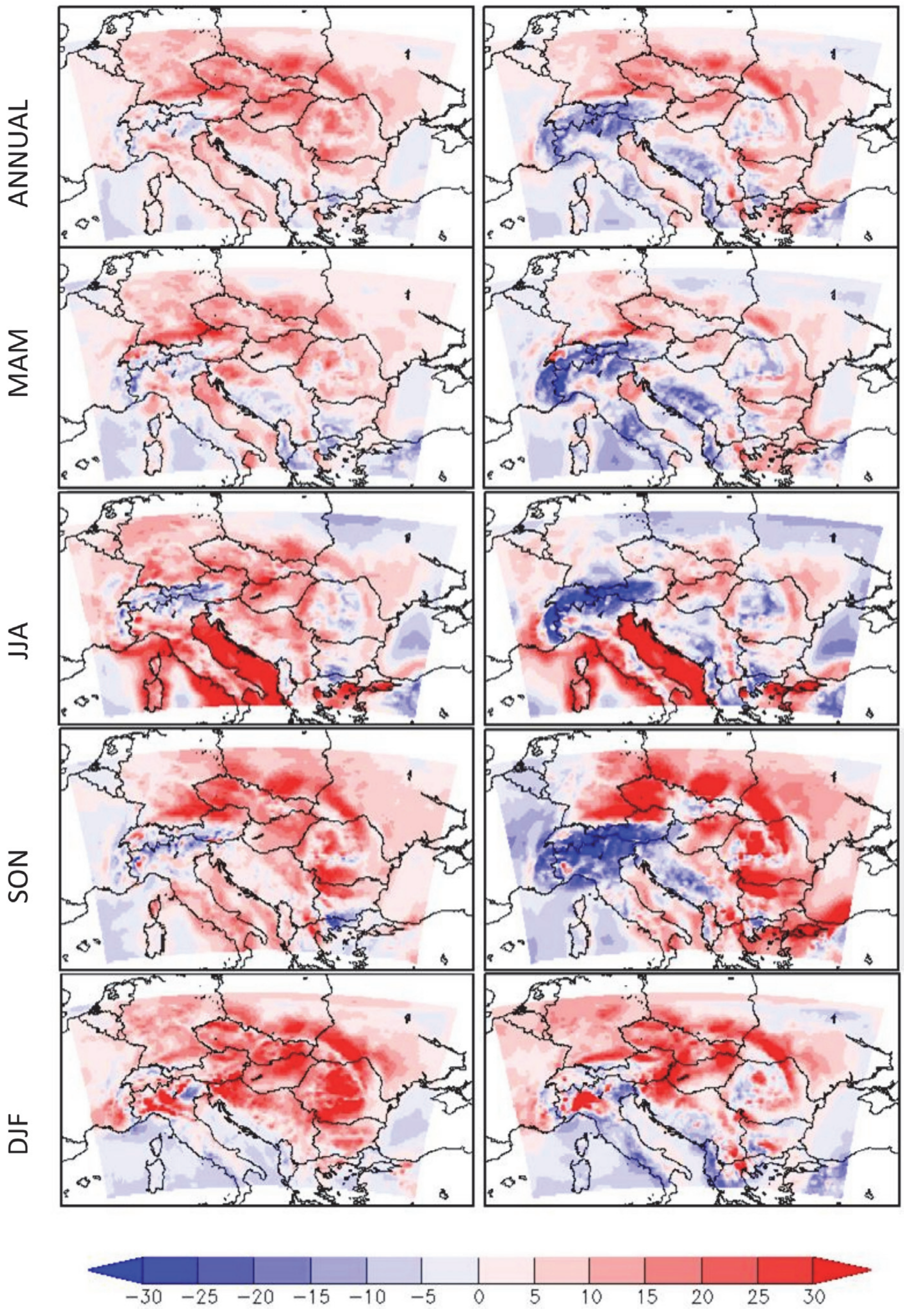
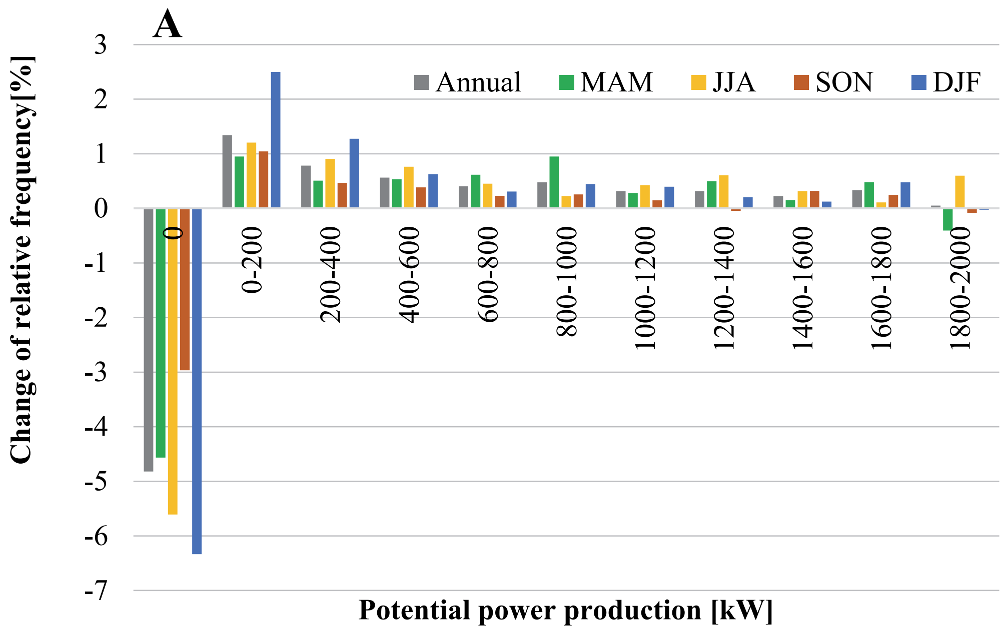


Fig. 13. Annual and seasonal mean changes (%) of potential wind power production at 100 m height based on ALADIN-ARP simulation results for 2021–2050 (left) and 2071–2100 (right) with respect to 1971–2000.



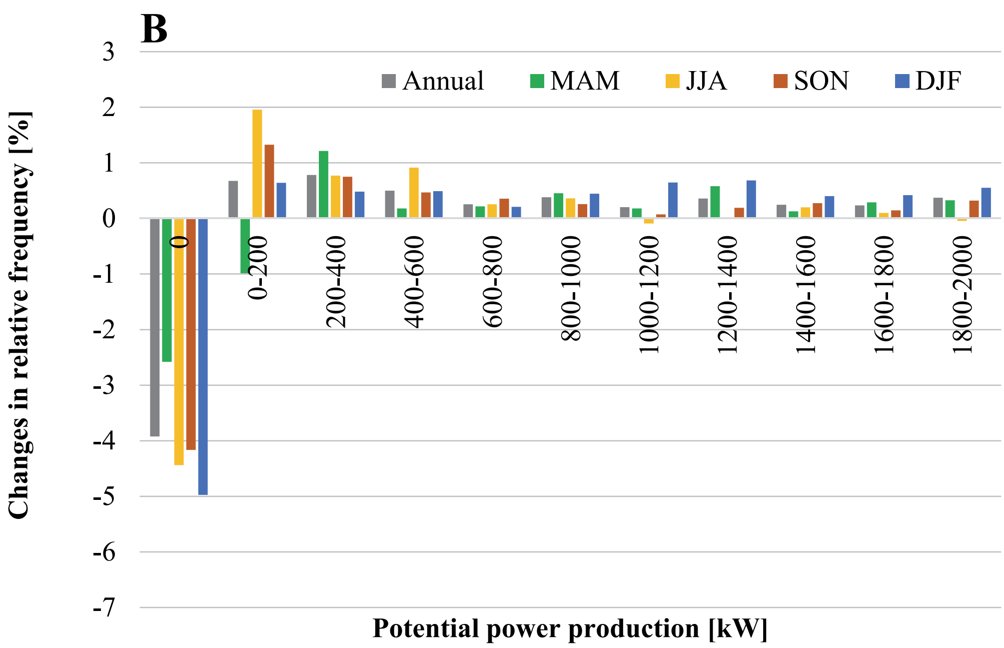


Fig. 14. Annual and seasonal changes (%) in the frequency of potential wind power production categories in point A (top) and B (bottom) based on ALADIN-ARP simulation results for 2021-2050 with respect to 1971–2000.

4. Outlook

Climate model results inherently contain uncertainties originating from the approximations of physical processes, anthropogenic effects, and the natural variability of Earth's climate system. This fact should not be ignored when evaluating simulation results. Ideally, a properly selected ensemble of model projections would be the best basis for future climate estimations. In our case, the focus was on establishing the evaluation methodology for upper-level wind conditions, and it was demonstrated on the outputs of a single climate model. Therefore, our conclusions regarding the climate change effects on near-surface wind climatology do not include information about the projection uncertainties. However, we can compare our results with other assessments of the future changes in wind potential. The comparison is not precise because of the different time periods or emission scenarios considered, nevertheless, it gives a basic overview about the position of ALADIN-Climate results in context of a wider range of climate simulations. As a general statement, it can be said that the expected changes in wind speed and wind energy potential over Europe are rather subtle, but several studies show a slight increasing tendency over Northern Europe and decreasing tendency over Southern Europe (*Pryor et al.,* 2005; *Hueging et al.*, 2013; *Tobin et al.,* 2014; *Reyers et al.,* 2016. Two of these studies are discussed here in detail, in which the upper level wind speed was extrapolated from surface data with the power-law wind profile.

Tobin et al. (2014) examined the changes in potential wind power generation by evaluating 15 RCM simulations downscaling 6 different GCMs under the SRES A1B emission scenario from the ENSEMBLES project. The ensemble mean showed changes within ±15% of extractable wind power by the end of the 21st century. There is a decreasing tendency over the Mediterranean areas (except the Aegean Sea) and an increasing trend over Northern Europe. Some relatively strong changes were found over a few sea gridpoints that resemble the summer change signal found in ALADIN-Climate results (*Fig. 15*).

In the research of *Reyers et al.* (2016), results of the 22 GCM simulations of Coupled Model Intercomparison Project Phase 5 (CMIP5) were downscaled over Europe with a statistical-dynamical method to estimate future changes of potential wind energy under RCP4.5 and RCP8.5 anthropogenic scenarios. A few percent increase of wind energy was found over Northern and Central Europe and a small decrease over Southern Europe and the Mediterranean Sea (*Fig. 16*). More robust changes are projected by the end of the century. The spatial pattern of the ensemble mean change in wind energy production is similar to our results, but its magnitude is smaller (±4%).

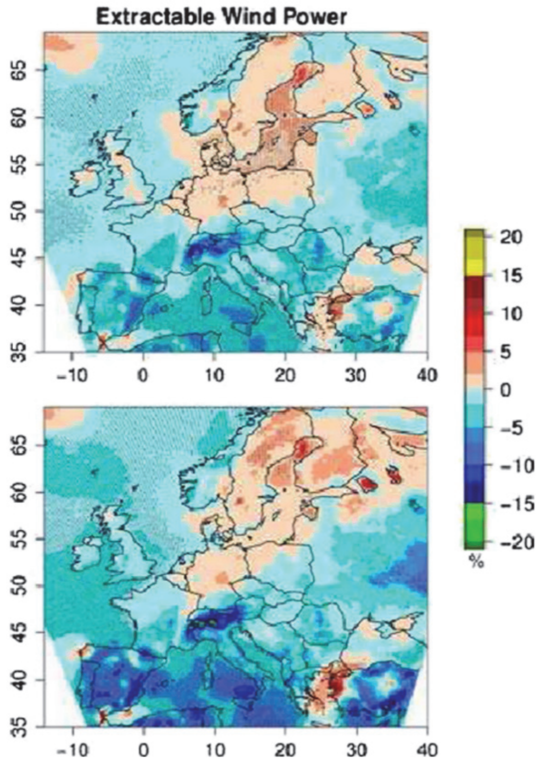


Fig. 15. Ensemble mean of annual changes in extractable wind power (%) for 2031–2060 (top) and 2071–2100 (bottom) with respect to the 1971–2000, based on results of RCM simulations in ENSEMBLES project using A1B emission scenario (*Tobin* et al., 2014).

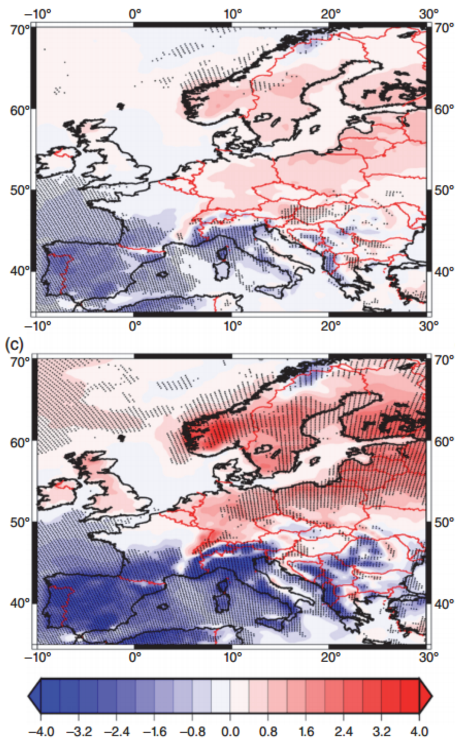


Fig. 16. Ensemble mean of annual change in extractable wind power (%) for 2021–2060 (top) and 2061–2100 (bottom) with respect to the 1961–2000 period, based on RCM simulations using RCP8.5 emission scenario (*Reyers* et al., 2016).

5. Summary

A methodology was developed and presented to assess past and future wind speed and potential wind power production on multiple height levels above the surface based on ALADIN-Climate regional model results. ERA-Interim re-analysis was used to validate the model results for the period of 1981–2000, and the future climate change was evaluated for the near- and far-future, i.e., for 2021–2050 and 2071–2100. The upper level wind velocities were calculated by interpolation of data from hybrid model levels in case of the model and the reference data, as well. It was shown that the applied interpolation method yields more accurate results compared to extrapolation from the 10-meter fields. According to the validation results, both the GCM- and re-analysis, driven simulations reasonably reproduced the near-surface wind climatology over the integration domain with a small underestimation. The interannual wind speed variability and the shape of the vertical profile are well represented in the simulations, however, the annual distribution is not accurate in the model results.

Future projections were carried out considering the RCP8.5 scenario. Results show a slight, 4–7% increase in wind speed over Hungary across the chosen height levels, which is found statistically significant over the majority of the country. Wind speeds under 2–3 m/s are projected to be less frequent in the future, while reduction in occurrence of the moderate wind speeds between 3 and 10 m/s is foreseen. The potential wind power production was produced from the 100-meter wind speed using the power curve of the Games G90 2 MW wind turbine. Projections showed an increase in average potential wind power production over Hungary with a magnitude of 8–13%, and a 3–5 % decrease is indicated in the occurrence of periods with zero power output. To place our findings in broader context, we briefly compared our projection results with outcomes of two recent studies which confirmed our main conclusions.

In the future, we would like to develop and further improve our method by validating model results with higher resolution references (e.g., with regional and new re-analyses) and by involving further regional climate simulations to address the projection uncertainties. Besides mean wind speed characteristics, we also plan to examine future changes in wind extremes.

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