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Validation of the dynamically adapted high-resolution wind forecasts for the wind power stations in Hungary

Gabriella Szépszó* and **András Horányi**

Hungarian Meteorological Service
P.O. Box 38, H-1525 Budapest, Hungary
E-mails: szepszo.g@met.hu; horanyi.a@met.hu

**Corresponding author*

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Abstract — In the recent years, the interest has been increasing regarding the more and more precise prediction of the low-level atmospheric wind characteristics over Hungary. At the Hungarian Meteorological Service this challenge had been completed with the application of the high-resolution dynamical adaptation originally developed in the framework of the ALADIN cooperation in the late 90s. The dynamical downscaling of the coarser wind fields is realized with the ALADIN meso-scale numerical weather prediction model by a half-hour model integration on 5 km horizontal and 15-level vertical resolution with simplified physical parameterization package. It is shown that this dynamical adaptation step improves the original 10-meter wind forecasts obtained with the 8 km operational version of the ALADIN model. The performance of the method was intensively verified with respect to the local observational data at 80 meters for a wind power station situated at the northwestern part of Hungary. The validation results indicate that the dynamically post-processed forecasts do not have systematic errors, however, the diurnal wind cycle is not properly simulated. In the seven-month evaluation period the low and high wind speeds are overrepresented, whereas the occurrences of intermediate velocities are underestimated. The results are rather satisfactory for the investigated location, however, ideas are also presented for further improvements of the wind predictions.

Key-words: numerical weather prediction, ALADIN limited area meso-scale model, dynamical adaptation, low-level wind, verification

1. Introduction

Precise wind forecasts for the near-surface are crucial for the wind power stations, since they are obliged to make a priori estimation of their daily energy production. For this purpose the only solution is provided by the application of short-range numerical weather prediction (NWP) models. Nevertheless, the accurate wind information is desired in such detail, which is not ensured by today's typical operational high- (8–10 km) resolution weather predictions. Therefore, the operational forecasts need to be further enhanced by appropriate (dynamical) methods.

Increasing the spatial resolution of the limited area models (LAMs) seems to be a natural and simple way to improve the quality of the predictions. Nevertheless, the horizontal mesh cannot be always excessively refined without reconsideration of the physical parameterization and dynamical core of the NWP models. One obvious and essential change together with the resolution increase is the abandonment of the hydrostatic approximation. The most important phenomena to be more precisely or explicitly described by the non-hydrostatic models are the cloud-, microphysics, and micro-scale processes (e.g., convection), which play key role on the 2–5 km horizontal resolution. The complexity of this kind of models is significantly higher, as besides the vertical velocity their microphysical part is also extended with further prognostic variables associated with the different phases of water. Thanks to these enhancements, not only the precipitation-related processes are better simulated in the non-hydrostatic manner, but also the strong wind events accompanying some of the extreme weather situations.

Today, non-hydrostatic modeling is an area of intensive research and development of numerical weather prediction; however, its computational demands are still too high for its widespread applications. The dynamical adaptation (DADA) procedure (*Žagar* and *Rakovec*, 1999) presents a brilliant (simple and elegant) solution for the more accurate description of the small-scale wind characteristics of the atmosphere. The main advantages of the method are, that it does not require huge efforts on model developments (like for non-hydrostatic models or for the implementation of sophisticated physical parameterization schemes), and additionally, it can be realized with modest computational resources. From the practical point of view, the first step of the DADA method is the interpolation of the coarser-resolution forecast onto a finer-resolution grid (not bringing any new information into the forecast), which is followed by a short model integration on this very high resolution for the adaptation of the large-scale fields to the detailed surface characteristics. This model running takes only 30–45 minutes, while the wind is adapted to the new representation of the orography and possibly to other surface features (*Žagar* and *Rakovec*, 1999). This integration does not use the full, complex numerical model: only those processes are taken into account, which can affect the near-surface wind field and those ones are excluded, which would need more time to develop than the applied 30–45 minutes (for instance, the diabatic processes as cloud water vapor condensation, precipitation formation, or temperature changes due to radiation). The simplification concerns also the vertical levels: since the wind is influenced by the topography mainly in the lower part of the atmosphere, the number of vertical layers is reduced in the stratosphere and upper troposphere. Further necessary precondition for the success of the method is the capability of the driving model to provide realistic forecasts for the target area, because DADA cannot cure the deficiencies of the original (large-scale) prediction, it only adds some fine-scale details developing due to the more precise surface conditions.

The dynamical adaptation method is a widely used efficient technique to improve the predicted wind field; its positive impacts are anticipated especially over terrains with complex topography (e.g., in mountains or at coastal regions), in case of strong wind events, and when the dynamical forces are determining the flow. Applicability of the dynamical adaptation in the prediction of extreme winds was investigated in the case studies described by *Ivatek-Sahdan* and *Tudor* (2004). They were studying two *bora* events, which usually evolve in winter due to the temperature gradient between the cold continental and mild sea surface at the eastern side of the Adriatic Sea and it is accompanied by strong wind speeds exceeding even 15 m/s in average. The dynamical adaptation procedure was applied on 2 km horizontal resolution for the original NWP products available on an 8 km grid. The "low-resolution" model was capable of predicting the start and end of the extreme events, however, their strengths were underestimated. DADA presented more realistic wind speeds, moreover, it was also shown, that neither the dynamical adaptation with the use of complete physical parameterization set nor the full model forecast on 2 km resolution could outperform it.

Combination of the method with a non-hydrostatic model was explored by *Alexandru* (2004). The 10 km resolution forecast for Romania was dynamically downscaled to 2.5 km, on the one hand, by the non-hydrostatic version of the ALADIN/Romania model, and on the other hand, with its hydrostatic version. The non-hydrostatic downscaling solution was not able to provide additional important details, which would justify its increased computational costs. In another investigation (*Vasiliu*, 2005), a thorough verification of the results produced by the hydrostatic setup was carried out for a 5-month period concentrating on two areas of interest: the Black Sea coast and a mountainous region of Romania. The improvement of the wind fields could be noticed over the mountain region, while at the coastal territory only minor advantages could be detected.

A new scope of the method was presented at the University of Vienna (*Beck et al.*, 2005), at the Hungarian Meteorological Service (HMS) (*Kertész et al.*, 2005), and in Ljubljana (*Žagar et al.*, 2005): dynamical downscaling of the ERA-40 re-analysis data (*Simmons* and *Gibson*, 2000) in order to produce high-resolution wind climatology over the Alpine region, Hungary, and Slovenia, respectively. The fact, that the coarse-resolution re-analysis dataset describes only the large-scale patterns of the flow, justified the relevance of the use of dynamical adaptation. Since the resolution difference between the initial global and the target domains was quite significant (125 km versus 12, 5, and 2.5 km, respectively), the downscaling was designed in a hierarchical structure with two nested short-range ALADIN model integrations with increasing resolution. In the final step, the special dynamical adaptation configuration of the ALADIN model (i.e., DADA as described above) was applied to reach the desired wind climatology. The results were validated against observations (*Beck* and *Ahrens*, 2006; *Kertész et al.,* 2005; *Žagar et al.,* 2006), and the verification indicated that the dynamical downscaling is able to produce improved and more detailed wind climatology than the initial large-scale data.

In the last decade, the technique is applied at the Hungarian Meteorological Service in order to operationally produce precise wind fields for aviation weather forecasts and in the last few years for the wind power stations to their energy production estimates. From the point of view of the wind energy potential, the northwestern region of Hungary possesses the most advantageous climatological characteristics: this territory lies along the relatively strong and dominant northwesterly flow (*Kertész et al.,* 2005). Some favorable area can be also found over the eastern part of the country, where the northeasterly winds are typical. Until recently, in Hungary the dynamically adapted wind fields could be verified only against 10-meter wind observations, but since the end of 2008, a cooperation has been started with the wind power stations: they continuously provide their measurement data valid at the hub height of the power plant, which make a comprehensive verification of the simulated higher-level wind results possible. The novelty of the utilization of this new source of information is, that the model performance will be known not only on the levels of SYNOP measurements, but also at the heights, where the results are directly used. Therefore, the present study is dedicated to the validation of the dynamical adaptation method applied at HMS for the prediction of the low-level wind fields.

After this introduction, Section 2 describes the most important characteristics of the wind forecasts and observational dataset used as input information for the evaluation, and the employed verification method is also briefly presented. Section 3 is devoted to the thorough analysis of the results obtained by the application of upper-level observational data at Mosonszolnok-Levél. In Section 4, several open issues are addressed and discussed together with those major conclusions, which can be drawn based on the 7-month validation.

2. Methodology

2.1. High-resolution dynamical adaptation of wind forecasts

In the operational practice, the short-range weather forecasts of the Hungarian Meteorological Service are based on the ALADIN meso-scale numerical weather prediction model. ALADIN (*Horányi et al.*, 2006) is a spectral limited area model, where the horizontal meteorological fields are represented by full harmonic functions (2-dimensional Fourier decompositions). In vertical a hybrid coordinate system is defined (*Simmons* and *Burridge*, 1981): terrain following at the lower model levels and pressure-type for the upper atmosphere. For the vertical equation of motion the model uses the hydrostatic assumption, its prognostic variables are the temperature, horizontal wind components, specific humidity on the model levels, and the surface pressure. Due to the combined semi-implicit and semi-Lagrangian schemes (*Temperton* and *Staniforth*, 1987) applied for the temporal integration, a very high computational efficiency can be realized: for instance, at 8 km horizontal resolution 5-minute integration time step can be used.

Presently, the ALADIN weather forecasts are produced operationally four times a day: at 00, 06, 12, and 18 UTC for 54-, 48-, 48-, and 36-hour periods, respectively. The integration domain covers mainly continental Europe with 8 km horizontal resolution and 49 vertical levels (see *Fig. 1* and *2*). The initial condition for the integration is provided by the 3-dimensional variational data assimilation procedure (*Bölöni*, 2006) developed for the ALADIN model. The time-dependent lateral boundary conditions in 3-hour frequency are ensured by the global NWP model of the European Centre for Medium-Range Weather Forecasts (ECMWF).

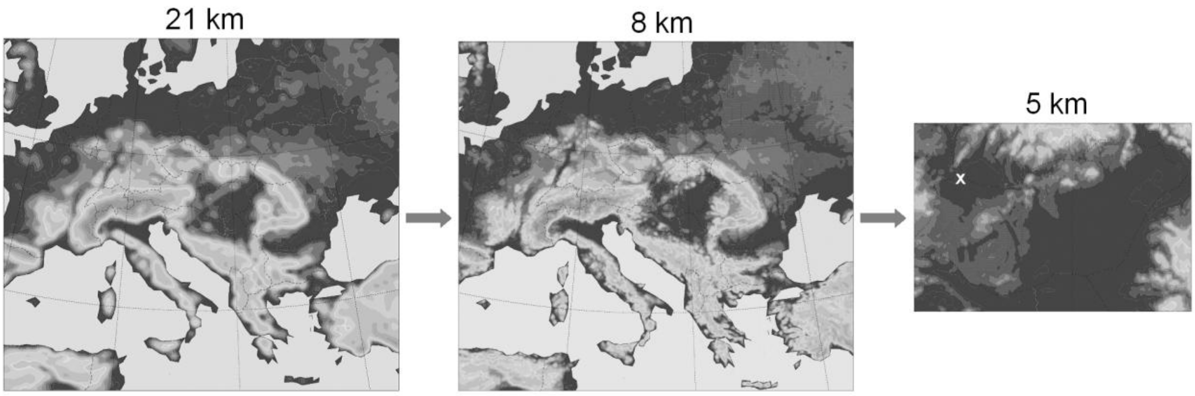

Fig. 1. Orography of the nested model integrations with increasing horizontal resolution: approximately 21 km for the global ECMWF grid (left; in the figure only the selected target integration domain can be seen), 8 km for the operational ALADIN forecast (middle), and 5 km over Hungary for the dynamical adaptation (right). The white “x” on the right represents the selected verification point, Mosonszolnok-Levél.

The raw wind predictions are dynamically refined in the planetary boundary layer, i.e., an additional dynamical adaptation step is performed on the operational model outputs. In practice, the original 8 km resolution information is interpolated onto a 5 km resolution grid (see *Fig. 1*), and the number of vertical layers is reduced in the upper atmosphere resulting in 15 model levels focusing on the planetary boundary layer (see *Fig. 2*). Using these fields as initial and lateral boundary conditions, a simplified model integration lasting 29 minutes (with 60-second time steps) is carried out applying DADA mentioned in the introduction (*Žagar* and *Rakovec*, 1999). This short dynamical post-processing method adapts the near-surface wind to the more detailed topography taking the "large-scale" forcing from the operational ALADIN model. The final output fields are obtained through vertical interpolation or extrapolation on the desired height coordinates, which are defined at every 10 meters between 10 and 500 m. Vertical post-processing (*Yessad*, 2009) consists of either a linear interpolation for the layers positioned between two model levels or an extrapolation (with the application of logarithmic profile) for heights below the lowest model level (e.g., at 10 meters).

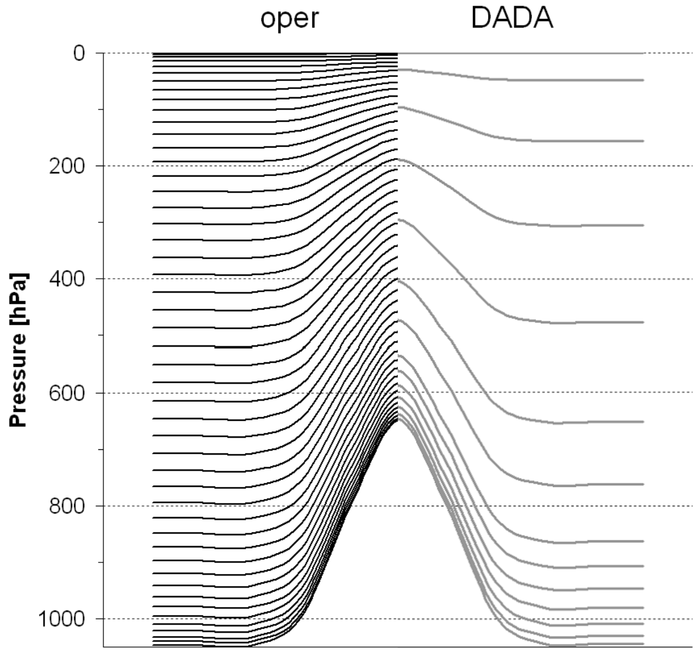

Fig. 2. Hybrid vertical coordinate levels used at the operational forecast ("oper", black curves on the left) and the dynamical adaptation ("DADA", gray curves on the right) with 49 and 15 levels, respectively.

2.2. Input data for the verification

The Hungarian Meteorological Service produces wind information operationally for the wind power plants based on its high-resolution dynamically adapted forecasts starting at 00 UTC and valid for 54 hours. The nearest grid point and height to the given power station is selected as the predicted value, therefore, the 5 km horizontal grid spacing applied at the final dynamical adaptation step allows 3.5 km precision, whereas in vertical the final levels at every 10 meters ensure 5-meter accuracy. The present wind forecast evaluation was carried out for the location of Mosonszolnok-Levél, which is situated in the northwestern part of Hungary at approximately 120-meter height above the sea level (see the white "x" in *Fig. 1*). This power station park stands in a relatively flat area in the gate of the northwesterly flow zone, which is a climatologically favorable position from the aspect of wind energy production. In this location the wind speed and direction forecasts are provided at the hub-height of the power plants, i.e., at 80 meters above the surface. The forecasts are started from 00 UTC, however, they are used from 9 a.m. (in local time) onwards until 1 a.m. (also local time) of the 3rd forecast day. The output frequency of the forecasted wind data is 15 minutes, and the model data describe the instantaneous wind components of the flow in these time steps. From the observation side, the measurements were available at every 10 minutes for the period of April 19 – November 17, 2008. The anemometer is located on an independent tower, at the same height as the hubs of power plants, i.e., in around 78 meters above the surface, and it provides the wind speed as an average over the preceding 10-minute period. It can be read from *Table 1*, that the ALADIN model precisely represents the elevation of the selected point, e.g., its altitude in the model is almost equal with its real height above the sea level.

Table 1. Main characteristics of the input wind datasets: provided wind information, temporal range of the forecasts (LT: in local time), temporal resolution of the produced data, height above the sea level and surface (respectively), and geographical location of the selected point

	Data	**Range**	**Frequency**	**Height**	**Coordinates**
Forecast	Instantaneous wind speed	40 hours from 9 a.m. LT	15 min	125 + 80 m	47.891°N; 17.166°E
Measurement	Mean wind speed (over the last 10 minutes)	-	10 min	124 + 78 m	47.887°N; 17.176°E

Since the data originating from two sources do not correspond to the same type of wind information (i.e., mean and instantaneous values), and moreover, they are available for different time intervals, their direct comparison is not possible. Therefore, the verification was realized on the basis of averages at every half an hour, which were calculated from the wind speed of two time steps in the forecast case and three measurements in the case of observational data. (For instance, for the evaluation at 10:30 UTC, the measurements at 10:10, 10:20, and 10:30 UTC, and the forecasts at 10:15 and 10:30 UTC were respectively averaged, then compared.)

2.3. Verification technique

Evaluation of the wind forecasts for Mosonszolnok-Levél was accomplished for the available seven-month period. On the one hand, the general flavor of the wind predictions during the verification interval is obtained by the unified assessment of all forecast ranges, and on the other hand, the quality of the simulated results is also investigated forecast range by forecast range, separately. Considering all time steps together, different pairs of forecasts, measurements, and forecast errors are examined in scatter plot diagrams; empirical distribution and density functions were generated on the basis of the simulated and observed data; histograms were also prepared about the forecast errors in function of their signed magnitude. The mean systematic and root mean square (RMS) errors of the forecasts are calculated for all time steps separately and together, as well; the temporal evolution of absolute errors is analyzed for each time step; while the Taylor diagram is used only for selected forecast ranges in every 3 hours. Hereafter, most of the applied verification scores and tools are supposed to be well-known (*Nurmi*, 2003), only the main features of the Taylor diagram are briefly detailed.

The Taylor diagram (*Taylor*, 2001) provides useful information about how well the reference (measured) and the test (simulated) patterns (wind speeds) match each other in terms of their statistical correlation, root mean square (RMS) difference, and ratio of their variances. The geometric relationship between these three statistics allows to plot them into the same diagram. The two (reference and test) samples are represented by two points in the diagram. The radial distances from the origin to each point are proportional to the pattern standard deviation normalized by the observational variance, therefore, the reference point is positioned usually at value 1. The azimuthal position gives the correlation coefficient between the simulated and reference time series. Finally, the distance from the reference point (along concentric circles around it) measures the centered RMS difference between the two fields (as a consequence of the relationship between the three statistics). In the present verification the normalized Taylor diagram was constructed, i.e., the standard deviation of the simulations and the centered RMS difference were standardized with the variance of the observations. The more accurate and consistent the forecast is, the closer its point is positioned to the reference point.

3. Results

First of all, an obvious question is, whether the high- (5 km) resolution dynamical adaptation is able to improve the wind predictions produced on the 8 km operational resolution. For the correct evaluation of this issue, the operational forecasts and the dynamically adapted wind values should be systematically compared at 80-meter height for the 7-month verification period. However, in practice it would mean the necessity of the re-running the ALADIN model for the investigated period. Therefore, it was chosen to study the question by the validation of the 10-meter wind speed values with respect to two nearby observational points (Győr and Mosonmagyaróvár) for an "independent" 3-month period. The 10-meter wind speeds based on the operational 8 km forecasts and the dynamically adapted 5 km ones were assessed in terms of bias and RMS error (*Fig. 3*).

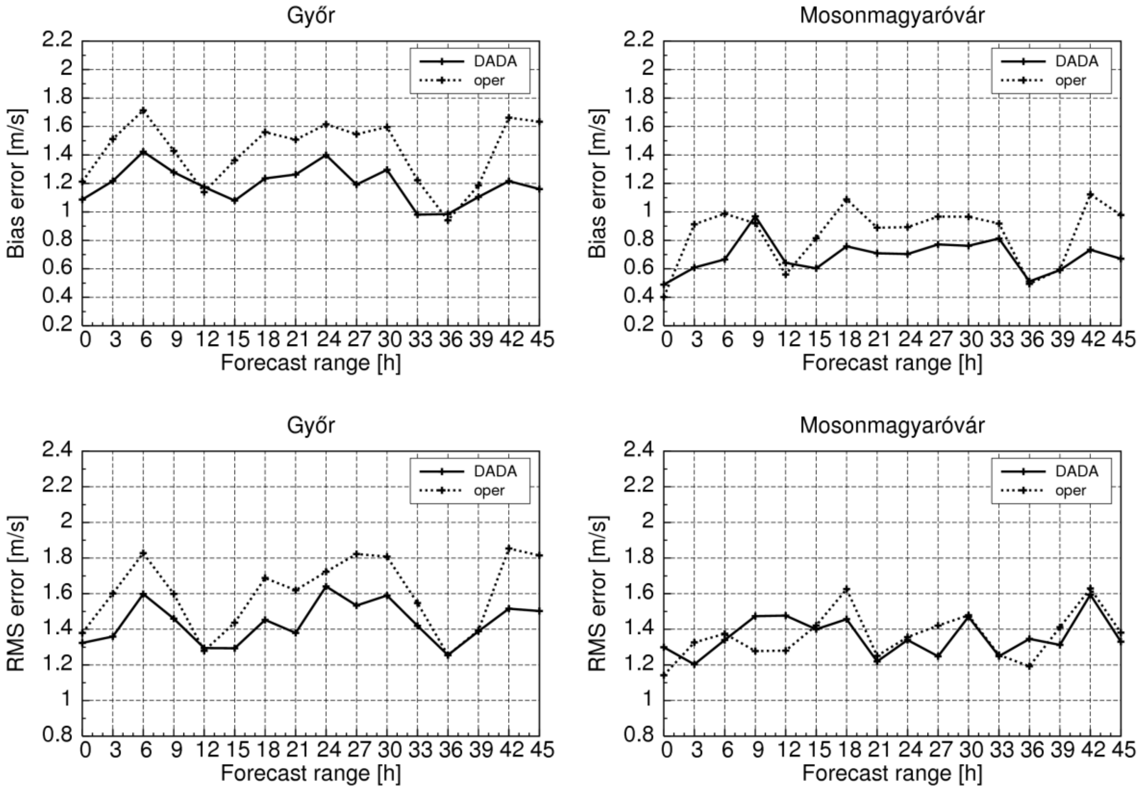

Fig. 3. Mean error (top) and root mean square error (bottom) of the operational ALADIN wind forecasts on 8 km horizontal resolution (dotted curve, "oper") and the 5 km resolution wind forecasts provided by the dynamical adaptation (solid curve, "DADA") for the different time steps (the time steps are considered from the analysis time at 00 UTC) with respect to two SYNOP stations close to Mosonszolnok-Levél: Győr and Mosonmagyaróvár. Verification period: December 1, 2008 – March 1, 2009; level: 10 m.

According to the 3-month verification, it can be generally concluded that the dynamical post-processing procedure improves the wind predictions. The results indicated, that the ALADIN 10-meter wind speed forecasts are hampered by a general overestimation (with 1.4 and 0.8 m/s in average for Győr and Mosonmagyaróvár, respectively), which cannot be fully cured by DADA (the corresponding bias values are 1.2 and 0.7 m/s), since the success of the dynamical adaptation process also depends on the quality of the "large-scale" constraints, which are provided by the 8 km resolution ALADIN forecasts. On the other hand, it is clear that in most time steps DADA outperformed the competing operational forecast in both error characteristics. It is remarked here, that there are some exceptions at the 12h and 36h ranges (i.e., at noon), when the operational results are characterized by identical bias and lower RMS errors than that of the dynamical adaptation (however, the differences between them are rather negligible). These relatively larger reductions in the added value of DADA compared to ALADIN might be associated with the fact, that there are several processes which cannot be more precisely described by this method. Such typical phenomenon is the convection being the most intensive at noon and early afternoon: since DADA uses only part of the physical parameterization schemes excluding convection, therefore, it has no chance to enhance the results prescribed by the 8 km ALADIN version in cases where these processes have important impact on the wind field. Nevertheless, all this concludes that the application of additional dynamical adaptation on the operational forecasts is useful to provide more accurate 10-meter wind predictions over this territory. Certainly, this conclusion cannot be directly interpreted at higher levels, because the 10-meter wind is an extrapolated diagnosed quantity based on fitting the logarithmic wind profile, whereas the 80-meter wind is rather determined by the dynamics.

Henceforth, the evaluation is concentrating on the 80-meter height, where the wind forecasts and measurements are available for Mosonszolnok-Levél. First, a general overview is given about the main features of the predictions in terms of "lead time independent" indicators, and then the quality is separately investigated in each forecast step. The empirical distribution and density functions (*Figs. 4* and *5*), where the latter ones were constructed by dividing the wind speeds between 0 and 20 m/s into bins of 0.5 m/s for both the model and observational data, provide information about statistical properties of the observed and simulated wind climatologies. (Certainly these are not climatological characteristics in its classical sense, because they are valid only for the investigated period.) It has to be remarked that for the distribution functions the inverse ones are computed (where the relative frequencies of the wind speed occurrences are inverted at the y-axis), since by this visualization the model over- and underestimations, with respect to the observed quantities, can be seen more transparently.

Comparing the histograms and distribution functions for the observations and forecasts, some similarities and also a few differences can be assessed in the simulated and observed wind climatology at the location of Mosonszolnok-Levél:

- Both the measured and forecasted wind speeds cover the range between 0 and 16 m/s.
- The median value (denoted in *Fig. 5*) is similarly around 5 m/s (for the exact values see *Table 2*), i.e., the half of the wind speeds exceeds the 5 m/s threshold in both datasets.
- In the measurements the dominant wind category is between 2.5 and 3 m/s with approximately 7% of relative frequency, in addition, the occurrence of the wind between 2 and 6 m/s exceeds 6% for every bin. The predictions are rather hampered by frequency underestimation between 2 and 7 m/s, which is most characteristic in the 2–3 m/s bins. All this results that the prevailing forecasted wind speeds are in the 5–5.5 m/s category.
- It is also interesting to see the sharp change in the error sign (from occurrence overestimation to underestimation) at the 2 m/s threshold.

(This feature might query the quality of the observations, however, such conclusions are not considered for this short verification period.) The weaker wind speeds below 2 m/s are overrepresented in the simulated results, i.e., the probability of wind speeds from every bin between 0 and 2 m/s is higher in the forecasts than in the reality. Although the level of the overestimation can reach even 80%, the related absolute frequency values are rather small (especially in the category between 0 and 0.5 m/s).

- For the wind speeds above 8 m/s the ALADIN model gives a bit high relative occurrences (though the magnitudes of these errors are even smaller than it was indicated at the lower and intermediate bins).

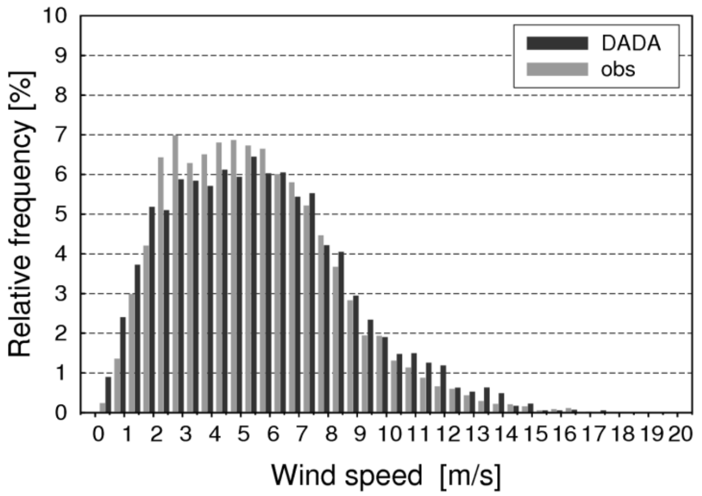

Fig. 4. Discrete density functions of the wind speeds for the model results (black) and the observations (gray). The range of wind speeds are divided into bins of 0.5 m/s. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

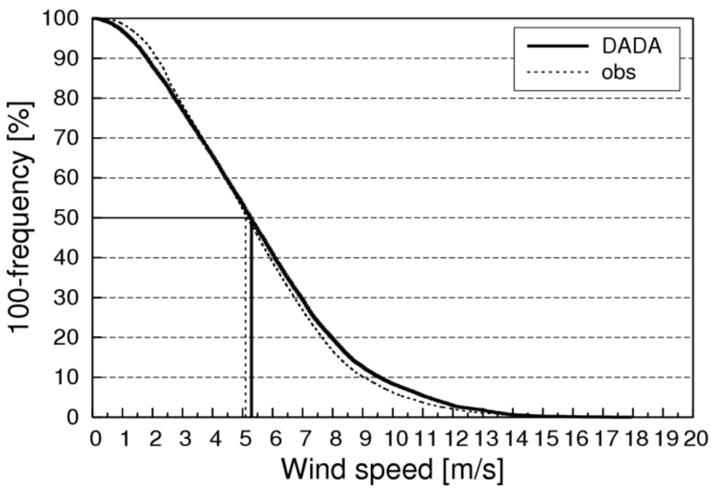

Fig. 5. Inverse empirical distribution functions of the wind speeds for the model results (solid curve) and the observations (dotted curve). Straight lines represent the corresponding median values. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

Table 2. Mean forecast errors and wind speed characteristics in the simulated and observed datasets (in m/s)

	DADA	**Observation**
Mean wind speed	5.5	5.4
Median value	5.3	5.1
Mean bias	0.1	-
Mean RMSE	2.2	-

The conclusions drawn on the basis of the empirical density and distribution functions (i.e., the frequency exaggeration of the lower and higher wind speeds and underestimation in the intermediate wind speed intervals) can be also identified in the scatter plot diagrams with several additional details. Looking at the diagram based on the forecast-observation pairs (first panel of *Fig. 6*), at the first glance it can be noticed that most points are situated rather symmetrically around the diagonal, which indicates that there are no systematic errors. This fact is also proved by the slight 0.1 m/s bias value calculated for the 80-meter level (see *Table 2*), and moreover, comparing it with the values for 10 meters, the performance of DADA is significantly improved with the altitude in terms of bias.

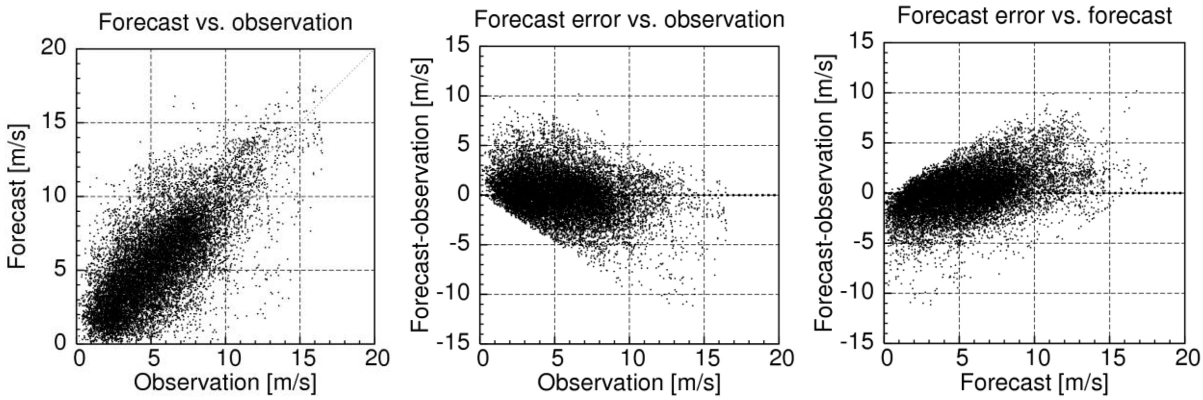

Fig. 6. Scatter plot diagrams (left: forecasts vs. observations, middle: forecast errors vs. observations, right: forecast errors vs. forecasts) for the 5 km resolution wind forecasts provided by the dynamical adaptation procedure. The plots were generated with the use of all time steps. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

Nevertheless, with a more careful look, also several asymmetric features can be found in *Fig. 6*. For the higher observed wind speeds (exceeding 10 m/s) the model tends to have underestimation, sometimes even with 5–10 m/s (the size of the error is naturally bounded above by the magnitude of the wind speed). This finding is confirmed by the similar diagram for the forecast errors as function of the observations (middle panel of *Fig. 6*), which additionally shows that the weaker winds (between 0 and 5 m/s) are simulated too large by ALADIN. At the right panel of *Fig. 6* it is also clearly visible that the simulated wind speeds reaching 10 m/s often exceed the measured values. All this is not in contradiction with the conclusions drawn from the histograms and distribution functions (which do not compose pairs from the simulated and observed values): the model is able to predict stronger winds, though these cases are not always at their real occurrences. In other words: when strong winds happen, the model underestimates them, whereas the weaker observed winds are regularly overestimated.

Investigating the scatter plot diagrams in the different time steps (not shown), it can be concluded that wind speeds above 5 m/s are mainly underestimated by the model at around the 12- and 36-hour forecast ranges (at around noon time), and for the interval of 5 and 10 m/s the overestimation has maximum at the 18- and 42-hour forecast ranges (i.e., in the evenings). Based on these features it can be suspected, that the diurnal cycle of the wind speed is not well represented in the simulated results, e.g., it might be shifted with a few hours. This fact can be analyzed in detail in *Fig. 7*, where the mean observed and simulated wind speeds with respect to the forecast range are displayed. (Forecasts over the 47-hour range are neglected since the sample from these time steps was small due to the change from daylight-saving time to the normal one at the end of October.)

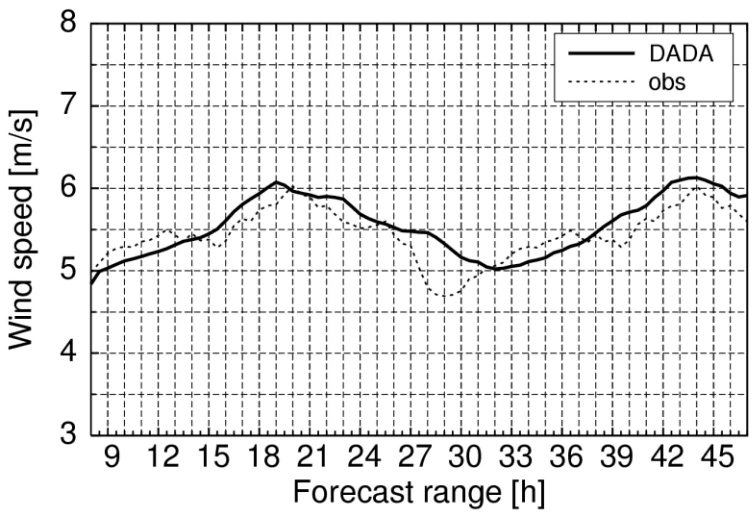

Fig. 7. The simulated (solid curve) and observed (dotted curve) mean wind speed for the different time steps (the time steps are calculated from the analysis time at 00 UTC). Verification period: April 19 –November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

It can be easily seen that the displacement of the simulated values is not constant all along the forecast range. Overestimations occur from the afternoons to the mornings and underestimations from the mornings to the very early afternoons. It implies that the afternoon intensification of the wind speed starts approximately one hour earlier in the model, therefore, the daily maxima are also reached one hour prior (at 19- and 43-hour forecast ranges instead of 20- and 44-hour ones). After getting the maximum, the wind weakening begins later and this process is slower in the simulations than in the reality resulting in a 3-hour delay of the minimum (at 32 hours forecast instead of its typical real occurrence at 29-hour range). Possible reasons behind the introduced error properties can be the insufficient parameterization of the convective processes as well as the weak description of the atmospheric stratification (however, these two factors are not completely independent from each other). Nevertheless, this hypothesis should be checked in the full ALADIN model at first, since as mentioned, DADA is unable to improve those processes which were insufficiently described by the "host" model. Inevitably, more experimentation would be needed to completely understand the physical background of this deficiency.

According to the systematic errors (*Fig. 8*), it can be seen, that in the wind speed forecasts the overestimation is somewhat more dominant than the underestimation resulting in a small (0.1 m/s) positive error for the complete verification period. This fact is supported by the empirical density function of the signed errors (*Fig. 9*), which indicates an almost symmetric pattern. It can be also seen, that the spectrum of the errors covers the range between – 8.5 and 8.5 m/s (though there are only few cases with error exceeding 7 m/s), i.e., the negligible mean systematic error is resulted by the balance between the positive and negative differences, which compensate each other. During the two forecasting days, the main systematic behavior of the predictions depends on the actual time steps (*Fig. 8*): the interval between the 8 and 13 hours at the beginning of the forecast period and between the 32 and 37 hours (i.e., 24 hours later) are characterized by small underestimation. The intermediate periods are mostly exacerbated by overestimation, which reaches its maximum (0.7 m/s) at the 28.5-hour forecast range. Looking at the mean and root mean square differences between the simulated and observed wind speeds, it is remarkable, that the model errors do not grow by the forecast range (excluding the first few hours). In each investigated time step the magnitudes of the mean errors basically do not exceed 0.5 m/s; the only exception is the abovementioned maximum at around 28 hours.

Nevertheless, the fact that the mean systematic error is small does not suggest, that the prediction would have equal accuracy in every forecast range, additionally, the minor bias in given time step does not guarantee the perfect prediction, since the positive and negative errors might compensate each other during a longer period. The mean RMSE value is 2.2 m/s for the entire forecast range (*Table 2*). The temporal evolution of the root mean square differences (*Fig. 8*) reveals that the errors are larger (reaching even 2.5 m/s value) when the overestimation is dominant, whereas the model performance is better in the periods of underestimation (the RMSE value is approximately 1.7 m/s in the

8–12 hours and 32–36 hours ranges). One reason might be behind the lower level of accuracy at the overestimation: since the wind speed is always positive, it can be underestimated only with its magnitude (i.e., the size of the negative errors has upper bound), whereas in the case of overestimation, the errors have basically no bound. The ranges of 9 hours and 33 hours are characterized not only by the smallest RMSE values, but they are also in best correlation (approximately 0.85 according to the Taylor diagram at *Fig. 10*) with the observation time series.

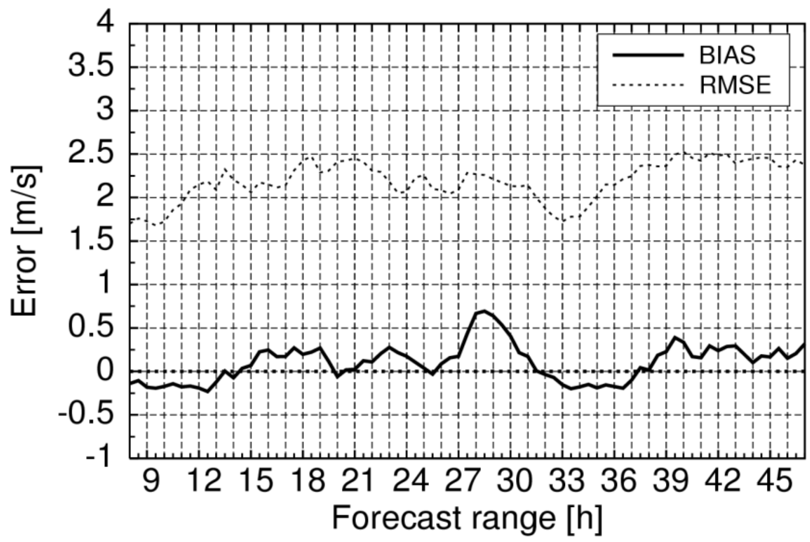

Fig. 8. Mean systematic error (solid curve) and root mean square error (dotted curve) for the different time steps (the time steps are calculated from the analysis time at 00 UTC). Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

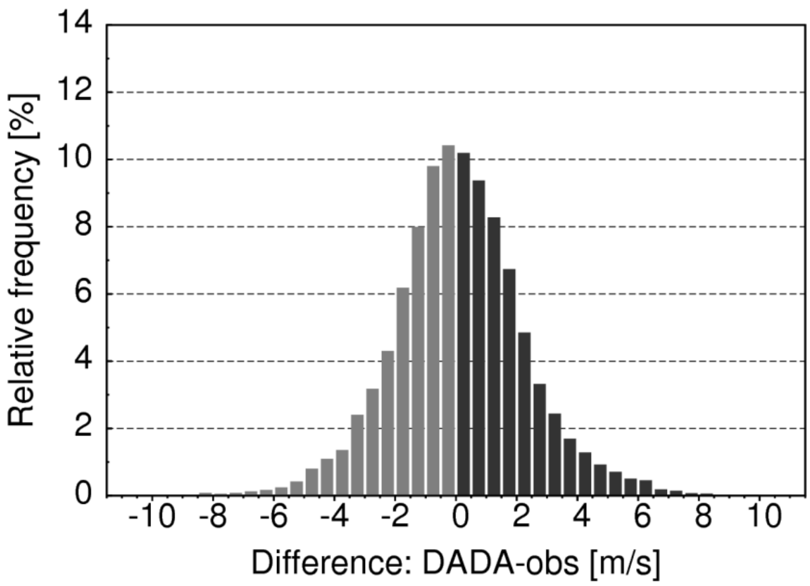

Fig. 9. Discrete density function for the signed model errors. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

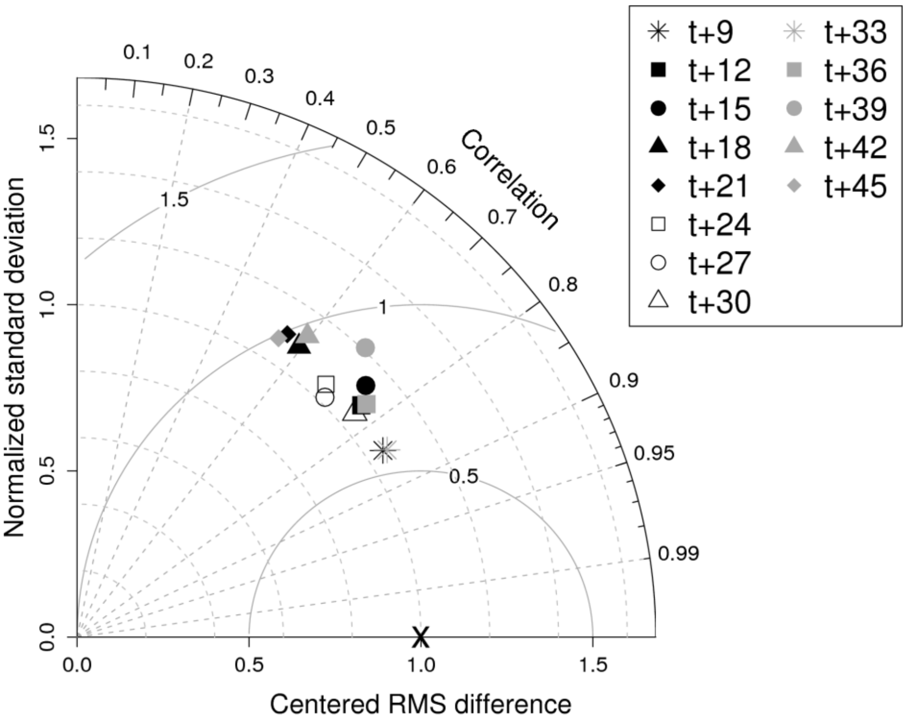

Fig. 10. Normalized Taylor diagram for the model results in different time steps. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

The temporal variation of the mean absolute error during the seven-month verification period was also examined for the different forecast ranges (only the 9- and 42-hour time steps are presented in *Fig. 11* as examples for the better and worse predictions). Rather large absolute simulation errors can be found in certain days: the deviations can reach even 6–8 m/s (although these errors occur quite seldom). Nonetheless, according to *Fig. 12* one can say, that the errors are under 1 m/s in around 40% of the cases, and the relative frequency of the errors exceeding 5.5 m/s does not reach 1%. The lowest absolute departures from the observations and the smallest error variability can be identified in the time step of 9 hours (*Fig. 11*), the errors mainly remain under 4 m/s all along the period. There are some forecast ranges when the larger errors are more frequent, for instance, the 42-hour step (right panel of *Fig. 11*) when the RMSE is also relatively high. Such dissimilarity between the 9 and 42 hours cannot be explained by the difference in the forecast ranges (i.e., the longer-range forecast is worse), because as mentioned earlier, the error patterns are rather uniform with respect to the lead time (*Figs. 8* and *10*). A more possible and plausible explanation might be again the imprecise description of the daily cycle in the model, which is also confirmed by the similar error characteristics for the 18-hour forecast range, i.e., in the evening one day before. In the Taylor diagram (*Fig. 10*), the points for the time steps of 18h, 21h, 42h, and 45h are positioned in a small group with somewhat negative properties: the predictions in these steps (i.e., in the evenings) are correlated in a weakest way with the observational time series accompanied by around 0.55–0.6 values; at the same time, they are situated in the largest distance from the reference point bringing the highest RMSE values during the 2-day forecast range. Regarding the temporal evolution of the scores, at some particular time steps (e.g., at 12h, 30h, 36h, not shown) one can conclude some temporary error reduction at the end of summer and the beginning of autumn. These features might be attributed to the particular meteorological situations, nevertheless, it is hard to find any seasonal behavior in the simulation results due to the short investigation period. For more detailed examination of the seasonal characteristics, it would be worthwhile, on the one hand, to extend the verification length, and on the other hand, to perform some smoothing and/or temporal averaging on the data in order to remove its large variability.

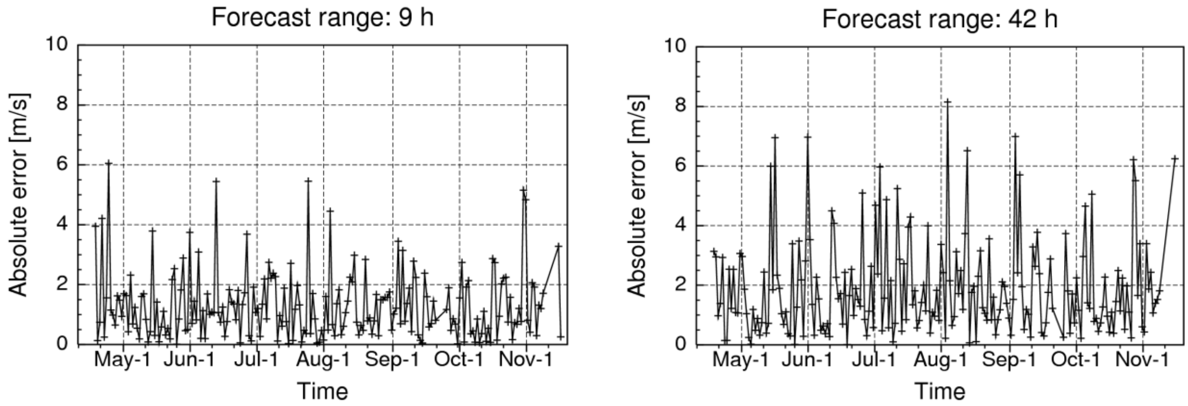

Fig. 11. Temporal evolution of the absolute error during the complete verification period in different forecast ranges (the time steps are calculated from the analysis time at 00 UTC): 9h on the left and 42h on the right. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

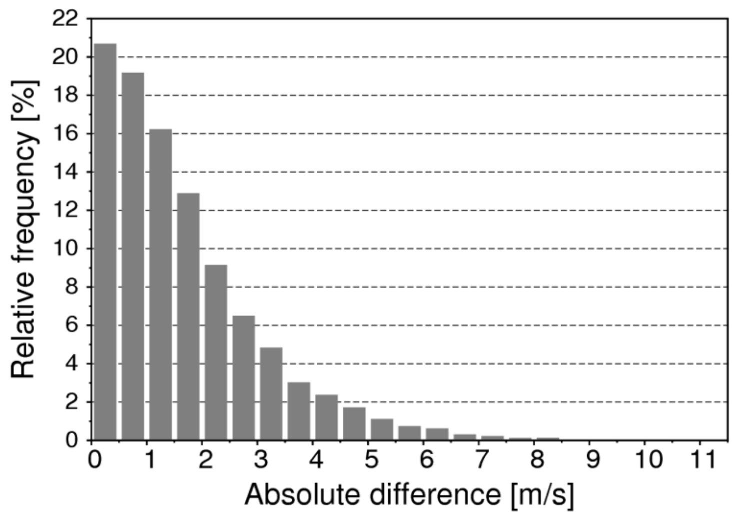

Fig. 12. Discrete empirical density function for the absolute errors. Verification period: April 19 – November 17, 2008; location: Mosonszolnok-Levél; height: 80 m.

4. Summary, conclusion, discussion, and future plans

In this article an overview was given about the applicability of the dynamical adaptation method originally developed by *Žagar* and *Rakovec* (1999) for wind power stations in Hungary. At the Hungarian Meteorological Service this special procedure is applied with the aim of improving operational wind predictions and providing more precise wind speed forecasts required by the wind power stations. The present paper is focusing on the validation results of the method: the dynamically adapted wind forecasts were compared and assessed with measurements at 80-meter height for a single location (namely Mosonszolnok-Levél) in a seven-month period. The selected point to be investigated in detail is situated at the northwestern part of Hungary, in approximately 120-meter height above the sea level. The anemometer stands in 78-meter height above the surface at a relatively strong wind tunnel, where the prevailing northwesterly flow streams over this flat area without barrier.

As far as the general quality of the operational forecasts is concerned, based on the verifications at two nearby SYNOP stations, it can be said that in the northwestern corner of Hungary the wind speeds are principally overestimated at the 10-meter height. The special dynamical downscaling improves the performance of the operational wind predictions, however, it cannot fully eliminate the positive bias. Regarding the main flavor of the fine-scale wind predictions at the higher 80-meter level for Mosonszolnok-Levél, it could be seen as follows:

- The wind speed forecasts during the 7 months are equally characterized by over- and underestimations resulting in almost no (0.1 m/s) systematic error;
- The intervals of 8 –13 and 32–37 hours are characterized by small systematic underestimations, which are accompanied with relatively minor RMSE values;
- The intermediate periods are mostly exacerbated by overestimation and higher RMSE values;
- The errors do not have temporal evolution, i.e., they basically do not grow by the forecast range;
- Concerning the climatological features of the wind datasets, the low and high wind speeds (below 2 m/s and over 7 m/s, respectively) are over-represented in the model, whereas the occurrences of intermediate velocities are rather underestimated.

All this can be attributed to the fact, that basically DADA is unable to correctly represent the diurnal wind cycle. This weaker description of the daily velocity cycle might be associated with the deficiencies of the driving model, however, this statement should be thoroughly examined in the future. It would be worthwhile to further extend the investigations with the study of the seasonal behavior of the model (this certainly requires longer verification period), additionally, the results should be scrutinized with respect to the wind direction, which could supply further hints regarding the strengths and weaknesses of the methodology in general and the ALADIN model in particular.

In spite of some identified deficiencies, the dynamical adaptation method provides not only an efficient, but also a reliable tool for the preparation of accurate wind predictions. At the same time, there are several further possibilities to "tune" the method in Hungary. The first "trivial" solution can be enhancing the spatial resolution of the target dynamical adaptation domain. The choice of 5 km horizontal grid spacing was motivated by that when the method was first tried, the topography was only available on this resolution, therefore, a further refinement of the applied grid would not make sense in the lack of more detailed surface description. Wind predictions are always valid at the gridpoint nearest to the given power plant, i.e., this resolution allows 3.5 km precision. It was indicated in *Table 1* that the orography on this resolution is relatively well described by the model in the investigated point: 125 versus 124 meters. Nevertheless, presently in the operational ALADIN model, an even finer topography is used, namely the GTOPO30 database (*Bliss* and *Olsen*, 1996) having 1 km resolution. The implementation of this detailed surface representation into the dynamical adaptation configuration can promise even better results. As far as the vertical resolution is concerned, the number of model levels could be still extended from the actually used 15 levels putting even more emphasis on the lower part of the atmosphere.

Regarding the Hungarian implementation of the dynamical adaptation procedure, another obvious concern is, whether the application of the half-hour model integrations for the operational outputs provided at every 15 minutes is correct from the aspect of temporal representativeness of the data. I.e., during this construction, the half-hour periods overlap each other, therefore, it is not evident on what time step the output of the DADA procedure can be considered (however, the same boundary conditions at the beginning and end of the short integration suppose that the forecast is valid for the initial time). Originally, the dynamical adaptation post-processing method was developed, when the model outputs were available only with 6- or maximum 1-hour frequency. But today the demands of the partners require the production of forecasts with denser temporal frequency.

One constraint of the method is that it is not able to attenuate the deficiencies of the applied initial and lateral boundary conditions, i.e., only the good-quality large-scale forcings can be improved by the dynamical adaptation procedure. On the other hand, even in case of correct driving fields, there are some small-scale phenomena that cannot be accounted by the larger-scale model, and the simplified dynamical adaptation is unable to additionally reflect them. In these processes other factors than the dynamic forcing are dominating (for instance, local thermal circulations or inversion situations), or for their accurate prediction the complete physical parameterization would have been needed on higher horizontal resolution (*Žagar* and *Rakovec*, 1999). Therefore, it is indispensable to simultaneously develop the driving model, as well. In the last years, the operational ALADIN model applied at the Hungarian Meteorological Service has been undergoing continuous improvements and there are also some additional plans for enhancing the low-level wind forecasts of the model. The main realized and intended developments are briefly listed hereafter:

- The three-dimensional variational data assimilation scheme of ALADIN (*Bölöni*, 2006) were improved from the point of view of background error computations (*Bölöni* and *Horvath*, 2010) and the inclusion of new and emerging observations types into the assimilation process. The near-future activities focus on the increase of the data assimilation cycling frequency (to 3 hours) and also the computation of flow-dependent background errors with the establishment of an ensemble data assimilation system (*Adamcsek et al.*, 2010).
- The lateral boundary conditions of the ALADIN model were recently updated by the use of the ECMWF/IFS (Integrated Forecast System), which resulted in essential positive impact on the performance of the ALADIN model (*Bölöni et al.*, 2009).
- Wind forecasts can be further enhanced with the application of probabilistic information, which can be obtained by the operational ensemble prediction system of HMS. This short-range limited area ensemble system consists of downscaling the 11-member global ARPEGE-based ensemble of Météo France with the ALADIN meso-scale model (*Hágel*, 2010). Currently, experiments are ongoing for generation of local initial condition perturbations by ALADIN (with the method of singular vectors as employed also in ARPEGE).
- The latest developments are related to the installation of the non-hydrostatic AROME model in light of its near-future operational introduction at HMS (*Horányi et al.*, 2006). At the moment, the model is exploited quasi-operationally providing 36-hour forecast over a domain covering Hungary with 2.5 km horizontal and 60-level vertical resolution.

All these developments contributed and will contribute to the further enhancements of the operational version of the ALADIN model, and consequently, that of its wind predictions. Finally, it is mentioned here that some wind forecast improvements can be also assessed with the statistical post-processing of the raw wind prediction information, which can account for the elimination of systematic model errors. Nevertheless, in the future we are going to concentrate more on the dynamical refinements of the wind forecasts (as listed above) instead of the statistical approach.

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