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VERIFICATION OF THE OPERATIONAL 10 M WIND FORECAST OBTAINED WITH THE ALADIN MESOSCALE NUMERICAL WEATHER PREDICTION MODEL

Verifikacija operativne prognoze vjetra na 10 m visine dobivena ALADIN mezoskalnim numeričkim modelom prognoze vremena

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Abstract: This paper presents the results of the verification of operational 10 m wind forecast obtained with the ALADIN mesoscale numerical weather prediction model. In the period 2010-2012 ALADIN/ALARO 8 km forecasts were initialized daily at 00 UTC and driven with the ARPEGE global model forecasts through the 72-hourly forecasting range. Obtained forecasts were further refined to 2 km grid spacing, using the simplified and cost-effective dynamical adaptation method (ALADIN/DADA 2 km forecasts). Since the primary objective of this study is to assess the efficiency of wind forecast in regions of complex terrain as well as high wind energy potential, eight stations from different wind climate regions of the eastern Adriatic coast were selected to perform the verification procedure. Based on variety of statistical and spectral scores, it is suggested that the wind forecast generally improves with the increase of horizontal resolution. At bora dominated stations, the multiplicative mean systematic error is reduced by more than 50%. The largest portion of root-mean square errors can be attributed to dispersion or phase errors at majority of stations and their contribution increases with model horizontal resolution. Spectral analysis in the wavenumber domain suggests that the slope of kinetic energy spectra of both models decreases from k^{-3} in the upper troposphere towards ~ $k^{-5/3}$ near the surface (corresponding to orography spectra) and shows minor seasonal variability. Spectral decomposition of measured and modeled data in the frequency domain indicates a significant improvement in simulating the primary and secondary maximum of spectral power (related to synoptic and diurnal motions) by using the ALADIN/DADA 2 km model, especially for the cross-mountain wind component mostly related to strong and gusty bora flows. Finally, the common feature of both models is a significant underestimation of motions at scales below semi-diurnal, which is a result of their absence in initial conditions and of limited model ability to represent small-scale processes.

Key words: wind forecast, complex terrain, ALADIN, statistical verification, spectral verification

Sažetak: U radu su dani rezultati verifikacije operativne prognoze vjetra na 10 m visine dobiveni ALADIN mezoskalnim numeričkim modelom. U razdoblju 2010.-2012. ALADIN/ALARO 8 km prognoze svakodnevno su inicijalizirane u 00 UTC, a pokrenute su prognozama globalnog modela ARPEGE kroz 72-satno prognostičko razdoblje. Dobivene prognoze dalje su profinjene na 2 km mrežu točaka korištenjem pojednostavljene i računski efikasne metode dinamičke adaptacije (ALADIN/DADA 2 km prognoze). Budući da je glavna svrha ovog istraživanja procjena uspješnosti prognoze vjetra u područjima složenog terena, ali i visokog potencijala raspoložive energije vjetra, za potrebe provedbe verifikacije odabrano je osam postaja s istočne obale Jadrana koje predstavljaju područja različite klime vjetra. Analiza više statističkih i spektralnih mjera točnosti sugerira da se prognoza vjetra općenito popravlja s povećanjem horizontalne rezolucije. Na postajama izloženim buri srednja multiplikativna sistematska pogreška smanjuje se za više od 50%. Najveći doprinos korjenu srednje kvadratne pogreške može se, na većini postaja, pripisati faznoj pogrešci čiji udio raste s povećanjem horizontalne rezolucije modela. Spektralna analiza u domeni valnog broja pokazuje da se nagib spektara kinetičke energije obaju modela smanjuje od k^{-3} u gornjoj troposferi prema ~ $k^{-5/3}$ blizu površine (odgovara spektru terena) te pokazuje malu sezonsku varijabilnost. Spektralna dekompozicija mjerenih i modeliranih podataka u frekvencijskoj domeni ukazuje na značajno poboljšanje pri simuliranju primarnog i sekundarnog maksimuma spektralne snage (povezani sa sinoptičkim i dnevnim gibanjima) korištenjem ALADIN/DADA 2 km modela, posebno za komponentu vjetra okomitu na Dinaride koja je uglavnom vezana uz buru. Konačno, zajednička karakteristika obaju modela je značajno podcjenjivanje spektralne snage na skalama manjim od poludnevne, što je posljedica neprisutnosti tih gibanja u početnim uvjetima, odnosno smanjenjih mogućnosti modela da reprezentira procese najmanjih prostornih i vremenskih skala.

Ključne riječi: prognoza vjetra, kompleksan teren, ALADIN, statistička verifikacija, spektralna verifikacija

1. INTRODUCTION

A common method used for the wind forecasting in the Atmospheric Boundary Layer (ABL) in complex terrain is dynamical downscaling with the use of mesoscale NWP models. Typical horizontal grid spacing of these models is below 10 km, with the option of further refinement depending on the spatial and temporal scales of observed phenomena in the target area. Generally, downscaling introduces new scales, both temporal and spatial, which results in better representation of mesoscale wind systems due to common action of model physics and dynamics. Predicable mesoscale wind systems are most often a result of surface and terrain inhomogeneities (e.g. sea-land breeze or valley winds) or interaction between the terrain and large-scale flow (e.g. downslope windstorms, gravity waves and gap flows) (Pielke, 2002).

Due to its strength and frequency, bora (e.g. Smith 1985; Grisogono and Belušić 2009; Belušić et al. 2013) and sirocco (Jurčec et al. 1996) are particularly important for forecasting wind conditions in Croatia. As they usually appear within the mesoscale cyclonic systems over the Mediterranean (Horvath et al. 2008), the desired property of mesoscale models used for the refinement of wind forecast should be the ability to simulate nonlinear flows, as well as flows over mountains for different types of background flow. As regards to many potential applications of high-resolution wind forecasting, such as in transport, energy, tourism, agriculture etc., forecast errors may profoundly affect all of those applications, but perhaps the most sensitive is wind energy sector since the wind power error is proportional to the cube of wind speed error. Therefore, we aim to quantify and distinguish among different sources of model errors and to compare the results of different verification techniques in order to help in further development of high resolution mesoscale NWP modelling.

Verification of mesoscale flows is a challenging task for which adequate approaches still need to be revised and defined. Traditionally used statistical scores (e.g. multiplicative mean systematic error (MBIAS; the ratio of mean modeled and observed wind speed), root-mean-square error (RMSE) and mean absolute error (MAE)) seem to be insufficient for that purpose since small spatial and temporal errors of generally well simulated phenomena can profoundly change the verification results (Mass et al. 2002; Rife et al. 2004). Therefore, we also utilized spectral analysis in wavenumber and frequency domains as a supplementary verification method to provide a scale-dependent measure of model performance. For example, the model ability to reconstruct theoretically expected shape of kinetic energy spectra can serve as a prime tool for qualitative model evaluation and for estimation of model effective resolution.

Furthermore, spectral decomposition in the frequency domain allows quantification of power distribution among different temporal scales and thus provides an information about exposure of particular station to diurnal and sub-diurnal forcing, as well as on model ability to simulate observations. One of major potential benefits of high resolution mesoscale modelling is to capture diurnal forcing by topography or surface inhomogeneity (Rife et al. 2004). Hence, at stations with significant diurnal component there exists a potential for improving the results using higher-resolution numerical models. On the other hand, scales below diurnal and in particular below semi-diurnal still represent a challenge for operational forecasting. Those scales include circulations that may result from far upstream landscape forcing or from nonlinear interactions. Due to sparse spatial character of wind measuring network (Bajić 2011.), these motions are not presented in the model initial conditions. Therefore, if not predicted through sub-diurnal forcing, they cannot be deterministically predicted regardless of the grid spacing and model physics.

The major objective of this study is to assess the ability of dynamical adaptation to forecast relevant wind conditions in the complex terrain of the eastern Adriatic coast. Other objectives include quantification of different sources of model errors and their changes in magnitude with decrease of grid spacing, as well as to perform more physical insight into the model ability to reproduce near surface winds by using the spectral decomposition.
The paper is organized as follows. The model setup and verification strategy are described in section 2. The results of statistical and spectral verification are given in section 3. Conclusions are given in section 4.

2. DATA AND METHODS

2.1. Model settings

Meteorological and Hydrological Service (DHMZ) of Croatia uses Aire Limitée Adaptation Dynamique développement InterNational (ALADIN; Bubnova et al. 1995) limited area model for the operational weather forecast. ALADIN is a primitive equation model built on the basis of the global models IFS/ARPEGE (IFS - Integrated Forecast System, ARPEGE - Action de Recherche Petite Echelle Grande Echelle) and it uses spectral technique for the horizontal representation of prognostic fields. Set of primitive equations is solved for wind speed components, temperature, specific humidity and surface pressure, using the two-time-level semi-implicit semi-Lagrangian integration scheme. In the vertical direction ALADIN model uses hybrid pressure-type coordinate (Simmons and Burridge 1981.) on 37 model levels with the finite differences method. Prognostic fields in spectral space are obtained using the double Fourier transform, while the biperiodicity is satisfied by applying the elliptic truncation, i.e. including the extension zone (Machenhauer and Haugen 1987). The vertical transfer of heat, momentum and moisture are described by turbulence parameterization based on Louis scheme (1982) with modified dependency on stability (Redelsperger et al. 2001). Physics package includes shallow convection parameterization (Geleyn 1987). Stratiform and convective processes are considered individually by using the Kessler type of parameterization (Kessler 1969) for resolved precipitation and modified Kuo scheme for deep convection (Geleyn et al. 1982). Radiation is parameterized according to Geleyn and Hollingsworth (1979) and Ritter and Geleyn (1992). The vertical transport of moisture and heat in the soil are parameterized in two layers following the Giard and Bazile (2000).

The operational model version at DHMZ is run in a hydrostatic mode with 37 vertical levels (the lowest level is approximately at 17 m above ground level (AGL)) and 8 km horizontal grid spacing. The model integration domain is shown on Figure 1. During the verification period initial and lateral boundary conditions (LBC) were obtained from analysis and forecasts of the ARPEGE global model. In the case of analysis the digital filter initialization (DFI; Lynch and Huang 1994) was used, while the frequency of LBCs was 3 hours. Model was initialized daily at 00 UTC and integrated over forecasting period of 72 hours with time-step of approximately 5.45 minutes (11 time-steps in 1 hour); but the output data were archived every 3 hours. After the start of the model, mesoscale energy starts to accumulate and it takes few hours for the stabilization of the results. Based on the analysis of yearly averaged lead-time dependent kinetic energy spectra the spin-up, i.e. stabilization period of 9 hours was allowed. This version of the ALADIN model setup is referred to as ALADIN/ALARO 8 km (AL8).

After integration, the prognostic fields of AL8 model were refined to 2 km grid spacing over

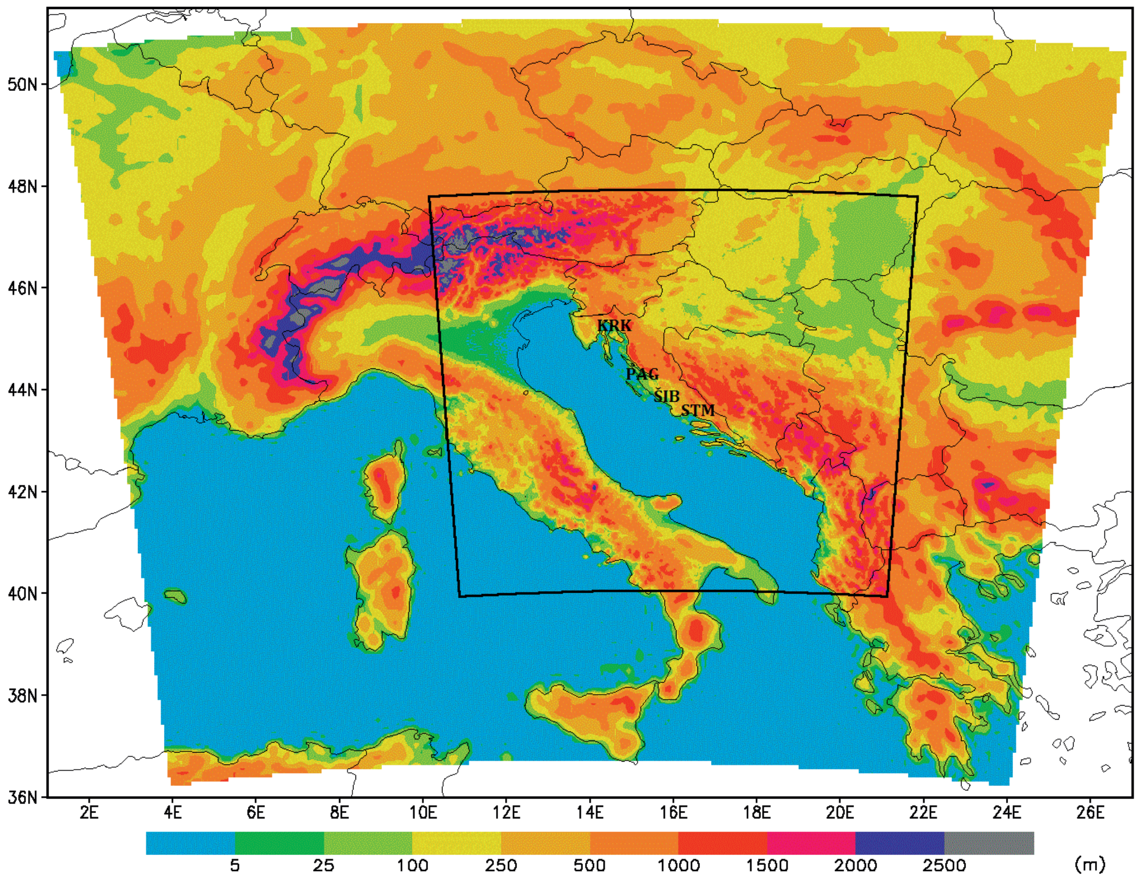

Figure 1. Integration domain of the ALADIN/HR model at 8 km horizontal grid spacing (AL8; outer domain) and the domain of dynamical adaptation at 2 km horizontal grid spacing (DA2; inner domain) with the corresponding orography and stations selected for the verification of model outputs.

Slika 1. Integracijska domena ALADIN/HR modela na horizontalnoj razlučivosti od 8 km (AL8; vanjska domena) i domena dinamičke adaptacije na 2 km horizontalnoj razlučivosti (DA2; unutarnja domena) s pripadnom orografijom i mjernim postajama odabranim za verifikaciju modelskih izlaza.

a sub-domain (Fig. 1), using the dynamical adaptation method (Žagar and Rakovec 1999; Ivatek-Šahdan and Tudor 2004.). Dynamical adaptation is simplified and cost-effective method used for dynamical downscaling of near-surface winds. The main simplifications include reduced number of vertical levels (15; opposed to 37 of AL8 model) above 1000 meters, as well as exclusion of moist processes and effects of radiation. A total 8 of these 15 vertical levels are placed within lowest 1000 meters and have the same spacing as in AL8 model. The dynamical adaptation procedure takes the prognostic fields from each AL8 output file and interpolates them to the 2 km resolution. Those files are then used as initial and lateral boundary conditions. As orography at 2 km resolution contains more details, the quasi-stationary balance is disrupted. The model fields adapt to higher resolution terrain by running the numerical model from this new initial state until the quasi-stationary state is achieved (in operative; 30 steps of 60 s each). As discussed by Žagar and Rakovec (1999), dynamical adaptation will be more successful when pressure gradients are stronger because: i) dynamical forcing is dominant mechanism, i.e. the large scale wind is strong enough to attenuate local thermal or convection-induced circulations and ii) adaptation period is significantly shorter. On the other hand, adaptation might fail in case of: i) valley inversions, ii) thermal circulations that are not resolved by the driver model, iii) quick passage of cold fronts and other errors in the input data. This version of the ALADIN model setup is referred to as ALADIN/DADA 2 km (DA2). More details on weather forecasting at MHS, as well as on both AL8 and DA2 model setups can be found in Tudor et al. (2013).

2.2. Observations and verification procedure

The verification was performed for AL8 and DA2 datasets in period 2010-2012, using the measured data from eight meteorological stations spread around eastern Adriatic coast. These stations represent different wind climate regions and by name they are: Jasenice, Most Krk, Most Pag, Makarska, Novalja, Split Marjan, Šibenik and Zadar. Jasenice, Most Krk and Most Pag stations are representative for bora dominated regions of northern part of Eastern Adriatic coast. Makarska and Split Marjan stations were selected for model verification of wind climate at central part of eastern Adriatic, where bora and sirocco are two dominant types of flow. Other stations (Novalja, Šibenik and Zadar) represent regions with relatively weaker winds and with significant portion of locally developed and thermally driven flows. The criterion for selection of stations was the record completeness (less than 10% of missing data), which is especially important for spectral analysis. Gaps in time series were filled by means of linear temporal interpolation. As we wanted to avoid spatial interpolation of model outputs, the closest land-placed point among four neighboring model grid points was selected as representative one. Wind components at 10 m AGL are obtained by vertical interpolation between the surface and the lowest model level, using the similarity theory (Geleyn 1988). Instrumental, calibration and representativeness errors were not taken into account during the verification process. This should be kept in mind during the evaluation of model performance, since some studies adduce the value of 1.15 ms^{-1} as representativeness error of near surface wind speed under well-mixed ABL in the complex terrain (Rife et al 2004).

Before the start of the verification procedure AL8 and DA 2 model data were reduced to 21 hours forecasting period, bearing in mind the spin-up period of 9 hours for both models. Statistical verification included calculation of MBIAS, RMSE and MAE, according to standard equations (e.g. Wilks 2006). As RMSE is affected by uncertainties both in time and space, we have performed the decomposition on its integral components (Murphy 1988; Horvath et al. 2012): bias of the mean (BM), bias of the standard deviation (BSD) and dispersion or phase error (PHE). Obtained values of moment-based scores were averaged over monthly periods to show their seasonal variability.

The kinetic energy (KE) spectra were calculated directly from spectral fields of AL8 and DA2 model files at levels in lower, middle and upper troposphere, using the ECTOplasm software (*http://www.cnrm.meteo.fr/gmapdoc/meshtml/ecto3.0*). Spectra were calculated every 3 hours (interval of availability for both AL8 and DA2 data) for the entire year of 2012. Here presented spectra are yearly averaged values corresponding to the 12-houry forecast. It should be noted that KE spectra of AL8 and DA2 models were not calculated on domains of the same size (Fig. 1), hence we have a shift in energy at particular wavenumbers. Since the method of calculation used here does not affect the slope of KE spectra at shortest wavelengths, the energy shift mentioned above does not affect the performed analysis and conclusions related to the effective model resolution.

Because majority of stations are located near the seashore or in very complex terrain and are characterized by motions of different temporal scales, the success of the analyzed models was verified using the spectral decomposition in the frequency domain. As typical diurnal rotation of winds in the Adriatic (Telišman Prtenjak and Grisogono 2007) partially hides the diurnal spectral peak if the decomposition is performed using the wind speed values, we have performed the decomposition of both horizontal wind components. The coordinate system is rotated such that u and v components correspond to the cross-mountain and along-mountain directions. Spectral decomposition of detrended time series was performed using the Welch periodogram-based method (Welch 1967) on segments that overlap by 50 %. The length of spectral window (L=256) was adjusted to optimally emphasize the diurnal and semi-diurnal spectral peaks. Measured and modelled data both corresponding to 10-min average values were sampled at regular 3-hourly intervals.

Quantification of these short-scale motions is important because the ability of their simulation is one of potential benefits of high-resolution mesoscale models compared to coarser mesoscale or global models. To compare results with Žagar et al. (2006) and Rife et al. (2004), although for somewhat different types of stations, we have defined: diurnal range (DIU) as periods between 22 and 26 hours, sub-diurnal range (SUB) which comprises periods between 6 and 22 hours and synoptic or larger than diurnal range (LTD) as one with periods longer than 26 hours and shorter than 7 days. The area under the power spectral density (PSD) curve by spectral ranges was calculated by means of numerical integration, using the trapezoidal rule. It should be noted that PSD analysis performed here contains the effect of aliasing, since 10-min values sampled every 3 hours will be necessarily contaminated by oscilations with periods shorter than 6 hours (here corresponding to Nyquist frequency) and thus aliased distorting the shape of analyzed frequency spectrum. While aliasing will affect all scales, testing of this effect on measured data suggested that the effect on scales larger than diurnal is rather small, while

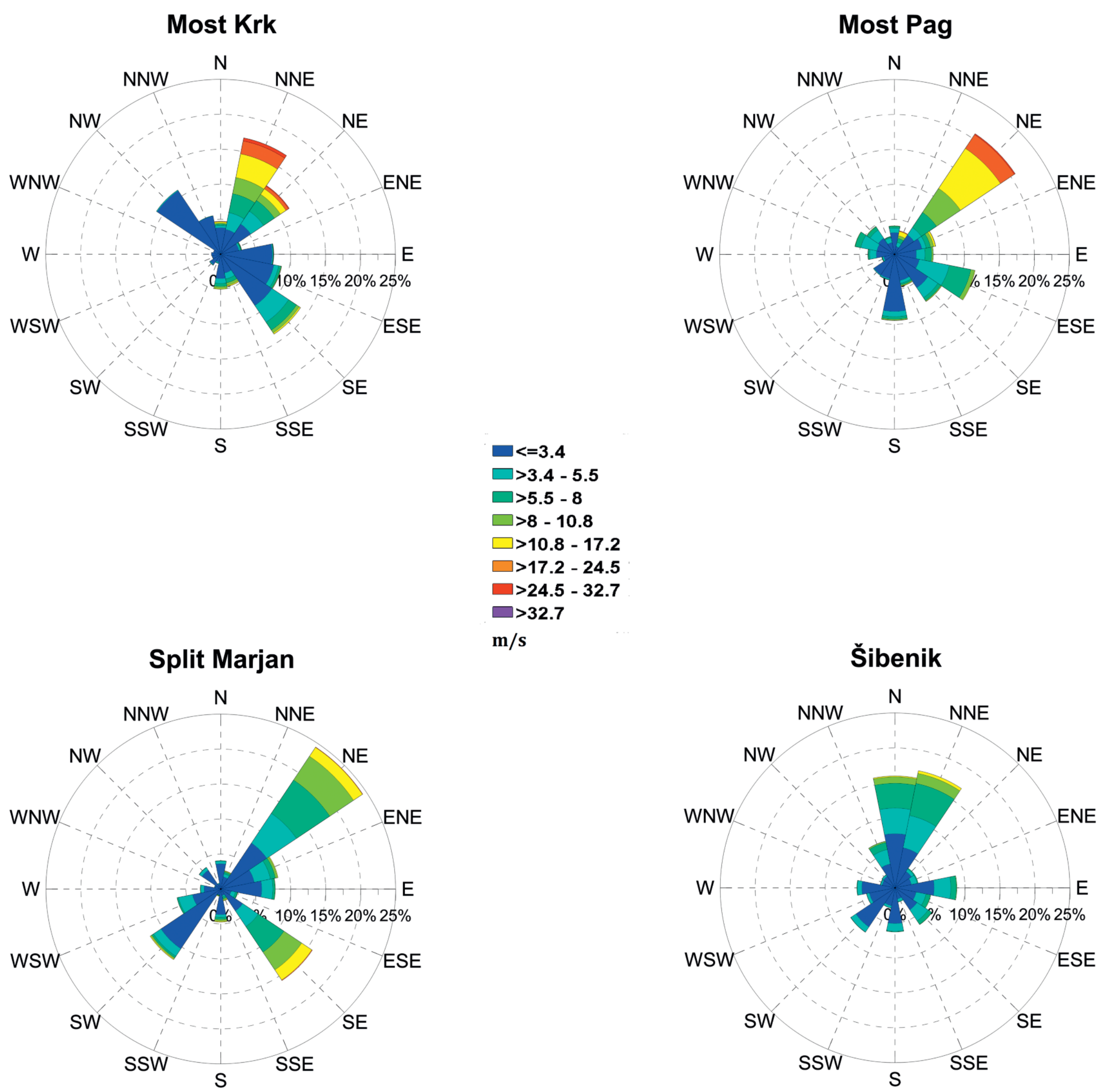

Figure 2. Wind roses from measurements at 10 m AGL for selected stations during period 2010-2012 (cf. Fig. 1 for exact location of stations). The percentage of missing data amounts 5.9% for Most Krk station, 2.2% for Most Pag station, 5.3% for Split Marjan station and 1.1% for Šibenik station.

Slika 2. Ruže vjetra, dobivene iz mjerenja, na 10 m iznad tla za odabrane postaje u razdoblju 2010.-2012. (vidi Sl. 1 za točne lokacije postaja). Postotak nedostajućih podataka iznosi 5.9% za postaju Most Krk, 2.2% za postaju Most Pag, 5.3% za postaju Split Marjan i 1.1% za postaju Šibenik.

significant effects may be found on sub-diurnal scales, especially near the periods corresponding to the Nyquist frequency. The effect of aliasing in the sub-diurnal range discussed above is estimated from measured data, and results in the energy of sub-diurnal motions being overestimated for around 40% on average for coastal stations. While we cannot circumvent this effect since the model data are stored every 3 hours, it may be noted that we chose to perform PSD analysis on 10-min measured data which are also sampled every 3 hours and are thus aliased in a similar manner. Therefore, for the purpose of verification performed in this paper, it is likely that the aliasing effect cancels out, at least to an extent.

3. RESULTS

3.1. Moment-based verification

In order to assess the reliability of wind forecast obtained with the ALADIN mesoscale NWP model for the Adriatic region, we have performed the statistical verification of AL8 and DA2 model outputs at eight stations from different wind climate regions. As verification scores we utilized MBIAS and RMSE, which was further decomposed on its integral components to quantify among different sources of spatial and temporal errors (cf. Section 2.2.).

As representative locations for presentation of verification results we have chosen Most Krk, Most Pag, Split Marjan and Šibenik stations exposed to bora, sirocco and other weaker flows on northern, middle and southern part of Eastern Adriatic (Figure 2). Obtained values of moment-based scores were monthly averaged over all forecasting lead-times and shown in form of an annual cycle (Figure 3; MBIAS and Figure 4; RMSE), while averaged values for the entire period of 2010-2012 are shown separately in Table 1. By applying the dynamical adaptation (DA2 model) the 10 m wind speed forecast improved at all stations, and in particular at bora dominated stations

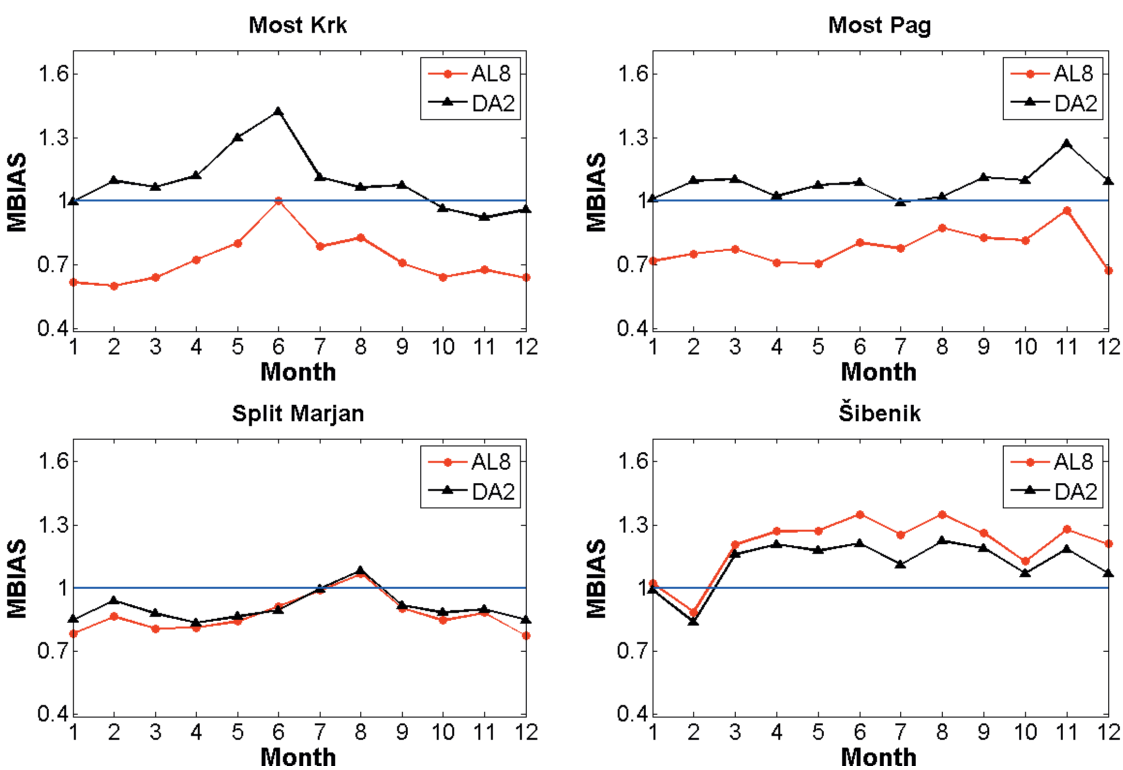

Figure 3. Mean monthly multiplicative systematic error (MBIAS; MBIAS=1 stands for the perfect agreement of measured and modeled data) of 10 m wind speed for AL8 and DA2 models at selected stations during period 2010-2012.

Slika 3. Srednja mjesečna multiplikativna sistematska pogreška (MBIAS; MBIAS=1 označava savršeno podudaranje mjerenih i modeliranih podataka) brzine vjetra na 10 m visine za AL8 i DA2 modele na odabranim postajama u razdoblju 2010.-2012.

Most Krk and Most Pag (Figure 3.). Coarser AL8 model underestimated the average wind speed values there by more than 20%, while the DA2 model reduced the systematic error to under 10%. However, the wind speed values obtained by DA2 model overestimate the measured data at bora dominated stations. The largest deviations from ideal MBIAS value were observed during late spring and summer months at Most Krk and Šibenik stations, as well as during late autumn and winter months at Most Pag and Split Marjan stations. As seen from the relative frequency histograms (not shown here), the first mentioned can be explained by the relatively poor performance in simulating near calm conditions (MBIAS is the most sensitive here) by both AL8 and DA2 models. On the other hand, besides winter calms, the second mentioned includes a problem with underestimation of the frequency of stronger winds (V > 10 ms^{-1}; Split Marjan station).

RMSE values are larger at bora dominated stations of northern and central part of the eastern Adriatic (Most Krk, Most Pag) than at other two analyzed stations (Split Marjan, Šibenik) (Figure 4). By applying the dynamical adaptation method, those values were reduced up to mostly 20% when compared to the AL8 model. The largest values of RMSE were observed during winter months, when the wind speed values are in average higher at all stations. This is somewhat expected as RMSE is generally proportional to the average wind speed. The largest portion of RMSE errors can be attributed to PHE, except maybe for AL8 model at bora dominated stations where BM has similar or even greater contribution (Figure 4; winter months). With the increase of model resolution BM and BSD generally decrease, while the PHE increases. The exception is Šibenik station where the general rule holds only for the BM.

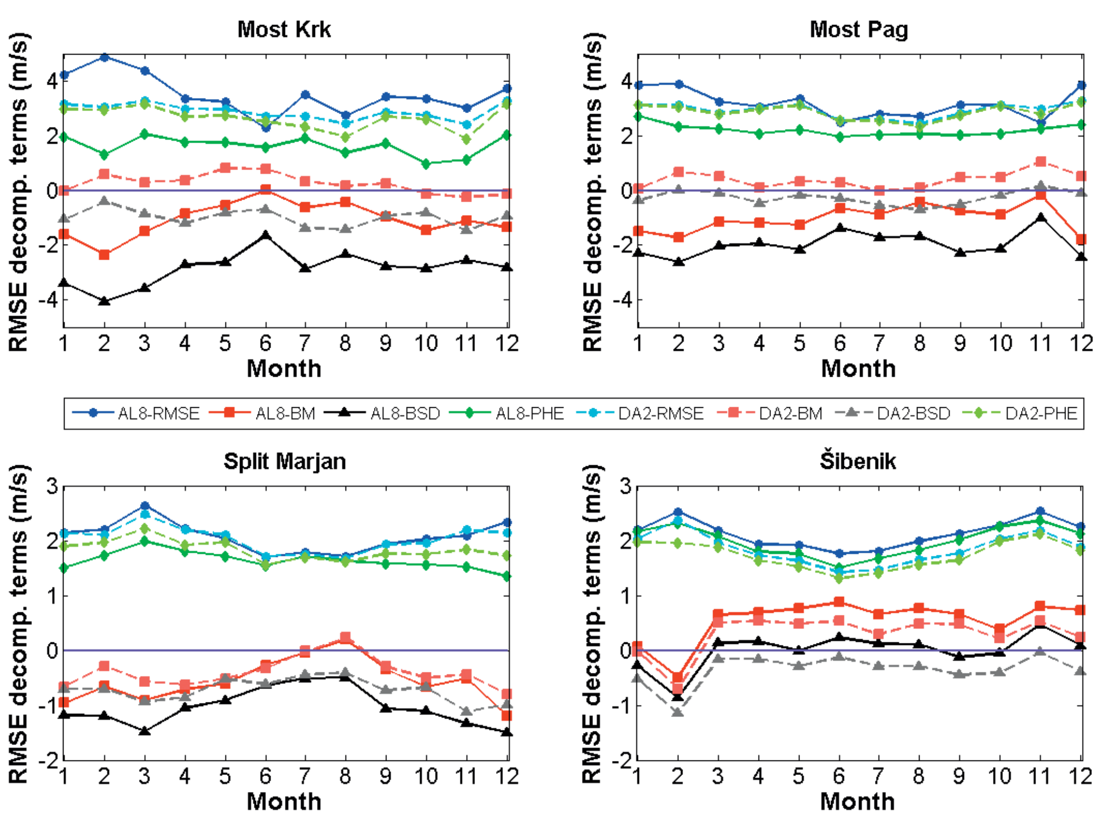

Figure 4. Decomposition of the root-mean-square error (RMSE) of 10 m wind speed for AL8 and DA2 models at selected stations in period 2010-2012. BM stands for the bias of the mean, BSD for the bias of the standard deviation and PHE for dispersion or phase error.

Slika 4. Rastav korijena srednje kvadratne pogreške (RMSE) brzine vjetra na 10 m za AL8 i DA2 modele na odabranim postajama u razdoblju 2010.-2012. BM označava pristranost srednjaka, BSD pristranost standardne devijacije, a PHE disperziju ili faznu pogrešku.

Table 1. The multiplicative mean systematic error (MBIAS), root-mean square error (RMSE) and measured 10 m wind speed during period 2010-2012 for selected stations (cf. Fig. 1). The MBIAS=1 denotes unbiased set, while MBIAS > 1 and MBIAS < 1 denote model overestimation and model underestimation of measured data.

Tablica 1. Srednja multiplikativna sistematska pogreška (MBIAS), korijen srednje kvadratne pogreške (RMSE) i izmjerena 10 m brzina vjetra tijekom razdoblja 2010.-2012. za odabrane postaje (vidi Sl. 1). Jedinični MBIAS (MBIAS=1) označava podatke bez sistematske pogreške, dok MBIAS > 1 i MBIAS < 1 označavaju modelsko precjenjivanje, odnosno podcjenjivanje izmjerenih vrijednosti.

STATION	Most Krk		Most Pag		Split Marjan		Šibenik	
MODEL	AL8	DA2	AL8	DA2	AL8	DA2	AL8	DA2
MBIAS	0.72	1.09	0.78	1.08	0.87	0.91	1.21	1.12
RMSE (ms^{-1})	3.51	2.88	3.16	2.92	2.07	2.03	2.12	1.84
V_{meas} (ms^{-1})	3.50		4.59		3.99		2.93	

3.2. Analysis of wind spectra in the wavenumber domain

By using multiple datasets, observational analyses of KE spectra have shown that inherently 2D large-scale motions (several thousand to several hundred of kilometers) in the free troposphere and lower stratosphere conform to the k^{-3} power law, while at smaller, i.e. inertial turbulence scales this dependence relaxes to $k^{-5/3}$ (Nastrom and Gage 1985; Lindborg 1999). The slope of KE spectra is remarkably universal as it has shown very little dependence on latitude, season or altitude (Nastrom and Gage 1985; Skamarock 2004). Between the above mentioned scales there are mesoscale spectra which are not understood well, as mesoscale motions are predominantly 2D but the KE spectrum is closer to $k^{-5/3}$ (like 3D turbulence). Less steep dependence of KE spectra on wavenumber at mesoscale and shorter scales suggests that motions of these scales are energetic and that error growth may be faster than at synoptic scales, as time scale of mesoscale phenomena is much shorter than typical forecasting range of mesoscale NWP models, so these existing errors have enough time to propagate upscale. Thus, the timely detection and elimination of errors on small scales potentially has a great importance for the successful operation of mesoscale NWP models. Without going further into the theory of KE spectra, we would like to state that KE spectra are an appealing tool for the analysis of properties of mesoscale models on various spatial scales and qualitative assessment of model performance.

On Figure 5 are shown the KE spectra for both AL8 and DA2 models at levels in upper, middle and lower troposphere. Although the vertical levels for the two considered models are numerated differently (legend), the curves of similar shades correspond to approximately the same altitude (according to the captions). As it can be seen, the dynamical adaptation has created a significant portion of mesoscale energy at scales below 100 km. Furthermore, the energy of meso-scale motions of DA2 model near the surface is much higher than in upper troposphere, which indicates the importance of small scale surface processes. At higher levels and for larger spatial scales, AL8 and DA2 models show similar behavior and conform to the k^{-3} law. Unlike expectations, there is no gradual transition towards the less steep behavior at mesoscale. This suggests that there is not enough mesoscale energy created in the upper troposphere in the ALADIN model, which was already reported by Horvath et al. (2011) and to some extent by Žagar et al. (2006).

In the mid-troposphere the slope of the kinetic energy spectra slightly flattens, while near the surface it flattens even more and resembles the spectra of orography. This feature of KE spectra suggests that surface winds in AL8 and DA2 models are primarily adapted to the orography. On the other hand, variation of the slope of KE spectra with height is most likely the result of presence of orographycally induced and vertically propagating gravity waves over the model domain. Similar behavior of KE spectra is reported by Horvath et al.

(2011) for the dynamical downscaling of ERA-40 reanalysis with the ALADIN mesoscale NWP model. The KE spectra may also be used for the estimation of model effective resolution by studying the deviation of modeled spectra from the expected values at spectral tails, i.e. short scales (Skamarock et al. 2004; Horvath et al. 2011). By taking k^{-3} as a reference slope in the upper troposphere and the orography spectra in the lower troposphere, we have estimated that effective resolutions of AL8 and DA2 models are approximately 5-6Δx of the corresponding grid spacing. It may be also inferred that the effective model resolution somewhat varies with height. The seasonal variability of KE spectra for AL8 and DA2 models was investigated as well (not shown here) and we have found that slope of the spectra remains unchanged, but the amount of energy decreases from winter to summer and opposite.

3.3. Spectral verification in the frequency domain

Here are presented the results of spectral verification in the frequency domain performed for Most Krk, Most Pag, Split Marjan and Šibenik stations. On Figs. 6. and 7. the PSD of cross-mountain and along-mountain measured and modeled wind components for Most Krk and Most Pag stations are shown. The largest portion of measured power at both stations is associated with LTD motions, which are more energetic for the cross-mountain component, related to the strong and gusty bora wind. These motions are reasonably well simulated with the DA2 model, unlike the along-mountain LTD motions which are severely underestimated at Most Krk station and slightly overestimated at Most Pag station. However, the PSD of both components in LTD range are better simulated than in the AL8 model. The secondary spectral maximum appears at diur-

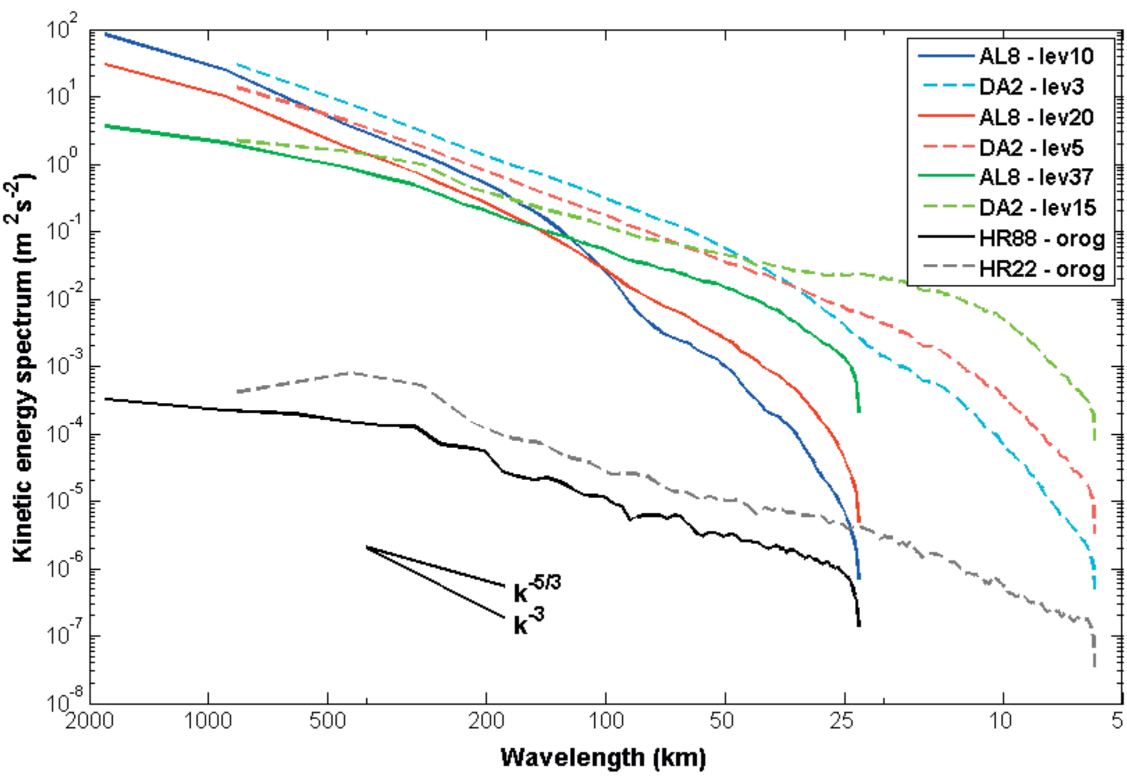

Figure 5. Kinetic energy spectra for AL8 and DA2 models at levels in upper (~ 400 hPa; blue shades), middle (~ 600 hPa; red shades) and lower troposphere (~ 1000 hPa; green shades). Normalized orography spectra of AL8 and DA2 integration domains are added too (black-grey shades).

Slika 5. Spektri kinetičke energije AL8 i DA2 modela na nivoima u višoj (~ 400 hPa; plave nijanse), srednjoj (~ 600 hPa; crvene nijanse) i nižoj troposferi (~ 1000 hPa; zelene nijanse). Normalizirani spektri terena AL8 i DA2 modela također su dodani (crno-sive nijanse).

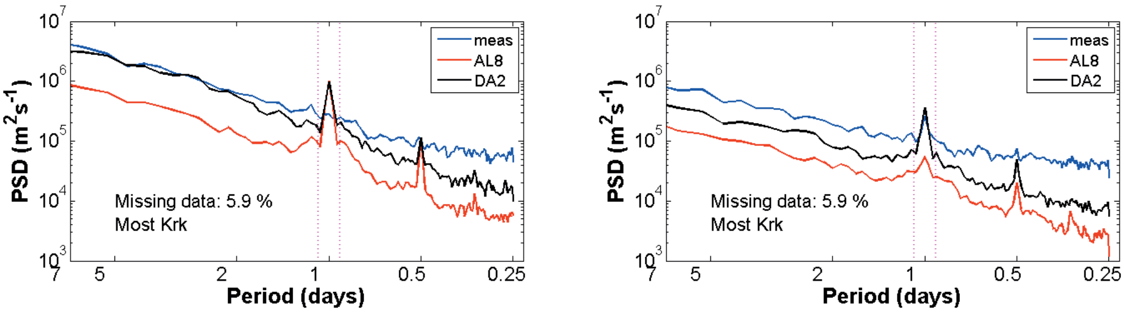

Figure 6. Power spectral density (PSD) of 10 m cross-mountain (left) and along-mountain (right) wind component of measured and modeled AL8 and DA2 data at Most Krk station in period 2010-2012.

Slika 6. Spektar snage (PSD) poprečne (lijevo) i uzdužne (desno) komponente vjetra na 10 m visine za mjerene i modelirane AL8 i DA2 podatke na postaji Most Krk u razdoblju 2010.-2012.

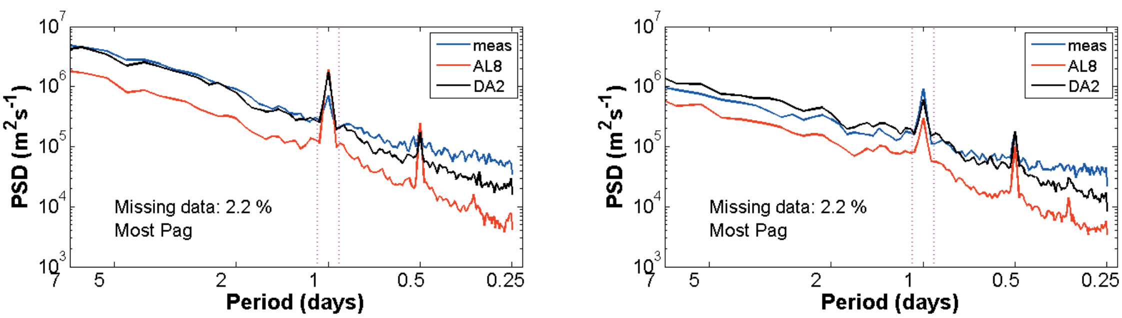

Figure 7. Power spectral density (PSD) of 10 m cross-mountain (left) and along-mountain (right) wind component of measured and modeled AL8 and DA2 data at Most Pag station in period 2010-2012.

Slika 7. Spektar snage (PSD) poprečne (lijevo) i uzdužne (desno) komponente vjetra na 10 m visine za mjerene i modelirane AL8 i DA2 podatke na postaji Most Pag u razdoblju 2010.-2012.

nal scales and it is characterized by very well simulated total amount of power in the DA2 forecast, although the larger amplitude than the one from measured spectra should affect the share of diurnal power in the total modeled power. Anyway, the DA2 model improves both the amplitude and amount of power in DIU spectral range over AL8 model for each of the bora dominated stations. This feature, along with the improved amount of modeled power in LTD spectral range presents the main added value of dynamical adaptation at Most Krk and Most Pag stations. One of the major characteristics of modeled spectra is a deficiency of power in sub-diurnal spectral range, and in particular for the scales shorter than semi-diurnal. Due to similarities with the other two stations this feature of the ALADIN model will be discussed in detail later.

Results of the spectral decomposition for Split Marjan and Šibenik stations are presented on Figures 8 and 9. As it can be seen, the improvements of DA2 model over AL8 are somewhat less than for the bora dominated stations, and are primarily observed for LTD and SUB ranges of cross-mountain component at Split Marjan station and LTD range of along-mountain component at Šibenik station. The amount of diurnal power and amplitude of the spectral diurnal peak are similar for both models and well compared with measurements. Unlike the bora dominated stations, the amount of power in LTD spectral range is similar for cross-mountain and along-mountain components. On the other hand, the amount of power within sub-diurnal range of cross-mountain motions is larger than at bora dominated stations, while the opposite stands for along-mountain motions. Contrary to the bora dominated stations, Split Marjan and Šibenik have pronounced semi-diurnal circulations which are presumably related to the land-sea breeze circulation. This motions are reproduced very accurately by both models and somewhat better for the cross-mountain component. The same was reported by Horvath et al. (2011).

Finally, the common characteristic of both AL8 and DA2 models is a severe underestimation of power at scales below semi-diurnal. Similar was already reported by Žagar et al. (2006) and was present in the results regardless on the domain size and positioning, as well as the used nesting strategy; direct nesting or by using the intermediate domain. This indicates the limited ability of currently used ALADIN model versions in simulating the proper amount of mesoscale energy at the very shortest scales, since those are not resolved by the model. As we have allowed very large spin-up period of 9-hours, it is likely that the reason for the deficiency of power at these scales can be related numerical diffusion in the ALADIN model.

In order to quantify the results of spectral decomposition in the frequency domain, we have calculated the amount of power in LTD, DIU and SUB spectral ranges for all eight stations included in the analysis. On Figure 10 we can see the spectral power distribution of cross-mountain wind component (measured or modeled) in different spectral ranges normalized by total power (measured or modeled; x-axis) and by the observed power in the same spectral range (y-axis) at the same station. If we firstly focus on measurements and the variability along x-axis, it can be noted that eight stations are classified into two groups of four stations. Due to similar spectral characteristics Makarska station is classified into group with previously mentioned bora dominated (BD) stations, although it has somewhat more energy in the mesoscale range. The other group of stations comprises of Split Marjan station with similar portion of bora and sirocco flows, and three stations with significant portion of locally developed and thermally driven (LDTD) flows. The distribution of spectral power among spectral ranges of LDTD stations is similar to the one for coastal stations in Žagar et al. (2006), i.e. 50-55% of power is contained in LTD spectral range, with significant portion of 15-20% and 25-30% in DIU and SUB ranges. On the other hand, the majority of

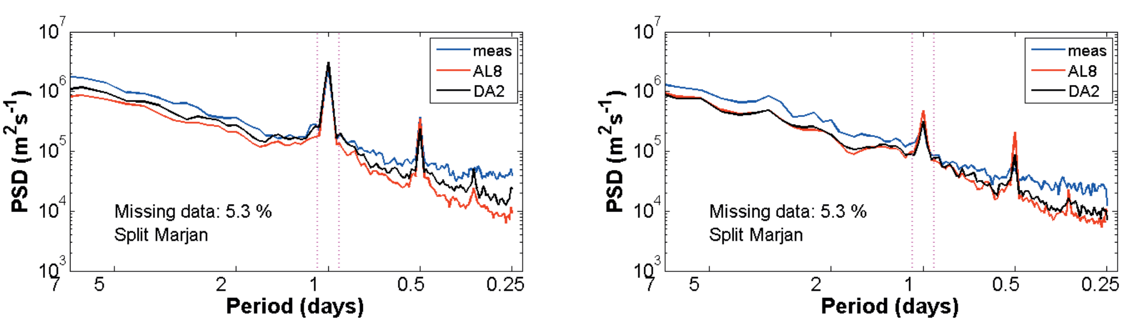

Figure 8. Power spectral density (PSD) of 10 m cross-mountain (left) and along-mountain (right) wind component of measured and modeled AL8 and DA2 data at Split Marjan station in period 2010-2012.

Slika 8. Spektar snage (PSD) poprečne (lijevo) i uzdužne (desno) komponente vjetra na 10 m visine za mjerene i modelirane AL8 i DA2 podatke na postaji Split Marjan u razdoblju 2010.-2012.

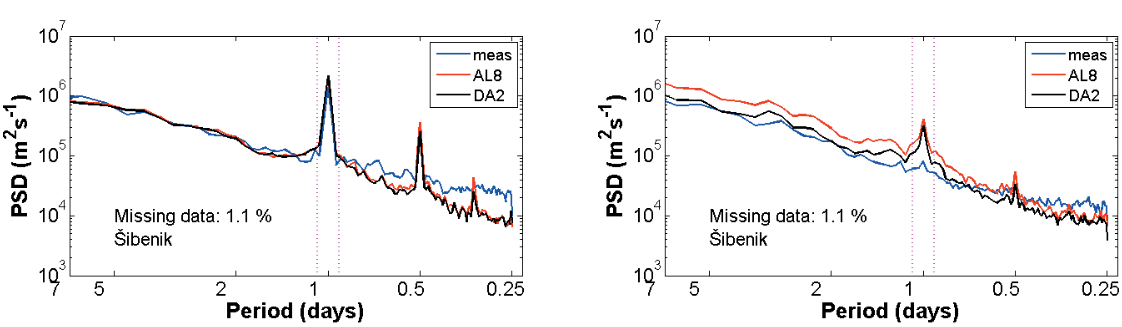

Figure 9. Power spectral density (PSD) of 10 m cross-mountain (left) and along-mountain (right) wind component of measured and modeled AL8 and DA2 data at Šibenik station in period 2010-2012.

Slika 9. Spektar snage (PSD) poprečne (lijevo) i uzdužne (desno) komponente vjetra na 10 m visine za mjerene i modelirane AL8 i DA2 podatke na postaji Šibenik u razdoblju 2010.-2012.

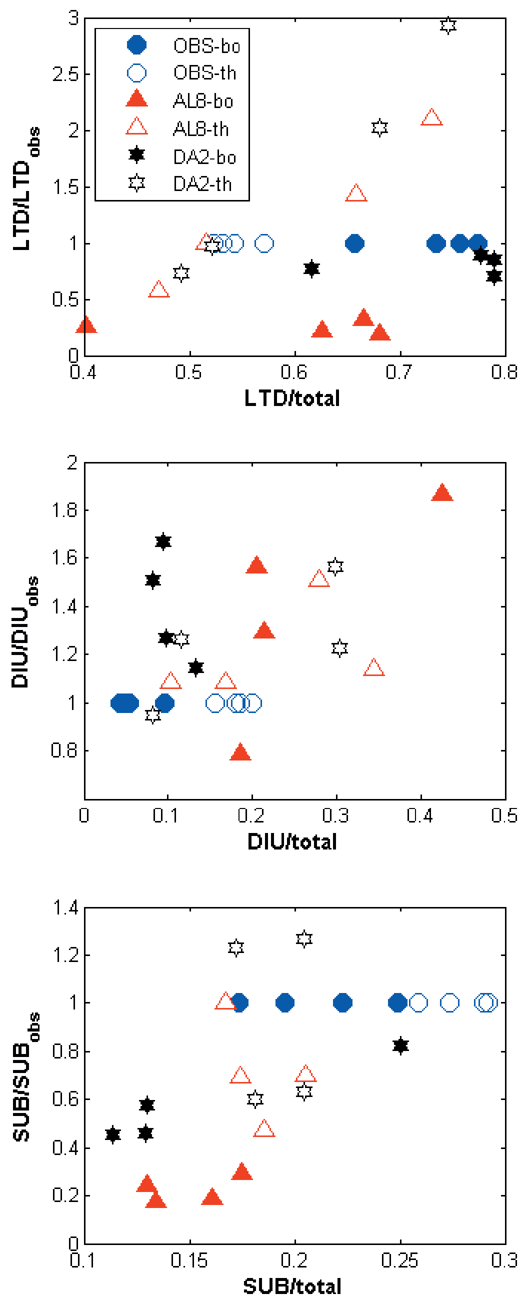

Figure 10. The spectral power distribution of cross-mountain wind component (measured or modeled) in different spectral ranges normalized by total power (measured or modeled; x-axis) and by the observed power in the same spectral range (y-axis) at the same station

Slika 10. Razdioba spektralne snage poprečne komponente vjetra (mjerena ili modelirana) u različitim spektralnim rasponima normalizirana ukupnom snagom (mjerena ili modelirana; x-os) te mjerenom snagom u istom spektralnom rasponu (y-os) na istoj postaji.

spectral power for BD stations is distributed in the LTD spectral range (65-80%). SUB spectral range of BD stations contains 15-25% of spectral power, while the amount DIU power is almost negligible (except for Split Marjan station). It shall be noted that the spectral power for SUB spectral range is overestimated, as discussed in Section. 2.2.

In contrast to the measurements, modelling results do not display such a difference between various wind climate regions. General characteristic of AL8 and DA2 models for both group of stations is that they significantly underestimate the share of SUB motions in total, as well as the ratio of modeled and measured power in the same range. At BD stations both models overestimate the share of DIU power, although the results are significantly improved with the dynamical adaptation. On the other hand, there is no much difference for the LDTD group of stations. Finally, the improvements in LTD range are once again related only to the BD stations, both for the share of LTD power in total and for the ratio of modeled and observed power in the same range. The results for along-mountain component are relatively similar, although the grouping is not pronounced that much because few BD stations have spectral power distribution closer to LDTD stations.

4. CONCLUSIONS

Here are presented the verification results of operational 10 m wind speed obtained with ALADIN/ALARO 8 km (AL8) and ALADIN/DADA 2 km (DA2) models in period 2010-2012. The results of statistical verification suggest that using the dynamical adaptation for surface mean wind speed prediction in complex terrain of eastern Adriatic coast reduces the multiplicative mean systematic error (MBIAS) at bora dominated (BD) stations by more than 50% compared to the coarser AL8 model. On the other hand, the improvement on stations with significant portion of locally developed and thermally driven (LDTD) flows is somewhat less, but that is expected considering the dominant wind regimes and simplifications included in the dynamical adaptation method. The signal of forecast improvement is also seen in the root-mean-square error (RMSE) score, which has largest values during winter months and reduces from north to south. The largest portion of RMSE errors for AL8 model can be attributed to dispersion or phase error (PHE), although the bias of the mean (BM) is quite large at BD stations. With the refinement of model horizontal resolution the share of PHE in RMSE generally increases, while BM and bias of the standard deviation (BSD) significantly decrease and become several times smaller compared to PHE. Thus, it appears that errors in creation and termination of certain process become the main reason for the error in high resolution mesoscale NWP models, and suggests that major improvements to the wind forecasting may be reached through reducing dispersion errors, such as through mesoscale data assimilation process.

The scale dependent evaluation of model performance, conducted by using the spectral analysis in wavenumber and frequency domains, enabled the model assessment on wide range of scales. Calculated kinetic energy (KE) spectra compare well to the theoretical and observational evidence in midlatitudes. In the upper troposphere and at scales above few hundred kilometers, both AL8 and DA2 KE spectra conform to the k^{-3} power law. From mid-troposphere towards the ground, the KE spectra of both models flatten and finally near the surface they resemble the spectra of orography ($\sim k^{-5/3}$), thus showing the influence of the orography on near surface flows in the ALADIN model. Furthermore, the variation of the slope of the KE spectrum with height is most likely related to the appearance and vertical propagation of orographycally-induced gravity waves in the model domain. The largest drawback of the AL8 model KE spectra seems to be the deficit of energy at scales below 200 km in upper troposphere, i.e. the existence of unfavorable steepening of spectral slope from k^{-3}, rather than theoretically expected flattening towards $k^{-5/3}$. On the other hand, DA2 does not show this behavior apart from the regular effective resolution effect evident. The main benefit of dynamical adaptations observed in the kinetic energy spectra seems to be the creation of significant portion of near surface energy at scales below 50 km.

Analysis of measured and modeled power spectra obtained by decomposition in the frequency domain suggested that using the dynamical adaptation improved the ability of simulating the amount of power in all spectral ranges over AL8 model. However, the major improvements are observed for both the amount of power compared to measurements and the share in total power for the longer than diurnal (LTD) and diurnal (DIU) scales of cross-mountain motions at BD stations. This is in large part related to the better simulation of higher wind speeds related to bora flows by the DA2 model. Major drawbacks of both models are related to the inability of grouping different wind climate regimes as seen in the measurements and the insufficient model performance at scales below semi-diurnal. The later one might even influence the applicability of mesoscale numerical weather prediction (NWP) models in the assessment of wind climatology in regions where the amount of power at the smallest scales in comparable with the amount of power at the larger scales. This study points out to some advantages of high resolution mesoscale NWP modelling using the dynamical adaptation, mostly related to decreasing the systematic error by improving the simulation of bora flows. However, there are few questions raised regarding the model uncertainties and drawbacks of the dynamical adaptation method. First of all, it would be crucial to quantify on disadvantages of reduced complexity of dynamical adaptation compared to the full-physics based models of the same horizontal grid spacing. A potential study should include evaluation over longer periods as the one presented here, as well as case studies, which should be involved as they bring more information on dynamics and extreme events. Furthermore, it would be beneficial to make an effort on advanced understanding of model errors through relating various aspects of physical and spectral verification measures. Finally, the analysis and forecasting of bora gustiness and turbulence remains to be one of major research challenges, both for the field of meteorology and applications to wind energy sector.

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