Hrvatsko meteorološko društvo
Croatian Meteorological Society

HRVATSKI METEOROLOŠKI ČASOPIS
CROATIAN METEOROLOGICAL JOURNAL

Časopis je izdan povodom 20. godišnjice ALADIN projekta u Hrvatskoj

50

Hrv. meteor. časopis	Vol. 50	p. 1-144	ZAGREB	2015

Hrvatski meteorološki časopis – Croatian Meteorological Journal, 50, 2015., 91–104

Review paper
Pregledni rad

OVERVIEW OF METEOROLOGICAL RESEARCH ON THE PROJECT "WEATHER INTELLIGENCE FOR WIND ENERGY" - WILL4WIND

Pregled meteoroloških istraživanja na projektu „Inovativna meteorološka podrška upravljanju energijom vjetra" - WILL4WIND

KRISTIAN HORVATH, ALICA BAJIĆ, STJEPAN IVATEK-ŠAHDAN, MARIO HRASTINSKI, IRIS ODAK PLENKOVIĆ, ANTONIO STANEŠIĆ, MARTINA TUDOR, TOMISLAV KOVAČIĆ

Meteorological and Hydrological Service, Grič 3, 10000 Zagreb, Croatia
Državni hidrometeorološki zavod, Grič 3, 10000 Zagreb, Hrvatska
kristian.horvath@cirus.dhz.hr

Recieved 19 May 2015, in final form 29 October 2015

Abstract: This paper presents an overview of the research results achieved during implementation of the project "Weather Intelligence for Wind Energy" - WILL4WIND (IPA2007/HR/16IPO/001-040507). The overall goal of the WILL4WIND project was to reduce the wind forecast uncertainties in coastal and complex terrain of Croatia in order to support a more efficient integration of wind energy in the national electric system.
The paper presents the following key results of applied meteorological research conducted on the project: i) evaluation of wind forecasts showed greater accuracy of the ALADIN/HR model when increasing the model resolution, ii) deterministic forecasting using analogue-ensemble post-processing method noticeably improved numerical weather predictions iii) probabilistic forecasting using analogue-ensemble method provided useful information on the uncertainty of wind predictions, and iv) targeted knowledge diffusion and extensive two-way networking supported identification of the joint research priorities of meteorology and wind energy communities and contributed to development of dedicated software to ease the use of ALADIN/HR forecasts in operational wind energy sector activities. PROJECT was implemented by a Croatian consortium led by Meteorological and Hydrological Service, Croatia, in collaboration with the University of Zagreb Faculty of Electrical Engineering and Computing, Croatian Transmission System Operator Ltd., RP Global Projekti Ltd. and Energy Institute „Hrvoje Požar". Europen Union co-funded the project through the Science and Innovation Investment Fund within the Instrument for Pre-Accession Assistance (IPA) for Croatia.

Key words: WILL4WIND project, ALADIN/HR prediction system, wind forecasting, statistical modelling and post-processing, probabilistic forecasting, wind energy management, Science and Innovation Investment Fund, EU Instrument for Pre-Accession Assistance (IPA)

Sažetak: U ovome radu daje se pregled rezultata istraživanja provedenih u projektu „Inovativna meteorološka podrška upravljanju energijom vjetra" - WILL4WIND (IPA2007/HR/16IPO/001-040507). Opći cilj projekta WILL4WIND bio je smanjiti meteorološke nepouzdanosti u prognozi smjera i brzine vjetra u obalnom i kompleksnom terenu Hrvatske za svrhu efikasnije integracije energije vjetra u nacionalni elektroenergetski sustav.
Ovaj rad opisuje sljedeće glavne rezultate primjenjenih meteoroloških istraživanja na projektui: i) evaluacija prognoze brzine vjetra modelom ALADIN/HR pokazala je veću točnost prognoze sa povećanjem rezolucije modela, ii) deterministička post-processing metoda ansambla analoga je znatno poboljšala rezultate numeričkih modela, iii) probabilistička prognoza metodom ansambla analoga je korisna za ocjenu pouzdanosti prognoze vjetra, i iv) ciljana difuzija znanja i intenzivno dvosmjerno umrežavanje su poduprijeli identifikaciju zajedničkih istraživačkih prioriteta područja meteorologije i energije vjetra i pridonjeli razvoju softvera za lakšu upotrebu ALADIN/HR prognoza u operativnim aktivnostima energetskog sektora. Projekt se

implementirao unutar hrvatskog konzorcija predvođenog Državnim hidrometeorološkim zavodom, u suradnji sa: Sveučilište u Zagrebu Fakultet elektrotehnike i računarstva, Hrvatski operator prijenosnog sustava d.o.o., RP Global Projekti d.o.o. i Energetski institut „Hrvoje Požar". Europska unija je sufinancirala projekt kroz Fond za ulaganje u znanosti i inovacije u sklopu Instrumenta predpristupne pomoći (IPA) za Hrvatsku.

Ključne riječi: projekt WILL4WIND, ALADIN/HR prognostički sustav, prognoza smjera i brzine vjetra, statističko modeliranje i post-processing, probabilistička prognoza, upravljanje energijom vjetra, Fond za ulaganje u znanosti i inovacije, EU Instrument predpristupne pomoći (IPA)

1. INTRODUCTION

For the EU and future member states, the energy challenge has become a top priority for policy makers. The insecurity of traditional energy supplies, climate change threats and creation of new jobs placed the renewable energy - and in particular the wind energy - as one of the main objectives of the EU sustainable development, as supported by adoption of "20-20-20" binding targets. Such targets promoted intensive collaboration between energy and meteorology communities on the topic of wind energy forecasting and integration of wind energy into electric grids. As the share of renewables in total energy consumption, especially wind energy, increasingly grew in last years, the need to predict the amount of produced energy from wind power plants over a period of the next few days showed essential for efficient and safe integration of wind energy into national electric grids Europe-wise. Therefore, pan-European collaboration focused on wind energy forecasting was stimulated and implemented through several programs such as FP5 (e.g. Anemos project, *http://forecast.uoa.gr/anemos*), FP6 (e.g. Anemos.plus project, *www.anemos-plus.eu*) and COST (e.g. WIRE Action, *www.wire1002.ch*).

In Croatia, however, regardless of the positive legislation, substantial interest of investors and abundance of wind resource, the uptake of the wind energy sector is still moderate. In part this is due to the fact that the interaction between meteorology and energy communities in last years and decades focused on resource estimates, while research in wind and wind energy forecasting, despite some exceptions (e.g. WINDEX project, *www.windex.hr*), did not earn substantial attention. However, due to the high intermittency of winds, especially related to frequent severe downslope bora windstorms (Zaninović et al. 2008; Grisogono and Belušić 2009; Horvath et al. 2011), wind energy integration without the support of high-performance prediction technologies (currently wind energy installations account for around 10% of the installed Croatian energy production capacity) becomes a major risk for the security of energy supply and results in excessive integration costs. To reduce meteorological uncertainties of wind energy integration, wind energy sector needs a dedicated probabilistic wind and wind power forecasting system designed for challenging wind climate in complex and coastal terrain of Croatia. Since the errors in predicted wind energy production are proportional to the cube of the wind speed errors, it is essential to improve as much as possible the accuracy of wind speed predictions at wind power plant locations.

As a response to the real needs of the Croatia economy, a consortium led by Meteorological and Hydrological Service (DHMZ) together with the University of Zagreb Faculty of Electrical Engineering and Computing (FER), Croatian Transmission System Operator Ltd. (HOPS), RP Global Projekti Ltd. and Energy Institute Hrvoje Požar (EIHP) conducted a project entitled "Weather intelligence for wind energy" - WILL4WIND (www.will4wind.hr). WILL4WIND project was designed to develop solutions to support wind energy sector based on recent research results and long-standing experience in analyzing specific wind conditions in Croatia (Fig. 1). Project lasted from 10 Apr 2013 - 9 July 2015, and engaged four young researchers on DHMZ and FER during its implementation.

Prediction technologies developed in the project WILL4WIND may be divided in two groups:

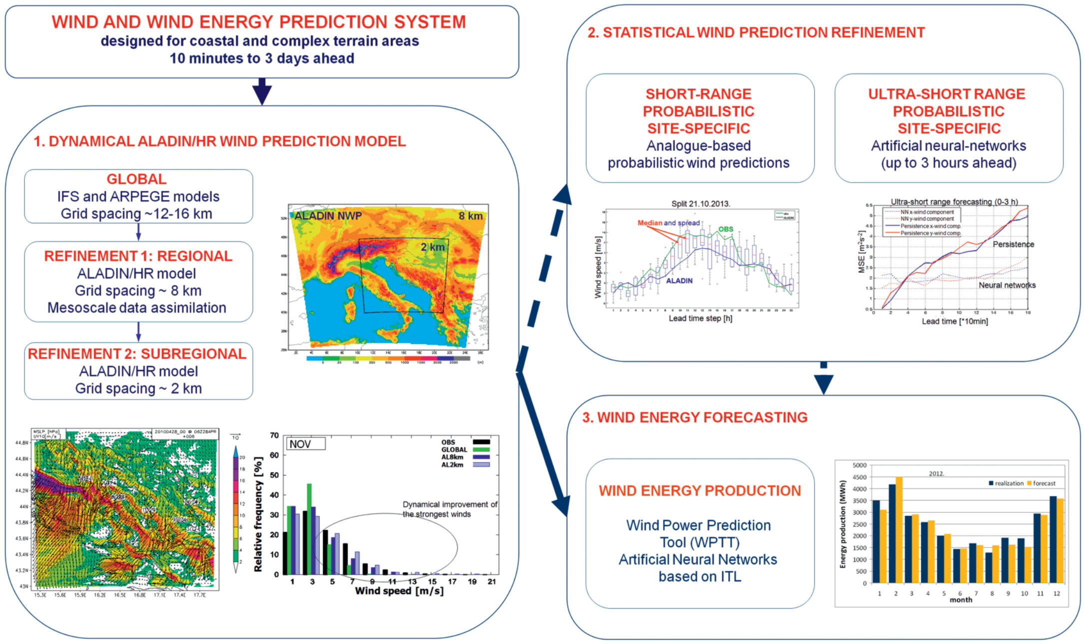

Figure 1. A design of prediction technologies used in the Weather Intelligence for Wind Energy - WILL4WIND project.

Slika 1. Dizajn prediktivnih tehnologija u projektu „Weather Intelligence for Wind Energy" - WILL4WIND

1. *Short-range forecasts* (3h - 72 h lead time, with 3-hourly output interval), performed on the basis of numerical weather prediction model outputs and statistical probabilistic post-processing methods
2. *Ultrashort-range forecasts* (10 min - 3 h lead time, with 10-min output interval) performed based on artificial neural networks that use observations and numerical weather prediction model output.

The goal of this paper is to describe development of prediction methods related to short-range forecasting within the WILL4WIND project. Section 2. will present the methodology, section 3. will demonstrate results of deterministic and probabilistic predictions, section 4. will present results of knowledge and information diffusion within meteorology and wind energy sectors, and section 5. will conclude this contribution.

2. METHODS

2.1. Numerical weather prediction

A Croatian version of the numerical weather prediction modelling system ALADIN (Aire Limitée Adaptation Dynamique Développement International, ALADIN International Team, 1997), ALADIN/HR, is since long in operational use on DHMZ. DHMZ operationally uses ALARO configuration of the ALADIN/HR modelling system on Lambert projection and on domain (Fig. 2) with a horizontal grid spacing of 8 km (henceforth HR88). The model was driven with lateral boundary conditions (LBCs) from the global model ARPEGE/IFS (Action de Recherche Petite Echelle Grande Echelle/Integrated Forecast System) until 2014, and henceforth with LBCs from the global model ECMWF (European Centre for Medium-Range Weather Forecasts).

Initial conditions are produced locally in DHMZ using the 3D-Var variational data assimilation for the upper-air fields and the optimal interpolation for the surface fields. In everyday practice at DHMZ, since 2014 numerical weather predictions have been updated every 6 hours.

After the model integration, wind speed and direction forecast fields are refined in the planetary boundary layer to a grid spacing of 2 km on a smaller domain by the computationally highly efficient dynamical adaptation method (henceforth HRDA, Ivatek-Šahdan and Tudor 2004). Furthermore, a non-hydro-

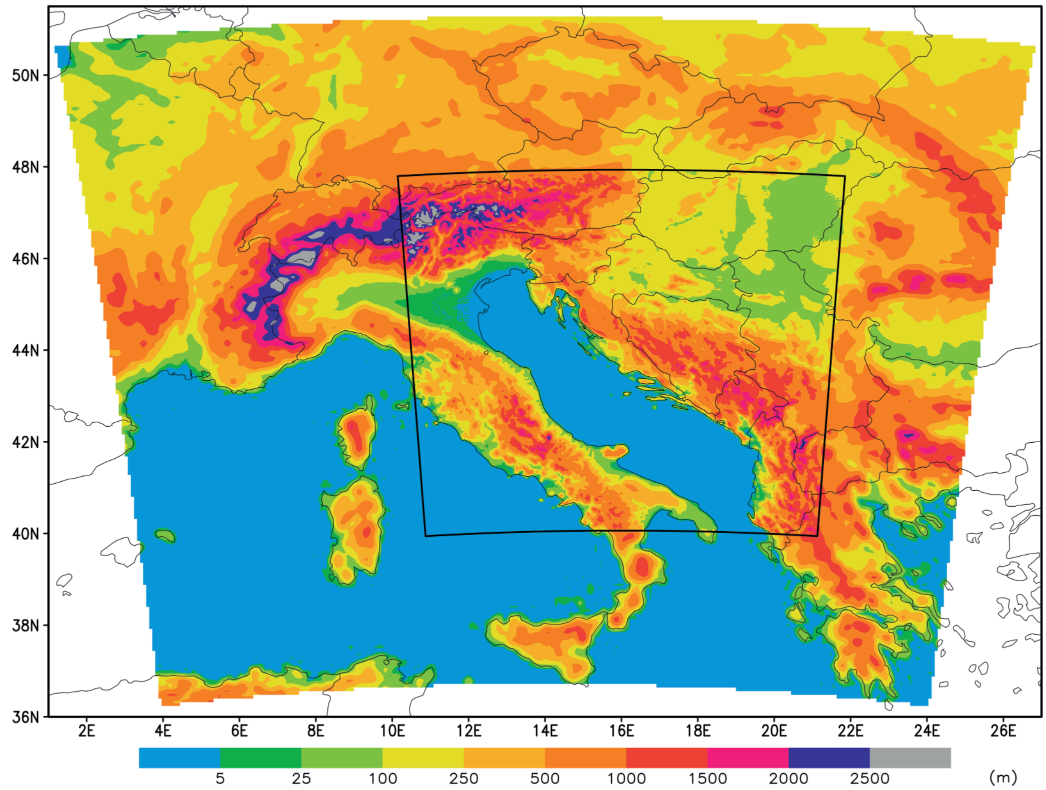

Figure 2. Model domains in the DHMZ's ALADIN model setup. Outer domain corresponds to 8 km grid spacing model, and inner domain corresponds to 2 km grid spacing models (for both dynamical adaptation and non-hydrostatic model).

Slika 2. Domene modela ALADIN u konfiguraciji na DHMZ-u. Vanjska domena ima horizontalni korak mreže 8 km, a unutrašnja domena ima horizontalni korak mreže 2 km (i za dinamičku adaptaciju i za ne-hidrostatički model)

static version of the ALADIN/HR model is run in test mode with the grid spacing of 2 km using full-physics set of physical parametrizations (henceforth HR22). The use of computationally efficient HRDA method in operational practice has the following characteristics: (1) the use of hydrostatic dynamical equations, (ii) the reduced number of vertical levels above planetary boundary layer (PBL) and (iii) omitted all physical parametrizations except the vertical diffusion (PBL) parameterization. Simplifications applied in the dynamical adaptation are designed to dynamically adapt wind fields over complex terrain, but have certain limitations in adding value to simulated thermal circulations and processes of formation of clouds and precipitation compared to the driving lower-resolution model HR88. These processes are better represented in the non-hydrostatic full-physics HR22 configuration. More information on the Croatian implementations of the ALADIN/HR model may be found in Tudor et al. (2013).

2.2. Statistical post-processing

Statistical post-processing is typically used for improvement of the direct model output accuracy at sites with existing wind speed measurements. Additionally, some of those methods can be used for estimation of the forecast uncertainty. Within the project, two groups of methods are tested for improving local wind forecasts:

1. Kalman filter (Kalman 1960);
2. Analogue ensemble (Delle Monache et al. 2011).

Kalman filter a method which is typically used for bias reduction which remains in the direct model output of forecast products. However, Kalman filter responds rather slowly to rapidly changing weather conditions since the forecast error prediction is typically based on the persistence. On the other hand, analogue ensemble methods do not assume persistent errors and respond rather quickly to rapidly changing weather. The additional benefit of the analogue ensemble method is that it can be used to provide probabilistic predictions for locations where both forecasts and observations are available. Strengths and weaknesses of these two methods are discussed in more detail in literature (e.g. Delle Monache et al. 2011; Delle Monache et al. 2013). However, a challenge for both methods are predictions of rare events, such as extreme wind speeds related to bora winds.

2.3. Evaluation of the results

The evaluation of developed dynamical and statistical methods used modeled time-series of ALADIN/HR forecasts and measurements from 14 stations in Croatia prepared for the period 2010-2012. The analysis covered three different model configurations of the ALADIN/HR modelling system:

1. HR88 model configuration with 8 km horizontal resolution, 72 h forecasting range and 3 hours interval of forecasting fields availability, model version 32T3 with ALARO0-3MT set-up, digital filter initialization, initial conditions in period 2010-Oct 2011 from ARPEGE/IFS and from the mesoscale data assimilation cycle in period Nov 2011-2012, and lateral boundary conditions from ARPEGE/IFS;
2. HR22 model configuration with 2 km horizontal resolution, 24 h forecasting range (starting from 6-hourly HR88 forecast) and 1 hour interval of forecasting fields availability, model version AL36T1 with the ALARO0 set-up of the physics parametrizations and non-hydrostatic dynamics, scale selective digital filter initialization, initial and lateral conditions from HR88;
3. HRDA model configuration with 2 km horizontal resolution, 72 h forecasting range and 3 hours interval of forecasting fields availability, model version 32T3, initial and lateral boundary conditions from HR88 configuration.

The analysis presented in this paper used forecasts produced every 24 hours corresponding to 00 UTC forecast initialization time.

3. RESULTS

3.1. Model ALADIN/HR

Statistical and spectral evaluation of three tested configurations of the ALADIN/HR mesoscale NWP model were performed using forecasts and measured data at meteorological stations during the period 2010-2012. Methods used to evaluate the models and achieved results are briefly highlighted here, while more detailed analysis can be found in Hrastinski et al. (2015).

Statistical verification included several statistical measures, such as systematic error, root-mean-square error, and mean absolute error, among others. The analysis of monthly values of the root mean square error from three tested versions of ALADIN/HR mesoscale NWP model on the example of Šibenik station (Fig. 3) has shown that its value for the HRDA and HR22 varies between 1.5 ms^{-1} and 2.5 ms^{-1}, depending on a considered month.

To study the properties of the root-mean-square error (RMSE), it has been decomposed to its integral components (e.g. Murphy 1988; Horvath et al. 2012): the bias of the mean (BM), the bias of the standard deviation (BS) and dispersion or phase error (PHE). An example of the RMSE decomposition for Šibenik (Fig. 3) shows that the dispersion (phase) errors are the main source of the model error, especially in models at higher resolution. This result suggests that errors in the starting and ending time of represented processes, including the formation and disappearance of wind circulations, are the dominant source of error in the ALADIN/HR modelling system.

Spectral verification is performed by quantitative spectral measures arising from spectral decomposition in wave-number and frequency domains (Rife et al. 2004; Žagar et al. 2006; Horvath et al. 2012). Such spectral decomposition provides information on the performance of the model in simulating the processes of certain time scales or a certain range of time scales at specific location and it is useful for the physical interpretation of the results.

Power spectral density functions depending on frequency (period) as inferred by measurements on Split Marjan locations shows that while expectedly a large share of energy vari-

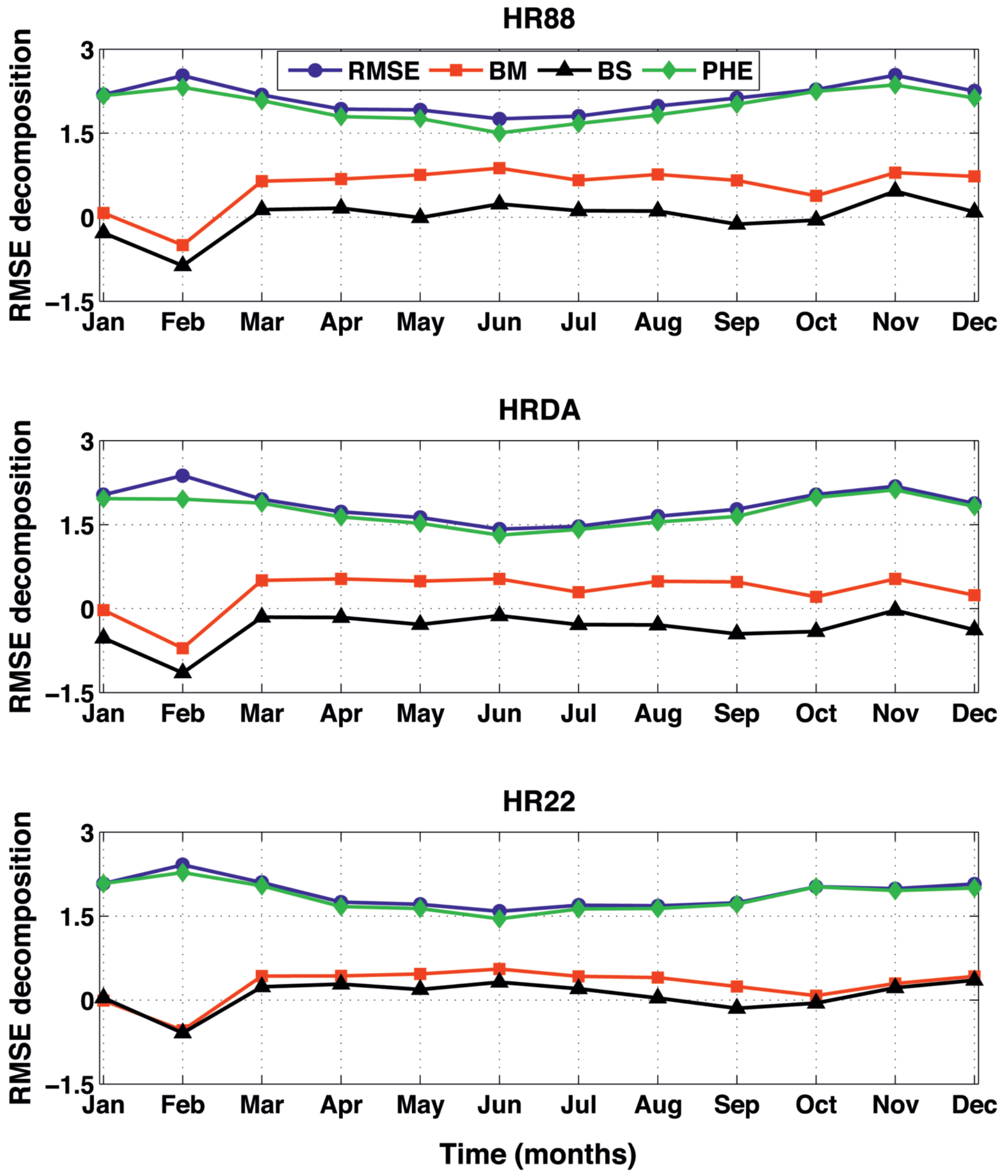

Figure 3. An example of decomposition of the root-mean-square error (RMSE) of ALADIN/HR mesoscale NWP model for station Šibenik: HR88 configuration (upper panel), HRDA configuration (middle panel), and HR22 configuration (lower panel) into bias of the mean (BM), bias of the standard deviation (BS) and dispersion error or phase error (PHE).

Slika 3. Primjer dekompozicije korjena srednje kvadratične pogreške (RMSE) numeričkog mezoskalnog modela za prognozu vremena ALADIN za postaju Šibenik: HR88 konfiguracija (gore), HRDA konfiguracija (sredina) i HR22 konfiguracija (dolje), u pristranost srednjaka (BM), pristranost standardne devijacije (BS) i pogrešku disperzije (PHE).

ance exists on synoptic scales and longer mesoscales, a prominent peak in the spectrum indicates that the large contribution of diurnal flows (Fig. 4). The lower and upper confidence intervals are added to the figure providing support to this conclusion. This peak is evident for both cross-mountain and along-mountain (with respect to orientation of Dinaric Alps) wind speed components and for both diurnal and semi-diurnal scales suggesting the rotational origin of diurnal circulation in the Adriatic which is a typical characteristic of land-sea breeze in the area (Telišman Prtenjak and Grisogono 2007).

Modelled power spectral density functions on station Split Marjan for three analyzed models are shown on Fig. 5. Results of the HR88 show the largest departures from the measurements for all scales of motions, other than daily. The total variability of wind energy is underestimated for longer mesoscale, synoptic motions, as well as for subdiurnal motions. Results of the HRDA are improved primarily for the NE-SW cross-mountain wind component in the direction of bora wind, while for the NW-SE along-mountain component there are no major differences in comparison to the performance of HR88. The smallest deviations from the measurements are given by the

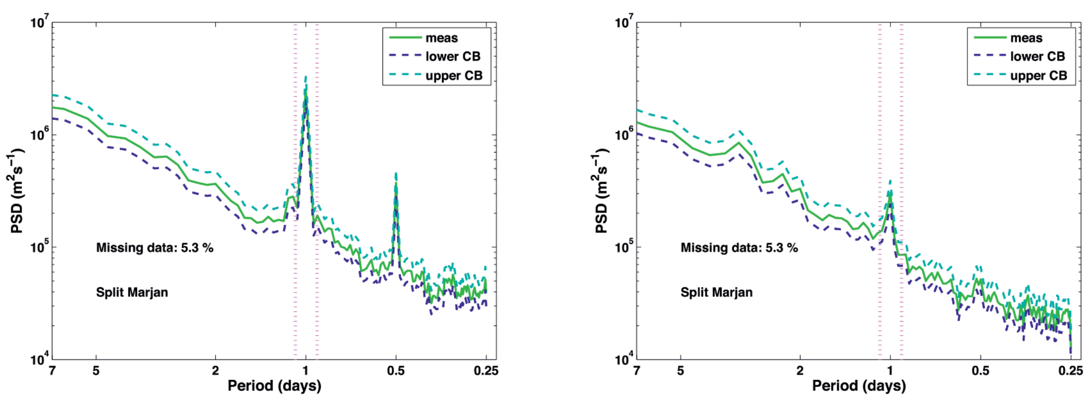

Figure 4. Spectral decomposition of wind speed measurements at Split Marjan station in the period 2010-2012 for the cross-mountain NE-SW wind speed component (left panel) and along-mountain NW-SE wind speed component (right). Confidence intervals are added to the figure.

Slika 4. Spektralna dekompozicija mjerenja brzine vjetra za postaju Split Marjan u razdoblju 2010-2012 za komponentu okomitu (SI-JZ) na primarni planinski lanac (lijevo) i komponentu paralelnu (SZ-JI) sa primarnim planinskim lancem. Slika prikazuje i intervale pouzdanosti.

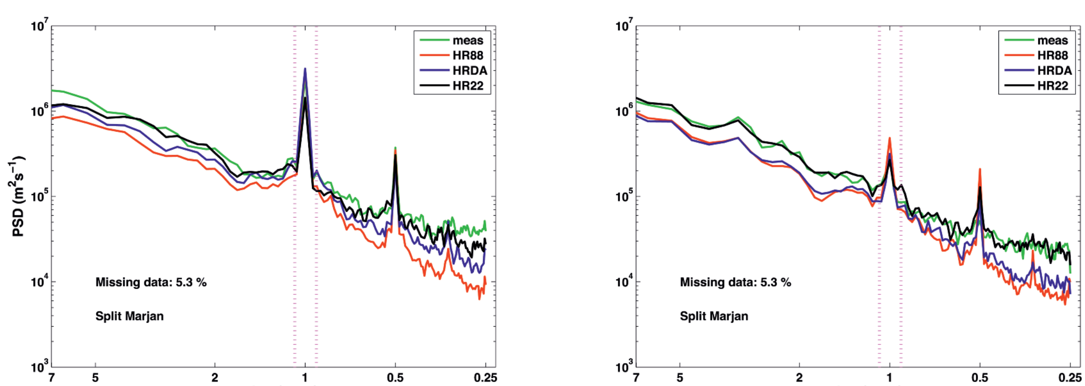

Figure 5. Spectral decomposition of measurements, HR88, HRDA and HR22 model configurations at Split Marjan station in the period 2010-2012 for the cross-mountain NE-SW wind speed component (left panel) and along-mountain NW-SE wind speed component (right).

Slika 5. Spektralna dekompozicija mjerenja, HR88, HRDA i HR22 modelskih konfiguracija za postaju Split Marjan u razdoblju 2010-2012 za komponentu okomitu (SI-JZ) na primarni planinski lanac (lijevo) i komponentu paralelnu (SZ-JI) sa primarnim planinskim lancem

HR22 which accurately simulates the spectral energy density at all time scales, other than those of a few hours. Since results are generally similar for other meteorological stations in Croatia, Therefore, it is suggested that the use of HR22 has a potential to improve the results and accuracy of the weather or wind forecasts in the area.

3.2. Statistical methods

Using the historical prognostic data from ALADIN mesoscale NWP model and measurements, the following deterministic statistical post-processing methods were developed:
Kalman filter - KF;

1. Analogue ensemble (mean value) - AE mean;
2. Kalman filter of analogue ensemble (mean value) - AE mean KF;
3. Analogue ensemble (weighted average) - AE w. mean;
4. Analogue ensemble (median) - AE median;
5. Kalman filter sorted analogue ensemble metrics - KFSM.

The training period for the deterministic analogues ensemble forecast are years 2010 and 2011, while the verification is performed for the year 2012. Prognostic values used in the statistical modelling were taken from the most representative of four models points surrounding a specific station. The stations shown here for analysis were classified in here different regions corresponding to three distinct winds regimes: (1) Group 1: coastal regime with high frequency of thermal circulations (Most Krk, Maslenički most, Šibenik, Split, Dubrovnik), (2) Group 2: mountain regime with high frequency of valley, slope, and other mountain flows (Ogulin, Gospić, Knin), (3) Group 3: continental regime with only flat terrain effects on the passing circulation systems (Zagreb Maksimir, Varaždin, Bilogora, Osi-

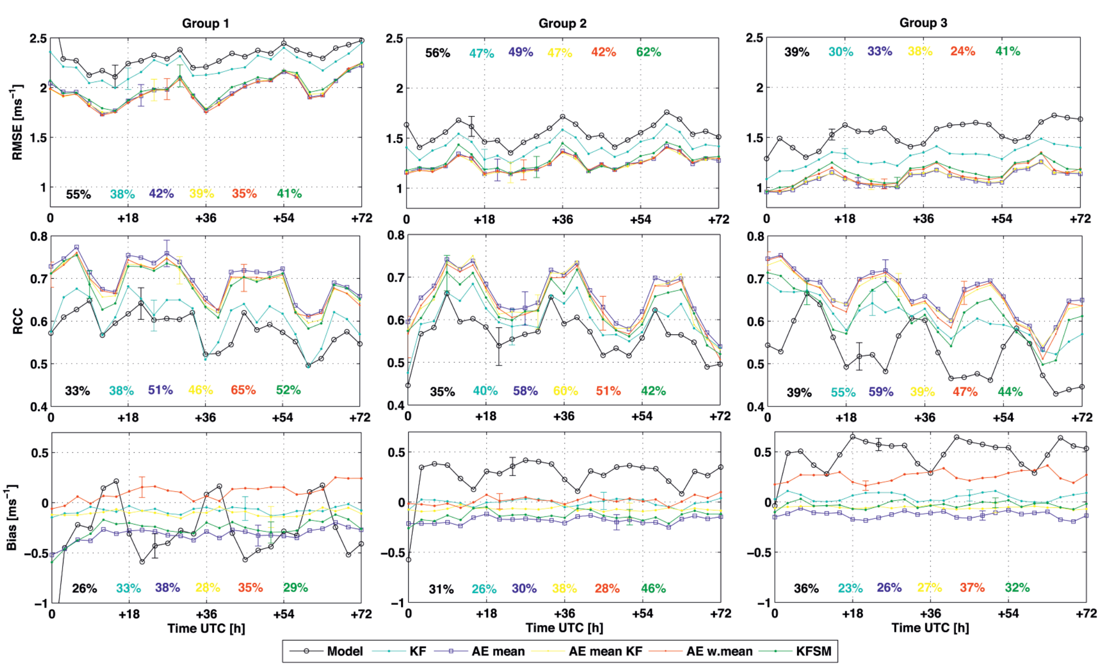

Figure 6. Root-mean-square error (RMSE), rank correlation coefficient (RCC) and systematic error (Bias) for six different deterministic statistical post-processing methods compared to the direct ALADIN/HR (HR88) mesoscale NWP model output for three groups of stations: coastal (left), mountain (middle) and continental (right) during the year 2012. Mean value of the confidence interval of statistical measure is shown for each measure and for each forecast, while its variability is shown numerically as a percentage in the corresponding color.

Slika 6. Korijen srednje kvadratične pogreške (RMSE), koeficijent korelacija ranga (RCC) i pristranost (Bias) za šest različitih determinističkih post-procesing metoda u usporedbi sa direktnim izlazom modela ALADIN/HR (HR88) za tri grupe postaja: obalne (lijevo), planinske (sredina) i kontinentalne (desno) tijekom 2012 godine. Srednja vrijednost interval pouzdanosti prikazana je za svaku prikazanu mjeru i svaku prognozu, a njegova promjenjivost je prikazana kao numerički podatak (postotak) u pripradnoj boji.

jek, Slavonski brod and Županja). While in this section we briefly highlight main findings of the performed research, more rigorous description of the developed post-processing methods and achieved results (as well as figure with denoted stations) may be found in Odak Plenković et al. 2015.

The performance of various statistical methods was tested with several statistical measures: systematic error, mean squared error, mean absolute error, and rank correlation coefficient. Other specific measures of accuracy which emphasize the wind speed categories, that were used but were not presented in this paper are Frequency Bias(FB), Polyhoric Correlation Coefficient (PCC), the Critical Success Index (CSI) and the Stable and Equitable Error Probability Space (SEEPS).

The forecast accuracy of the direct ALADIN/HR modelling system output (HR88 configuration) and different statistical models applied to the ALADIN/HR model forecasts in 2012 is shown in Fig. 6 for three groups of stations: coastal (left), mountain (middle), and continental (right). All statistical methods reduce the root-mean-square error of the direct model output, wherein the methods based on analogues are slightly more successful than the methods based only on the Kalman filter. As demonstrated further in

Table 1. Root-mean-square error (RMSE), rank correlation coefficient (RCC) and bias (Bias) change (positive is improvement, negative is deterioration of accuracy) of three different deterministic forecasts (Kalman filter, AE mean and Kalman filter of AE mean) at 3 different groups of stations when HR88 (top), HR22 (middle) and HRDA (bottom) starting ALADIN model configuration is used. Results are averaged for all of lead times and shown as percentages.

Tablica 1. Promjena korijena srednje kvadratične pogreške (RMSE), koeficijenta korelacija ranga (RCC) i pristranosti (Bias) (pozitivna promjena je poboljšanje, negativna je smanjenje točnosti) za tri različite determinističke prognoze (Kalmanov filter, srednjak ansambla analoga i Kalman filter srednjaka anasambla analoga) za tri grupe postaja za HR88 (gore), HR22 (sredina) i HRDA (dolje) konfiguracije ALADIN modela. Rezultati su usrednjeni za sva nastupna vremena prognoze i prikazani kao postotci.

[%]	**HR88**								
	KF			**AE mean**			**AE mean KF**		
	Group 1	**Group 2**	**Group 3**	**Group 1**	**Group 2**	**Group 3**	**Group 1**	**Group 2**	**Group 3**
RMSE	7.87	8.55	14.49	29.19	19.63	29.11	28.91	20.1	28.61
RCC	-3.06	8.24	16.74	27.6	21.02	28.75	21.14	18.4	26.8
Bias	66.77	91.13	89.33	60.41	40.98	73.45	86.49	76.88	88.49
[%]	**HR22**								
	KF			**AE mean**			**AE mean KF**		
	Group 1	**Group 2**	**Group 3**	**Group 1**	**Group 2**	**Group 3**	**Group 1**	**Group 2**	**Group 3**
RMSE	2.07	11.59	18.44	14.64	40.59	36.48	14.35	41.65	36.01
RCC	4.5	8.93	16.72	23.26	22.69	29.46	17.04	20.85	27.63
Bias	51.09	73.06	87.97	-60.64	69.26	82.04	54.69	91.69	92.08
[%]	**HRDA**								
	KF			**AE mean**			**AE mean KF**		
	Group 1	**Group 2**	**Group 3**	**Group 1**	**Group 2**	**Group 3**	**Group 1**	**Group 2**	**Group 3**
RMSE	-0.01	9.9	17.21	9.52	30.26	30.07	9.01	31.17	29.96
RCC	0.69	7.98	18.55	26.74	24.48	27.33	20.79	24.82	26.46
Bias	58.86	89.43	91.62	-104.14	62.8	75.86	37.57	86.24	90.36

Odak Plenković et al. (2015), the amplitude of the error reduction is dependent on the location, i.e., the group of stations and on the forecasting period.

Furthermore, all statistical methods almost completely reduce systematic errors which are found in the ALADIN/HR mesoscale NWP model outputs. It can be seen that apart from reducing the overall bias, a daily cycle of the bias is removed as well, which is particularly pronounced at coastal stations. Finally, the rank correlation coefficient is substantially increased for all methods, particularly for those based on analogues. A summary of the performance improvement of different statistical methods expressed as percent of improvement in magnitude of the statistical measures is shown in Table 1.

Among three tested methods shown in Table 1., Kalman filter of the analog ensemble (AE mean KF) shows most consistent results and best improvement of scores in all three groups of stations. Application of AE mean KF on the operational model results of dynamical adaptation, on average for all three groups of stations, results in the following improvements: around 23% for RMSE, around 24% for rank correlation coefficient and around 71% for systematic error.

Finally, the analogue ensemble method was used for deriving probabilistic forecast information. This method is computationally affordable for assessing e.g., confidence intervals of wind speed and direction forecasts, but only for locations where measurements do exist. It should be noticed that this method may not be considered as a substitute for the ensemble probabilistic systems generated using different initial conditions and performing an ensemble of simulations for the evaluation of uncertainty of the three-dimensional state

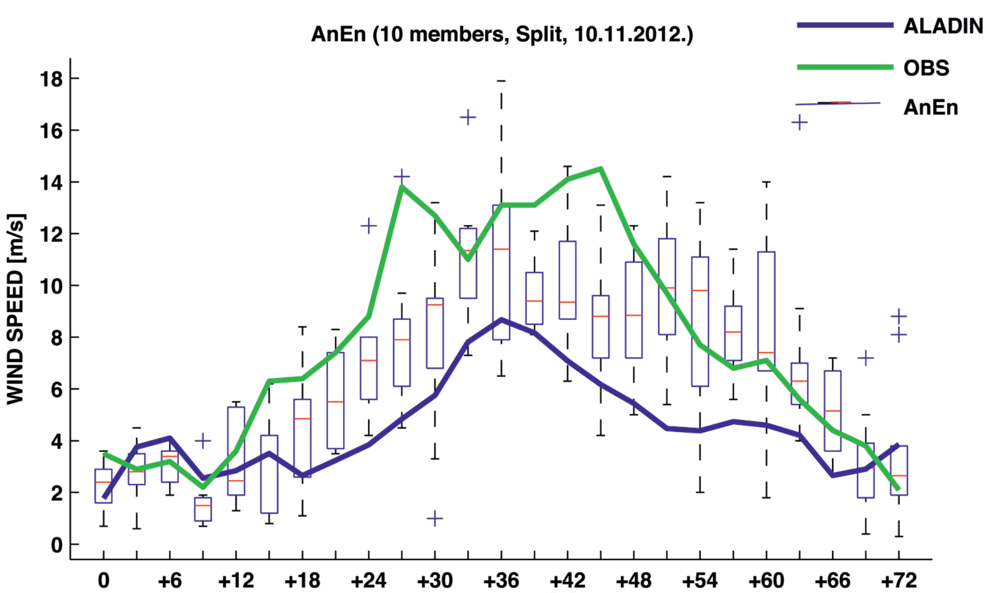

Figure 7. Example of a probabilistic forecast for Split Marjan station using the ALADIN mesoscale NWP model and analogues ensemble. Forecasting lead time is shown on the x-axis (each step corresponds to 3 hours interval), while wind speed is on the y-axis. The blue line denotes ALADIN/HR (HR88) model forecast, green line represents measurements, while red lines correspond to deterministic estimates of wind speed using analogues ensemble. Corresponding distributions provide probabilistic information about the reliability of forecast.

Slika 7. Primjer probabilističke prognoze za postaju Split Marjan uz upotrebu modela za numeričku prognozu vremena ALADIN i metode ansambla analogona. Nastupno vrijeme prognoze prikazano je na x-osi (svaki korak odgovara 3-satnom intervalu), a brzina vjetra je na y-osi. Plava linija označava prognozu modela ALADIN/HR (HR88), zelena linija označava mjerenja, a crvene linije odgovaraju determinističkoj procjeni brzine vjetra metodom ansambla analogona. Pripadne raspodjele pružaju probabilističku informaciju o pouzdanosti prognoze.

vector of the atmosphere. An example of such forecast is given in Fig. 7, which shows single 72-hourly forecast for the location of Split Marjan. The figure clearly indicates that the mean value of analogue ensemble improves the wind forecast obtained by the ALADIN model. The method also provides corresponding information of (un)certainty of wind forecasts. From this type of forecasts it is furthermore possible to calculate the probabilistic forecast information, such as probability of wind speed exceeding a certain value at a particular location.

4. KNOWLEDGE AND INFORMATION DIFFUSION

Important aspect of the project was integration of wind and wind energy forecasts into decision making processes of the target groups, with on the emphasis transmission system operator and wind power plant owners and managers.

In collaboration with DHMZ, the project partners developed a wind energy production forecast module to support the target groups of the project in everyday operations. Namely, transmission system operator as well as wind power plant owners and managers need to include information of the forecasted wind speeds and estimated energy production over next few days into their daily operation to be able to manage efficiently the produced wind energy. For that purpose, these dedicated users require an easy access to viewing and managing wind and wind energy forecasts, and inserting them into their decision making process. For that reason, the project team has developed a web application to allow not only an easy management of forecasts but also to allow tailor-made adaptations of the relevant forecast information provided. An example of a wind forecast graph in the web application for location of one Croatian wind power plant is given in Figure 8. These efforts are complimented by improvement of the DHMZ’s monitoring system, which in the first six months of 2015 resulted in 100% of forecast delivery success and around 99% of forecasts being timely delivered without any delays. Compared to 2014, timeliness of the minor number of forecasts being delayed was improved for 54,51%.

Knowledge dissemination and diffusion was a second equally important type of activities for this project and of similar relevance to research and development as well as integration of information aspects. The key goals of the knowledge dissemination were to promote the meteorology in the energy community, gather information and measured data from wind farms for research activities and identify joint research priorities of the energy and meteorology communities.

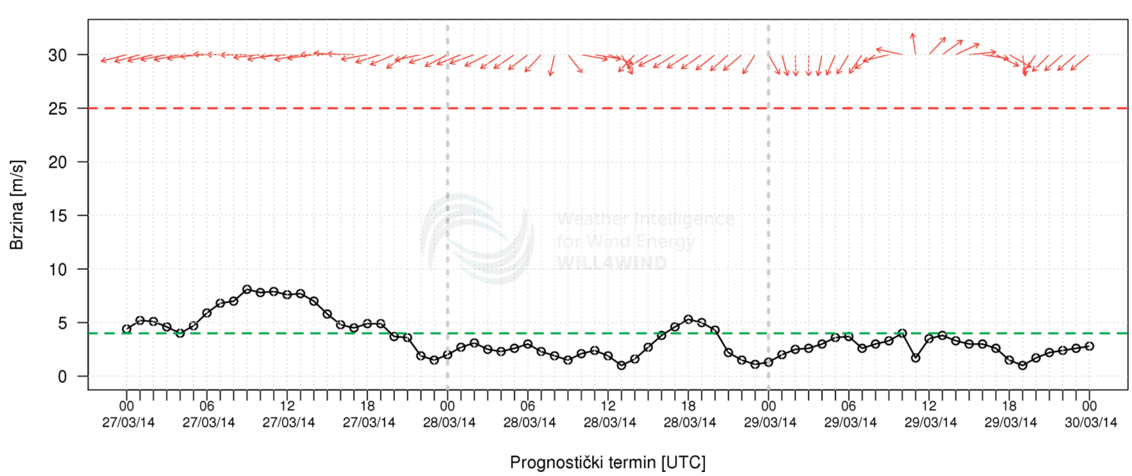

Figure 8. An example of the ALADIN/HR wind forecast graph for the use of the wind energy sector partners and users.

Slika 8. Primjer prikaza prognoze vjetra modela ALADIN/HR za upotrebu partnera i korisnika u sektoru energije vjetra.

For that purpose, the project consortium accomplished the following:

- Organized two workshops and a final conference for broad range of experts from Croatian wind energy and meteorology sectors
- Assessed needs of the wind energy sector for meteorological information summarized in a needs analysis report
- Prepared and distributed research interest questionnaires and organized a round-table on the joint research priorities of researchers and business/economy in meteorology and wind energy sectors
- Developed and maintained virtual knowledge transfer network
- Advised wind energy sector on the use of meteorological information
- Presented research results on national and international conferences
- Disseminated information about the project through the TV and other media

Using direct communication channels, the project team established a personal contact with over 500 experts from meteorology and energy communities, which was complimented by 15.000 visits to the www.will4wind.hr webpage and substantial dissemination of information to general public.

Identification of the joint research priorities promotes further collaborative work primarily on wind and wind energy forecasting, wind resource atlases and site-specific estimates, integration of wind energy into national electric power network, and climate change of wind resource (Fig. 9).

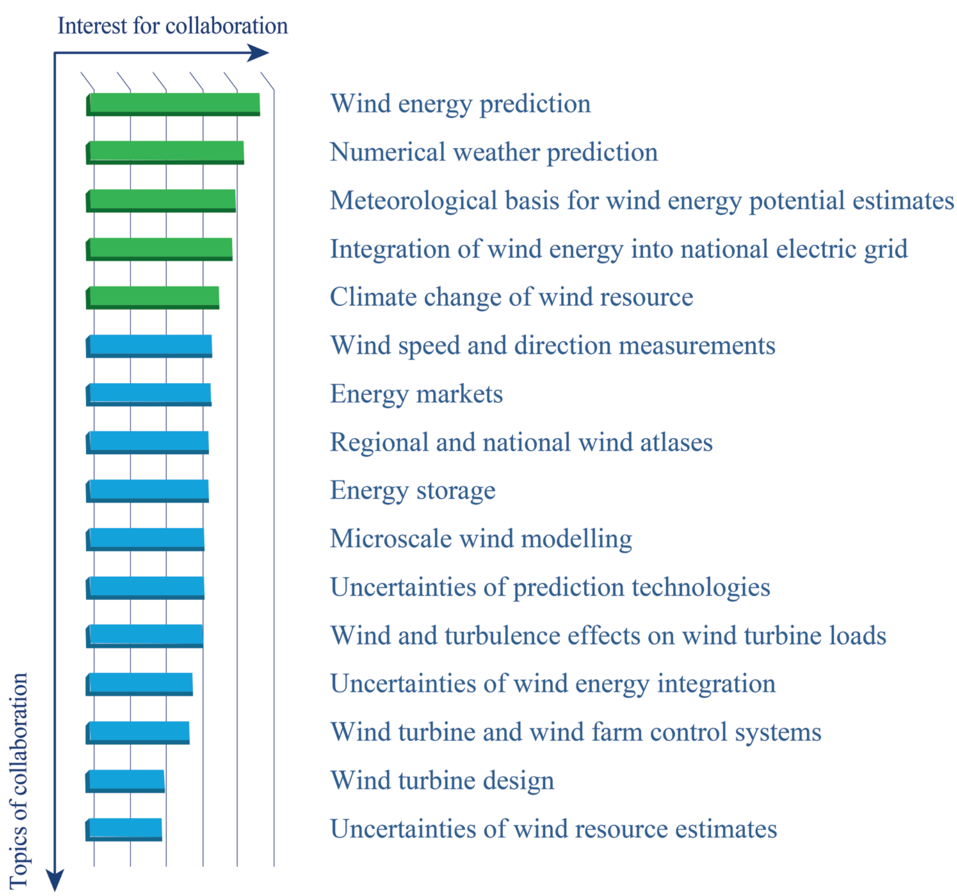

Figure 9. Joint research priorities of the research and business/industry in meteorology and wind energy sectors, as inferred by the analysis of collected questionnaire data.

Slika 9. Zajednički istraživački prioriteti znanstvenika i gospodarstvenika iz područja meteorologije i energije vjetra prikupljeni kroz analizu upitnika.

5. CONCLUSIONS

Despite the growing use of wind energy in Croatia, the wind energy sector lacks prediction tools for the efficient and safe management of produced electric energy from wind power plants. This especially applies to the wind predictions (and thus wind energy forecasting) in very complex wind regime that prevails in the coastal complex terrain areas prone to strong bora flows which are responsible for the largest share of wind energy production. Therefore, accurate, reliable and timely weather forecast system site-specific for wind power plant locations that accounts for the specific wind climate in Croatia is the essential basis for accurate forecasting of wind power plant electricity production and raising social well-being through increasing the security of energy supply for the end consumers. Therefore, based on these real needs of the Croatian industry and society, project “Weather Intelligence for Wind Energy” - WILL4WIND (www.will4wind.hr) aimed to reduce meteorological uncertainties related to wind energy exploitation in Croatia.

The key results of the WILL4WIND project are: i) evaluation of wind forecasts showed greater accuracy of the ALADIN/HR model when increasing the model resolution, ii) deterministic forecasting using analogue-ensemble post-processing method noticeably improved numerical weather predictions iii) probabilistic forecasting using analogue-ensemble method provided useful information on the uncertainty of wind predictions, and iv) targeted knowledge diffusion and extensive two-way networking supported identification of the joint research priorities of meteorology and wind energy communities and contributed to development of dedicated software to ease the use of ALADIN/HR forecasts in operational wind energy sector activities.

These results supported the improvement of the ALADIN/HR prediction system on DHMZ through implementation of both very high-resolution numerical weather prediction modelling and statistical post-processing in the operational practice. Furthermore, probabilistic part of the forecast system shall include cost-effective probabilistic analogue ensemble forecasting methods in order to complement on-going developments of the dynamical ensemble prediction system. Finally, among the identified joint research priorities the wind and wind energy predictions across all weather and climate temporal scales, thus predictions from seconds to decades ahead, seem to be the most prominent cross-cutting research issues in meteorology and wind energy sectors.

ACKNOWLEDGEMENT:

This project was supported by the EU grant IPA2007/HR/16IPO/001-040507 through the project Weather Intelligence for Wind Energy - WILL4WIND (www.will4wind.hr).

REFERENCES

ALADIN International Team, 1997: The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research. *WMO Bull.*, 46, 317-324.

Delle Monache, L., Nipen, T., Y. Liu, G. Roux, R. Stull, 2011: Kalman filter and analog schemes to post-process numerical weather predictions. *Monthly Weather Review*, 139, 3554-3570.

Delle Monache, L., T. Eckel, D. Rife, B. Nagarajan,2013: Probabilistic weather prediction with an analog ensemble. *Monthly Weather Review*, 141, 3498-3516.

Grisogono, B., and D. Belušić, 2009: A review of recent advances in understanding the meso- and microscale properties of the severe Bora wind. *Tellus*, 61A, 1-16.

Horvath, K., A. Bajić, S. Ivatek-Šahdan, 2011: Dynamical downscaling of Wind Speed in Complex Terrain Prone to Bora-Type Flows, *Journal of Applied Meteorology and Climatology*, 50, 1676-1691.

Horvath, K., D. Koracin, R. Vellore, J. Jiang, R. Belu, 2012: Sub-kilometer dynamical downscaling of near-surface winds in complex terrain using WRF and MM5 mesoscale models, *J. Geophys. Res.*, 117, D11111, doi:10.1029/2012JD017432.

Hrastinski, M., K. Horvath, I. Odak Plenković, S. Ivatek-Šahdan, A. Bajić, 2015: Verification of the operational 10 m wind forecast obtained with the ALADIN mesoscale numerical weather prediction model, *Croatian Meteorological Journal*, 50, 105-120.

Ivatek-Šahdan, S. and M. Tudor, 2004: Use of high-resolution dynamical adaptation in operational suite and research impact studies. *Meteorol Z*, 13, 1-10.

Kalman, R. E., 1960: A new approach to linear filtering and prediction problems. *J. Basic Eng.*, 82, 35-45.

Murphy, A. H., 1988: Skill scores based on the mean square error and their relationships to the correlation coefficient, *Mon. Wea. Rev.*, 116, 2417-2424.

Odak Plenković, I., L. delle Monache, K. Horvath, M. Hrastinski, A. Bajić, 2015: Post-processing of ALADIN wind Speed Predictions with an Analog-based Method, *Croatian Meteorological Journal*, 50, 121-136.

Rife, D. L., C. A. Davis, Y. Liu, 2004: Predictability of low-level winds by mesoscale meteorological models. *Mon. Wea. Rev.*, 132, 2553-2569.

Telišman Prtenjak, M., B. Grisogono, 2007: Sea/land breeze climatological characteristics along the northern Croatian Adriatic coast. *Theor. Appl. Climatol.*, 90, 201-215.

Tudor M., S. Ivatek-Šahdan, A. Stanešić, K. Horvath, A. Bajić, 2013: Forecasting Weather in Croatia Using ALADIN Numerical Weather Prediction Model, Climate Change and Regional/Local Responses, Dr Pallav Ray (Ed.), ISBN: 978-953-51-1132-0, InTech, DOI: 10.5772/55698. Available from: http://www.intechopen.com/books/climate-change-and-regional-local-responses/forecasting-weather-in-croatia-using-aladin-numerical-weather-prediction-model.

Zaninović, K., i suradnici, 2008: Klimatski Atlas Hrvatske 1961-1990, 1971-2000 (Climate Atlas of Croatia 1961-1990, 1971-2000). Državni hidrometeorološki zavod, Zagreb.

Žagar, N., M. Žagar, J. Cedilnik, G. Gregorič, J. Rakovec, 2006: Validation of mesoscale low-level winds obtained by dynamical downscaling of ERA-40 over complex terrain. *Tellus*, 58A, 445-455.