ESTIMATING WIND RESOURCE USING MESOSCALE MODELING

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Abstract

The application of numerical simulations to preliminary wind resource assessment requires an extensive validation effort in order to better assess the uncertainties arising from such method. This paper has the main objective of exposing the verification of applicability and perceived accuracy of simulated wind data against local observations, through the characterization of errors between the distinct data sources.

The methodology applied is based on the numerical simulation of the wind resource for four different areas, with the same set of parameterizations and numerical configurations, in order to better represent a blind test. Data obtained using the Weather Research and Forecasting (WRF) model is evaluated against wind resource assessment campaigns.

Comparisons are made with horizontal wind speed measurements and its respective prevailing direction, using simultaneous data at equivalent heights, exclusively with measurements containing over 85% valid data. The test cases were summarized and further divided according to local characteristics, such as average wind speed, altitude, altitude difference, distance to coastal area, terrain complexity, Weibull distribution shape factor and frequency, and seasonal behavior. With this analysis probable tendencies in errors can be assessed according to each parameter.

Results further corroborate the known applicability of numerical simulations on preliminary wind resource characterization, and identifies specific tendencies on some of the parameters evaluated.

Introduction

An accurate wind resource characterization relies on a comprehensive regional observation network [1], characteristic often not available on emerging markets, and generally not extensive on established markets. In these cases the use of Mesoscale modeling can provide a large-scale analysis with regional features [2]. Considering existing limitations, this approach can be used to support an early stage ranking and selection of sites for potential wind farm projects. Consequently, it is needed to assess and identify uncertainties arising from such approach.

Mesoscale wind data were validated quantifying the statistics of error between observed and simulated wind data, in order to better understand the possible sources of deviations. The observed wind data is obtained from anemometrical masts instead of traditional meteorological stations, being duly instrumented for measuring wind data and evaluate local wind behavior.

Methodology

The employed approach is based on using data from wind measurement campaigns to assess results from the WRF numerical model. Since the simulated results represents instantaneous values, its results were only compared against instantaneous hourly wind measurements. Invalid or non-existent records from local measurements were equally invalidated on the simulated results. Only measurement masts with over 85% of the data available were considered.

In order to better assimilate large-scale conditions, three numerical domains were used during the numerical integration (Table 1), employing a two-way nested scheme. Domain placement (figures 1 to 4) takes into consideration major local characteristics (such as valleys and mountains) located near or at domain edges, thus being properly placed to include said characteristics in the simulation, allowing for a better representation of the local flow. Since a two-way nested scheme is used, results from the inner domain replace the coincident points on its parent domain, thus smaller scale phenomena can be propagated to outer domains.

Each test case was evaluated using a single numerical simulation, with static parameterizations options and configurations, in order to better represent a *blind test*.

Table 1 - Grid Placement.

	Parameter	Intermediate Grid 9x9km	Inner Grid 3x3km
Portugal Simulation 1	Center	39.28; -7.26	39.92 -7.68
	Number of points	46X46	46x46
Portugal Simulation. 2	Center	38.88 -8.05	39.52 -8.47
	Number of points	46X46	46x46
Poland	Center	50.95 21.21	50.23 21.17
	Number of points	55x61	73x73
Romania	Center	44.66 28.93	44.63 28.66
	Number of points	55x55	85x85

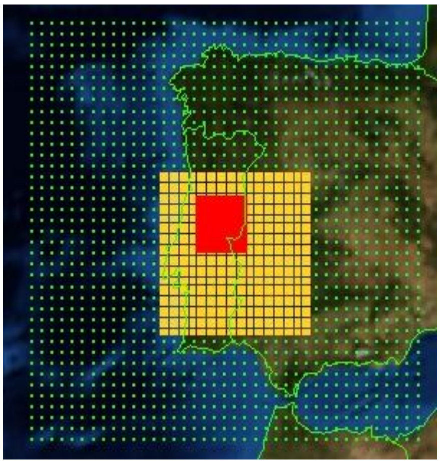

Figure 1 - Grid placement for Portugal – Simulation 1, outer grid - green, intermediate grid – yellow, inner grid - red.

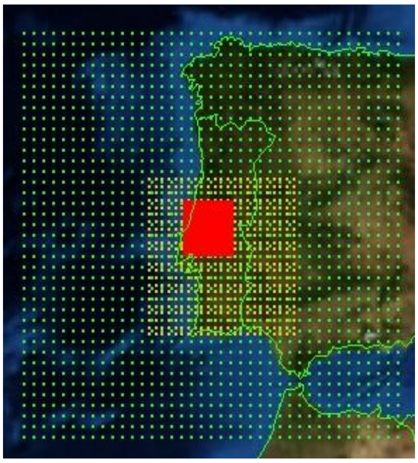

Figure 2 - Grid placement for Portugal – Simulation 2, outer grid - green, intermediate grid – yellow, inner grid - red.

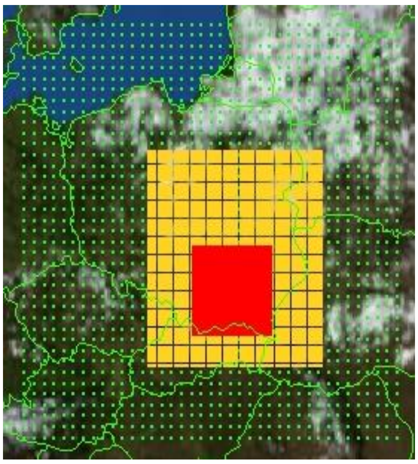

Figure 3 - Grid placement for Poland, outer grid - green, intermediate grid – yellow, inner grid - red.

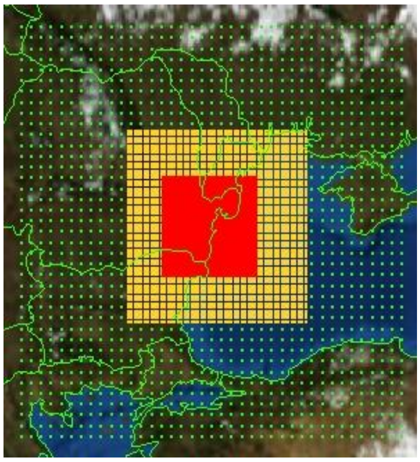

Figure 4 - Grid placement for Romania, outer grid - green, intermediate grid – yellow, inner grid - red.

Several comparison indices were used in order to evaluate the modeled results, using the horizontal wind speed and prevailing directions as variables, assessing deviations in Weibull parameters and statistical analysis.

The statistical analysis includes calculations of the mean absolute error (MAE) (1), root mean square error (RMSE) (2), BIAS (3), and standard deviation (STDE) (4), being commonly used parameters in modeled wind resource evaluations [3, 4].

$$MAE = \frac{1}{N}\sum_{I=1}^{N}\left|\Theta_{\mathrm{i}}^{'}\right| \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{I=1}^{N}\left(\Theta_{\mathrm{i}}^{'}\right)^{2}} \quad (2)$$

$$BIAS = \frac{1}{N}\sum_{I=1}^{N}\Theta_{\mathrm{i}}^{'} \quad (3)$$

$$STDE = \sqrt{\frac{1}{N}\sum_{I=1}^{N}\left(\Theta_{\mathrm{i}}^{'} - \frac{1}{N}\sum_{I=1}^{N}\Theta_{\mathrm{i}}^{'}\right)^{2}} \quad (4)$$

Where $\Theta^{'} = \Theta_{s} - \Theta_{o}$, being Θ_{s} the simulated value and Θ_{o} the local observation.

Measured local data

Data used in this validation analysis were obtained from wind measurement campaigns with the sole purpose of wind resource assessment. The anemometrical masts are equipped with sensors from either NRG or Thies, calibrated according to IEC/MEASNET parameters, in multiple heights. The standard data acquisition frequency is 1 Hz, however measurements are recorded in 10 minutes intervals. A throughout quality check is performed, invalidating any record that contains anomalies, generally occurring during extreme weather events or due to equipment failure.

To validate the simulated data were used records from 14 masts in Portugal (center and coastal regions), 6 in eastern Poland, and 14 in southeast Romania. Due to different measurement campaigns characteristics comparisons were done using 6 or 12 consecutive months.

During the validation procedure the test cases were organized according to several factors (average wind speed, altitude, altitude difference, distance to coastal area, terrain complexity, k-shape factor, Weibull distribution, and seasonal behavior), with the objective of identifying a relation from such factor to observed deviations.

Local data obtained from measurement masts were not assimilated on the numerical model initialization, and are not part of the data used on the Reanalysis project [5].

Mesoscale Numerical modeling

A key element for estimating wind resource is reliable meteorological data including, but not limited to, surface observations and upper-air conditions. The U.S. National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) maintains the Reanalysis project [5], which aims to provide a consistent source of meteorological observations for the entire world, with data obtained from several sources over the past decades.

Reanalysis dataset is routinely used as a climatic database [6], offering the means to promote analysis at spatial resolutions above the horizontal resolution of the dataset (208km). Due to this limitation, this dataset alone cannot be used to determine the wind resource on a regional scale, since any local feature smaller than 208km will not be represented. In order to circumvent this limitation it is proposed the usage of a dynamical downscaling technique applying a mesoscale numerical model.

The Reanalysis project uses a dynamic data assimilation system to ingest locally observed and remote sensing data to create a regular grid with 208km (2.5°) spatial resolution, from a T62/28 global spectral model with refined levels on the boundary layer and terrain following sigma vertical coordinates. The variables from this dataset are classified according to their reliability to the original source, being the "A" type variables most influenced by the actual observations, which includes the zonal and meridional wind (U and V) variables, among others. The output frequency follows standard WMO (World Meteorological Organization) definitions for surface (synoptic) stations, with data at 00, 06, 12 and 18 hours GMT (Greenwich Mean Time).

A dynamical downscaling can be shortly described as a the process of initialization of a limited area model (LAM) by using mass, momentum and thermodynamic data from a general circulation model (GCM) [7] or another LAM with greater area, and by providing lateral boundaries conditions during the numerical integration of the LAM. This technique offers the advantage of enhancing the simulation of regional features due to the increase in the horizontal resolution (and the consequent refinement of lower boundary discretization) and by allowing the representation (as opposed to parameterization) of dynamical features such as deep convection, for instance.

The LAM used in this project is the Weather Research and Forecasting (WRF) model [8]. This model consists of several modules created to ingest observational data and simulate atmospheric conditions, describing the dynamics and thermodynamics of the atmospheric flow in limited areas. The numerical integrator consists of a fully compressible, Eulerian and nonhydrostatic equation set, employing a terrain-following, hydrostatic-pressure vertical coordinate being the top of the model a constant pressure surface, in a Arakawa-C horizontal grid. A third-order Runge-Kuttan time integration scheme with a 2nd to 6th order spatial discretization is used during the integration. This model is under active development mostly by an association between the NCAR, National Oceanic and Atmospheric Administration (NOAA), U.S. Air Force Weather Agency (AFWA), Naval Research Laboratory, Oklahoma University and Federal Aviation Administration (FAA). As a community-driven initiative [9], it also receives constant collaborations from various researches and users. This model has been chosen due to its collaboratory organization, fact that brings the improvements from the latest research developments in rapid deployment cycles.

Land characteristics are provided by the USGS 30-second Global Elevation Data [10] (United States Geological Survey and University Corporation for Atmospheric Research), are terrain elevation information in a horizontal grid of 30 arc seconds (approximately 1 km) [11]. Land cover data is provided by the Global Land Cover Characteristics Data Base (USGS, National Center for Earth Resources Observation and Science – EROS, Joint Research Centre of the European Commission). It consists of a 1 km resolution global land cover characteristics dataset, [7, 10, 12].

Results

In order to establish the model capability and limitations of describing the wind resource of a region, different validation experiments were undertaken. Three distinct regions, ranging from a low complexity coastal terrain to complex sites, located in different countries and climates, are presented. The data obtained from such simulations were compared\ against different meteorological stations, with wind speed and direction records mostly at 60m a.g.l..

Global Results Analysis

The following analysis considered data from all the masts used during the validation process.

Table 2 - Statistics for all the cases.

	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
Global	0.66	0.76	-0.14	0.75

The statistical figures (table 2) suggest that the mesoscale model can produce acceptable results for an initial analysis of the wind resource, mainly due to low BIAS and RMSE.

Mean Wind Speed

Results are compared based on the observed average wind speed. The analysis suggests a decrease in BIAS with increase average wind speed.

Table 3 - Statistics according Mean Wind Speed.

Wind Speed (m/s)	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
< 6	0.65	0.80	0.35	0.72
≥6 <7	0.68	0.73	-0.16	0.72
≥7 <8	0.50	0.66	-0.32	0.58
>8	0.75	0.85	-0.37	0.77

Altitude (m.s.l.)

Comparison of deviation with altitude of observations site point to a decrease in BIAS with increase in altitude of observation site.

Table 4 - Statistics according height measurement.

Height (m)	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
<200	0.73	0.79	-0.67	0.35
≥200 <400	0.87	0.93	-0.18	0.91
≥400 <600	0.74	0.87	0.09	0.87
≥600	0.49	0.60	0.29	0.48

Altitude Resolution Error

The difference between the model's assumed elevation and real elevation (Model – Real = Δy) ranges from -253m and 11m.

As expected, MAE and RMSE show a tendency to increase with Δy.

Table 5 - Statistics according height deviation between measured and WRF topography.

Δy (m)	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
<-100	0.74	0.86	-0.44	0.74
≥-100 <-50	0.74	0.75	0.06	0.76
≥-50 <0	0.66	0.71	-0.17	0.69
≥0	0.51	0.65	-0.05	0.65

Distance to Coastline

Although RMSE is somewhat larger for the sites nearest to shore, the tendency is not very patent. (table 6).

Table 6 - Statistics according coastal distance.

Δx (km)	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
< 25	0.63	0.71	-0.51	0.49
≥ 25 <50	0.83	0.91	-0.57	0.71
≥ 50 <100	0.58	0.69	-0.56	0.41
≥ 100	0.63	0.75	0.60	0.45

Terrain Complexity

Terrain characteristics have a significant impact on local wind resource. Therefore, each mast was classified according to the perceived complexity of its surroundings, dividing the test cases in low complexity coastal terrain (LC_CT), low complexity interior terrain (LC_IT), complex coastal terrain (CP_CT), and complex interior terrain (CP_IT). Results (table 7) indicate BIAS and STDE slightly higher for more complex sites.

Table 7 - Statistics according terrain complexity

Complexity	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
LC_CT	0.66	0.76	-0.66	0.39
LC_IT	0.81	0.70	-0.48	0.51
CP_CT	0.58	0.59	-0.22	0.54
CP_IT	0.69	0.82	0.26	0.78

K – Weibull Shape factor

Comparing errors with weibull shape factor (k) from the a best fit distribution to both simulated and observed data series (table 8), it can be seen that BIAS seems to decrease with k.

Table 8 - Statistics according form factor.

k	MAE	RMSE	BIAS	STDE
≥1.5 <2.0	0.66	0.76	0.38	0.66
≥2.0 <2.5	0.60	0.70	-0.46	0.53
≥2.5 <3	0.85	0.93	-0.63	0.69

Seasonal Analysis

When organizing errors on a seasonal basis, it can be noted that BIAS for Spring periods are much higher than for the other periods, while Winter periods show the lowest BIAS.

Table 9 - Statistics according seasons.

Seasons	MAE (m/s)	RMSE (m/s)	BIAS (m/s)	STDE (m/s)
Spring	0.73	0.81	-0.45	0.68
Summer	0.82	0.88	-0.13	0.87
Autumn	0.61	0.71	-0.14	0.69
Winter	0.74	0.91	0.04	1.04

Specific Case

A comprehensive evaluation of deviations is summarized for a specific region in Romania. This particular site has a generally low terrain complexity, being located relativity close to the Black Sea. Local data was available for an entire year, at 60m a.g.l. height.

The yearly average wind speed obtained from the numerical model is 0.09m/s lower than measured values (table 10), thus having a negative deviation of 1.56%. The numerical model was able of reproducing the predominant wind direction sectors (figure 5), however it generally attributes higher occurrence figures. The wind speed histogram (figure 6) indicates higher deviations on the 6 and 7m/s intervals on simulated results, nonetheless it was capable of reproducing the Weibull distribution (figure 6, table 11) with reduced deviation.

Table 10 - Wind Speed (observed, simulated) and respective deviation.

Wind Speed (m/s) Obs.	Wind Speed (m/s) Sim.	Deviation (m/s)	Deviation (%)
5,78	5,69	-0,09	-1,56

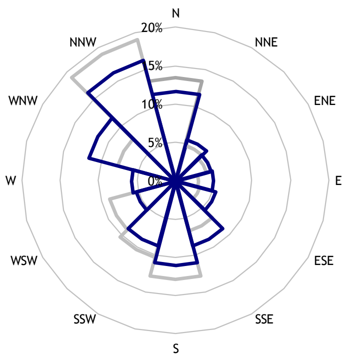

Figure 5 - Wind Rose, station (blue), WRF (grey).

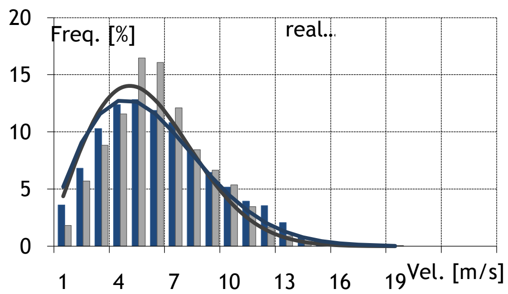

Figure 6 - Wind Speed Histogram, station (blue), WRF (grey).

Table 11 - Weibull parameters (observed, simulated) and respective deviations.

k Obs.	k Sim.	Dev.	A (m/s) Obs.	A (m/s) Sim.	Dev. (m/s)
1,91	2,09	0,18	6.50	6.30	0.2

Conclusions

Global deviations between observed and simulated average wind speed were within expected indicate that mesoscale results can be adequate for wind resource assessment in a Greenfield or early stage phase of a wind farm project.

Although some tendencies where found between some error statistics physical characteristics of the sites, none was sufficiently clear to draw improvement strategies in the mesoscale modeling. More thorough analysis should be performed.

The most marked tendency comes from differences in model's altitude and real altitude. This should indicate benefits for accuracy from higher resolutions in the mesoscale model or from coupling mesoscale results with microscale (linear or CFD) models or from the use of different (more detailed and accurate) elevation models. Related to the latest, the authors have already tested and implemented the use of 1 arc-second SRTM altitude database, with clear improvements in accuracy of results.

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