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Using downscaled NCEP/NCAR reanalysis data for wind resource mapping

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Abstract
Two problems arise when estimating numerically wind energy resources, namely: The low resolution of global-scale atmospheric models and the scarcity of meteorological observations to be used as boundary conditions for smaller-scale models. Downscaling techniques were developed to overcome these issues. These methods consist of using global-scale model output as boundary conditions of smaller-scale models. In this research a downscaling tool to refine NCEP/NCAR Reanalysis data using WAsP is presented. The downscaling technique proposed consists of extrapolating the wind climate at a given point using meteorological observations from another point by means of the WAsP model. Then, using time-marching NCEP/NCAR Reanalysis wind velocity values, on-line refined profiles of wind velocity and direction can be obtained. In order to assess the accuracy of the described tool, data of two episodes of 48 hours are downscaled and compared to meteorological observations at two different climates. A sensitivity analysis is performed in order to assess the effect that atmospheric stability and terrain roughness, among others, exert on the results. Results are not as accurate as expected, probably due to atmospheric instability or other factors neglected by the model. However, the main trends are followed when validating the model output using field measurements.
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Keywords: Wind energy; Numerical modeling; Downscaling; NCEP/NCAR reanalysis data; WAsP.

1. Introduction

Atmospheric flow is one of the most complex and challenging to describe in the field of Fluid Mechanics. Indeed, its study led Edward Lorenz to postulate the widely known Chaos Theory. The author described a deterministic chaos as a system in which, despite the governing equations are well known, the number of degrees of freedom involved is so large that it is extremely sensitive to initial conditions. For this reason, exact long-term forecasting is not feasible [1].

Nevertheless, different approaches exist in order to provide sufficiently reliable weather and climate predictions. Most of them are based on numerical modeling, although some authors also conducted wind tunnel experiments [2]. The main difference among numerical atmospheric models is the scale at which they work, as a very wide range of scales coexist in the atmospheric flow. Such a large difference between coexisting-phenomenon scales makes that, when it comes to assessing wind energy resources over a given area, no mathematical model provides a general definitive solution.

On the one hand, micro-scale models of atmospheric flow are the most widely used in the field of wind resource estimation. Nevertheless, as stated in [3], they require data from a dense coverage of meteorological stations as input, which is often not available. On the other hand, larger-scale models, according to Badger *et al.* [4], provide currently a worldwide set of data on overall weather conditions. However, they cannot be used to estimate wind farm sites for power production purposes. This is due to the fact that micro-scale orography and roughness features are not explicitly resolved by those models: results are grid-averaged at too large resolutions. Therefore, despite meso-scale models can increase their horizontal resolution down to 2km, the mismatch between numerical weather predictions and actual field observations can only be reduced to a certain extent [5].

In order to overcome this problem, the downscaling techniques arise as an attempt to combine the advantages of both global and smaller-scale models (i.e. high accuracy and data availability, respectively). Such techniques represent a case of numerical nesting, as they consist in taking output data from large-scale models and adding information at scales smaller than the original grid resolution. Their final purpose is to refine the results from large-scale models, in which local features are not explicitly resolved, using a smaller-scale model.

The downscaling methods fall into three general types or approaches, namely: statistical, physical and hybrid. The statistical downscaling methods in their pure form are an attempt to find the relationship among a series of variables in a non-deterministic way, i.e. disregarding the physical laws that govern the phenomenon under study. The so-called physical, dynamic or deterministic methods use the laws of fluid mechanics and physics of the atmosphere to obtain a good estimate of wind conditions. The third family of downscaling methods consists of the so-called physical-statistical or hybrid methods which, according to Giebel *et al.* [6], turn out to be the most successful ones. In this kind of methods, despite they are mostly statistically-based, certain knowledge on the physical behavior of the atmosphere is used to improve the results. Many authors, such as Roy and Kok [5], claim that downscaling wind speed techniques should always combine both physical and statistical approaches in order to achieve a good accuracy.

The aim of this research is to develop a downscaling tool in order to refine global-scale model results by means of a micro-scale model. The proposed approach belongs to the aforementioned hybrid downscaling methods. In this case, the global-scale model used is the NCEP/NCAR Reanalysis. This dataset is provided by the U.S. National Center for Environmental Prediction (henceforth, NCEP) and the National Center for Atmospheric Research (henceforth, NCAR). The micro-scale model used is the commercial code WAsP (Wind Atlas Analysis and Application Program).

Many authors have successfully developed and validated wind forecasting methods based on the downscaling concept [7]. The most similar is that of Frank *et al.* [8], in which also NCEP/NCAR Reanalysis data are combined with WAsP. However, unlike the method proposed in this article, Frank *et al.* [8] use Karlsruhe Atmospheric Meso-scale Model (KAMM) to process the NCEP/NCAR Reanalysis data. Other authors, such as Stephen *et al.* [9] and Essa and Embaby [10], obtained good results but their approaches are more probability-based. Also using black box models, Bechrakis and Sparis [11] and Barbounis *et al.* [12] conducted accurate wind climate estimations using artificial neural networks (ANN). For a more detailed discussion on wind resource assessment, several extensive reviews are available in the literature [13-15].

2. Materials and methods

2.1 NCEP/NCAR Reanalysis data

The NCEP/NCAR Reanalysis [16] is the dataset used as global-scale model data in this model. It consists of a continuously-updated gridded dataset, which provides a wealth of atmospheric variables (air temperature, humidity, pressure, wind velocity, etc.) consistent in time and space at respective resolutions down to 6h in time and 2.5° in horizontal coordinates. In the Y-axis (N-S), this is approximately 280km, whereas in the X-axis (W-E), it represents approximately 200km at mid-European latitudes. As regards vertical resolution, data are defined at 17 different pressure levels[1]. The NCEP/NCAR Reanalysis time coverage ranges from 1948 to the present.

Once data have been harvested and assimilated, a reanalysis process is carried out. This process consists of blending global circulation models (GCM) with observations, in order to detect inconsistencies in data spanning long periods of time so that a good description of the state of the atmosphere is achieved.

[1] Vertical coordinates are defined by pressure levels instead of geometric heights.

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The most relevant variables provided by the model are the wind velocity horizontal components (U and V, respectively). These variables are taken at a single grid point at the 17 pressure levels available spanning from 1000mb to 10mb every 6h. Obviously, not every wind velocity value is relevant in order to determine the near-surface wind resources (e.g. pressure level 10mB is generally dozens of kilometers above the ground level). For this reason, which pressure levels are taken into account is a relevant decision (this topic is discussed below).

2.2 WAsP

WAsP is a commercial code developed by the Danish Risø National Laboratory and it is widely used to predict wind climate and wind energy resources. This program is an implementation of the Wind Atlas methodology, whose details are explained in depth in [17]. The main advantage of WAsP is that, thanks to the use of semi-empirical linearized equations instead of the Navier-Stokes Equations, the model can be run in a regular computer using reasonable computation times. It is worth remarking that, despite its severe simplifications, WAsP yields good results.

The WAsP most basic assumption is, according to Landberg *et al.* [3], that for a specific micro-scale area, the overall wind conditions (i.e. the geostrophic wind climate) change so slowly that the wind climate can be extrapolated from a meteorological station (e.g. Point A) to any point within the same the region (e.g. Point B) just taking into account the local effects of both points.

The so-called local or site effects are the effects exerted on wind climate by surrounding obstacles and terrain roughness and orography in the vicinity of the points under study. They are taken into account by WAsP as follows: the observed wind climate (henceforth, OWC) at Point A is affected by the particularities of the surrounding topography, the terrain roughness and the shelter produced by close obstacles. In order to extrapolate this wind climate to Point B, the wind conditions in Point A have to be "cleaned" of the site effects, resulting the so-called regional wind climate (henceforth, RWC). This generalized wind climate, "the wind climate for standard conditions given by flat terrain of uniform roughness" [4], is considered extrapolable to all points within the same region. Therefore, to estimate the wind resource at Point B, it only has to be affected by Point B site effects (see Figure 1).

2.3 Model limitations

As models are just simplified representations of the reality, it is crucial to be aware of their limitations since, to a certain extent, they explain the mismatch between model output and observed values. In the case of WAsP, as in most models, one of the main limitations is the scale: its computational domain must extend horizontally at least 10km away from all the points under study [8]; otherwise internal boundary layers (henceforth, IBLs) may develop out of the modeled region. On the other hand, larger scales are not desirable as global-scale effects, which are not taken into account by WAsP (e.g. thermally driven winds, etc.), may play an important role. Eq. 1 [17] determines the IBL height (h') as a function of a roughness change horizontal distance (x).

$$\frac{h'}{z_0{}'}\left(\ln\frac{h'}{z_0{}'}-1\right)=0.9\frac{x}{z_0{}'} \tag{1}$$

Where $z_0{}'$ is the larger roughness length of the roughness change that creates the IBL. The height above which IBL effects are no longer perceived (h_{max}) can be estimated using Eq. 1. In this case a roughness length of $z_0^{'}=1.00m$ and a fetch of $x=10km$ are considered. This height threshold turns out to be $h_{max}=1440m$.

Another important source of bias in models like WAsP, which are based on the assumption of potential flow, is terrain ruggedness. As Landberg *et al.* [3] report, flow over rugged or complex terrain, where separation is likely to occur, will in many cases not be modeled accurately. Several authors, such as Wood [18], consider complex terrain all surfaces steeper than 0.3. Typical annual energy prediction errors for wind turbines are about 10% in normal conditions, whereas in rugged terrain larger errors can be expected [8]. To overcome this violation of the potential flow assumption, correction algorithms are often implemented [3]. Indeed, this method was successfully applied and compared to CFD results by Berge *et al.* [19], obtaining no significant differences in accuracy.

Another known issue of WAsP is the flow over forested areas, which represent an unfortunate type of terrain for wind turbines due to the high turbulence intensity and shear of the flow over the tree canopy. The difficulty to predict the characteristics of such flows, as Manning *et al.* [20] report, has led to a lack

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of consensus on how to model forestry in WAsP among the wind-energy scientific community and industry. Another relevant issue of the WAsP model is atmospheric instability: despite its effects are corrected in the model implementation, this phenomenon is still a significant source of error [21].

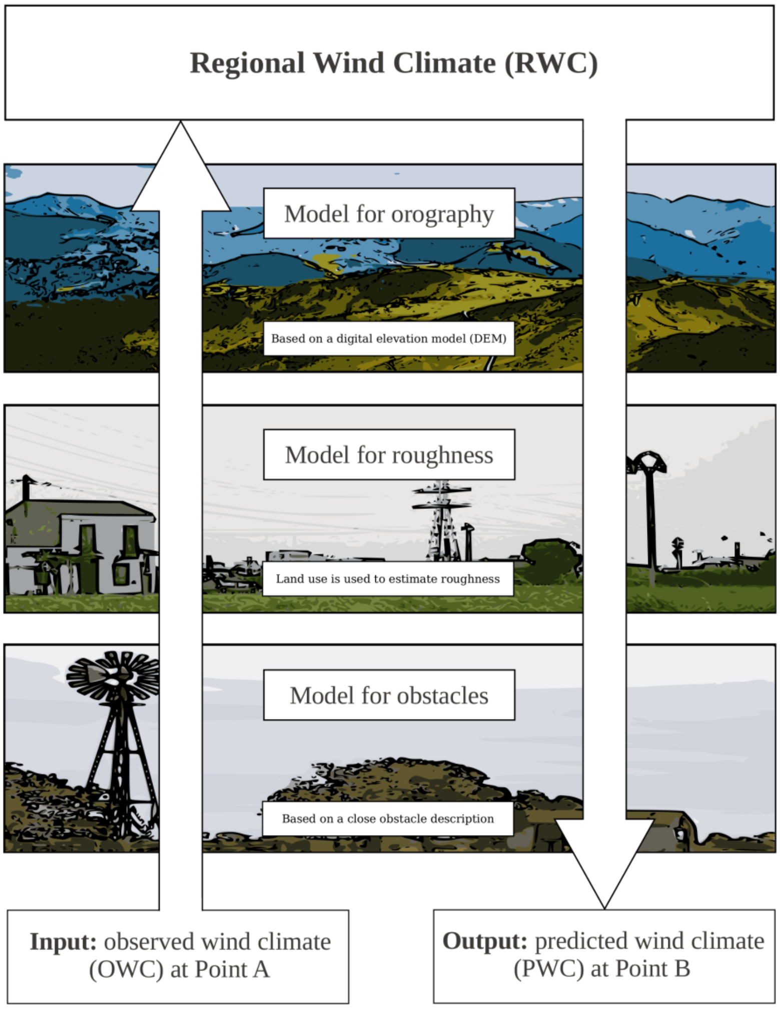

Figure 1. Scheme of the Wind Atlas methodology; self-elaborated from [17]

2.4 Downscaling process

The final goal of the described downscaling tool is to obtain a set of time-marching direction-wise wind velocity profiles out of NCEP/NCAR Reanalysis data (global-scale model) using WAsP (micro-scale model) to refine them. Thus, WAsP provides high-resolution direction-wise time-averaged (static) wind velocity profiles whereas the NCEP/NCAR Reanalysis introduce the time variability of wind velocity and direction. Figure 2 outlines the whole downscaling process and how NCEP/NCAR Reanalysis data and WAsP model output are combined.

The link between the wind velocity profiles provided by WAsP and the NCEP/NCAR Reanalysis data is made assuming that at a given point of the terrain, at a given reference height (z_{ref}) and at a given time, the wind condition is the same in both the refined and non-refined datasets (i.e. WAsP and NCEP/NCAR Reanalysis) and so they are reciprocally convertible, as site-surrounding features do not affect the wind condition. That reference height has to be in the vertical meso-scale in order to be a reliable liaison between both models. How it is estimated is discussed in detail below. Eq. 2 summarizes in an elegant way how both models, WAsP and NCEP/NCAR Reanalysis, are combined. Indeed, this simple equation is the core of the entire downscaling process:

$$u_k(t_j, z_i) = \frac{u_{W,k}(z_i)}{u_{W,k}(z_{ref})} u_{N,k}(t_j, z_{ref}) \quad (2)$$

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where:
- $u_k(t_j, z_i)$ is the resulting refined wind velocity profile for direction k at time step t_j,
- $u_{W,k}(z_i)$ is the average wind velocity profile provided by WAsP for direction k,
- $u_{W,k}(z_{ref})$ is the average wind velocity provided by WAsP for direction k at z_{ref},
- $u_{N,k}(t_j, z_{ref})$ is the wind velocity provided by NCEP/NCAR Reanalysis at direction k, at z_{ref} and t_j.

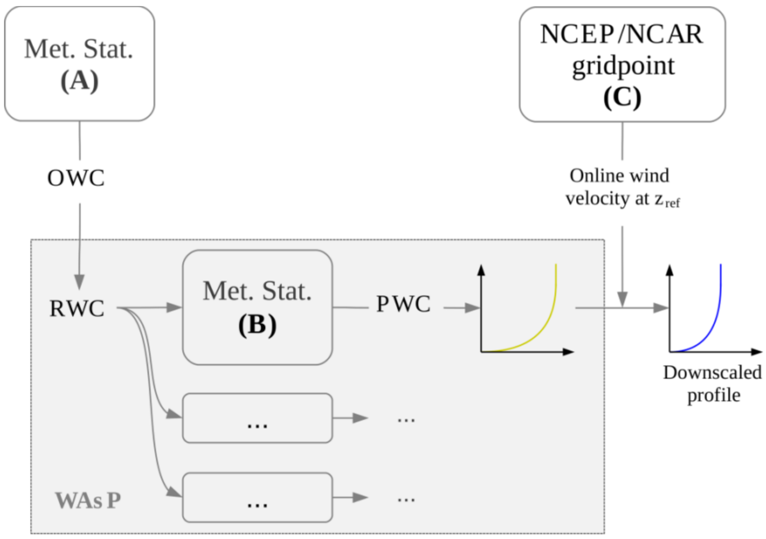

Figure 2. Downscaling scheme

Another way to see it is the following: the first term of Eq. 2 provides a long-term averaged wind velocity profile, which is adimensionalized using the velocity at the reference height (u_{ref}). Thus, the second term can be seen as a factor representing the wind magnitude and direction with respect to time, which multiplied by the dimension-less profile yields the downscaled wind velocity profile at a given timestep. Figure 3 shows an example of a time-averaged WAsP profile $u_{W,k}(z_i)$ and a resulting profile $u_k(t_j, z_i)$. As mentioned above, it is worth pointing out that, when dealing with NCEP/NCAR Reanalysis data, a problem arises: wind profiles are referred to pressure levels instead of geometric height. To overcome this problem, a conversion has to be carried out. This operation and the wealth of secondary operations which have to be performed are explained in the following lines.
There are several ways to transform the vertical coordinate of the profiles provided by the NCEP/NCAR Reanalysis (e.g. hydrostatic equation, barometric formula, etc.) but they are normally based on the assumption of constant temperature or constant vertical temperature gradient. Such assumption is only valid in certain stable regimes, but cannot be applied to all cases. Hence, another approach is necessary. Although NCEP/NCAR Reanalysis data provides temperature values (which makes possible an accurate hydrostatic approach), there is a simpler and more elegant way to convert wind velocity data with respect to pressure levels to geometric-height profiles: via the geopotential height.
The geopotential height is a "gravity-adjusted height" which is widely used in numerical weather prediction (NWP) as it allows neglecting centrifugal forces and air density effects, which are complex to model. Indeed, the geopotential height difference between two consecutive pressure levels is proportional to the mean temperature in that range and such relation is used to perform the aforementioned conversion. The geopotential height is defined as follows:

$$z_g = \frac{\Phi}{g_0} \tag{3}$$

Where g_0 is the gravity acceleration at the sea level in function of latitude (ϕ), which can be estimated in a highly accurate way by means of the World Geodetic System (WGS84) expression:

$$g_0 = 9.780327 \frac{1+0.00193185 \sin^2 \phi}{\sqrt{1+0.00669438 \sin^2 \phi}} \tag{4}$$

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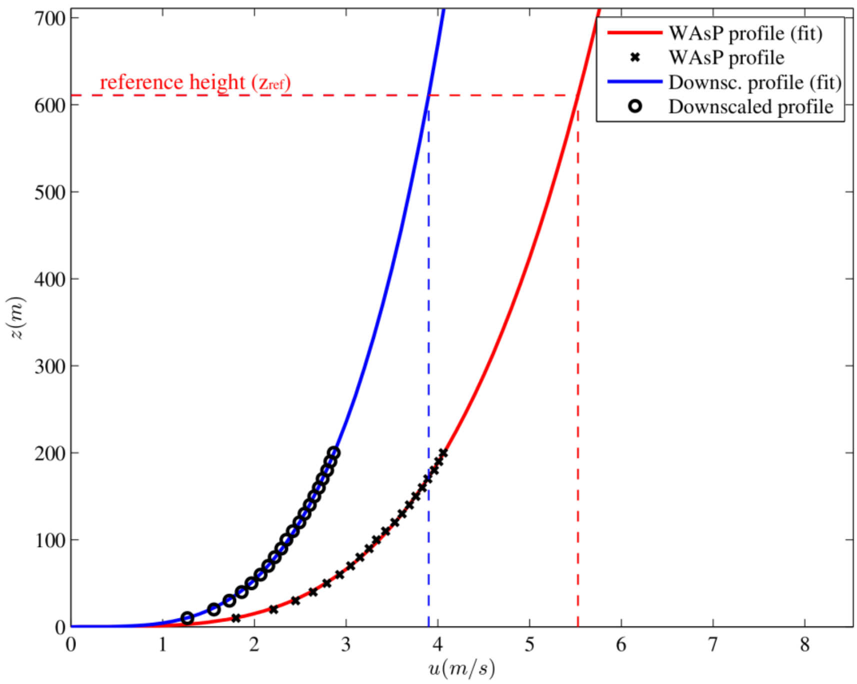

Figure 3. Example of wind velocity profiles (time-averaged and downscaled)

And where Φ is the geopotential, defined as follows:

$$\Phi = \int_0^H g(\phi, z)\, dz \tag{5}$$

Being $g(\phi, z)$ the gravity acceleration in function of latitude (ϕ) and height (z), which can be computed using the following expression:

$$g(\phi, z) = g_0 \left(\frac{r}{r+H}\right)^2 \tag{6}$$

Where r is the mean Earth radius, defined under a spheroidal approach in function of the latitude (ϕ) and the Earth Equatorial and Polar Radii (according to the WGS84: $r_e = 6{,}378{,}137m$ and $r_p = 6{,}356{,}752$m, respectively), as follows:

$$r = \sqrt{\frac{(r_e^2 \cdot \cos\phi)^2 + (r_p^2 \cdot \sin\phi)^2}{(r_e \cdot \cos\phi)^2 + (r_p \cdot \sin\phi)^2}} \tag{7}$$

And H is the the total geometric height above the sea level, i.e. the sum of the terrain elevation above the sea level and the height above the ground level. Bearing this in mind, Vedel [22] demonstrates that the relation between geopotential and geometric height is the following:

$$H = \frac{z_g Q}{r + z_g} \tag{8}$$

Being $Q = r \cdot g_0 / (9.80665\ \mathrm{m/s^2})$ the gravity ratio. Since NCEP/NCAR Reanalysis data provides both wind velocity and geopotential height at the same given point, pressure level and time, using Eq. 8, wind velocities can be easily expressed as a function of the geometric height. Once geometric heights and horizontal velocities are known, wind velocity profiles can be represented.
As regards WAsP data, only the predicted wind climate (PWC) at heights from 10m to 200m (at 10m-intervals) have to be introduced into the downscaling tool. The PWC must be computed at the point under study using the RWC obtained at any point within the same region.

To do so, long-term averaged climatic data (i.e. wind atlas) are obtained from the European Wind Atlas [17]. Terrain orography is obtained by means of GIS tools out of the GTOPO30 dataset, a global digital elevation model (DEM) in geographic coordinates (datum WGS84) with a horizontal grid spacing of 30" and a vertical resolution of 1m, which is provided by the U.S. Geological Survey [23]. Terrain roughness length was obtained out of the CORINE Land Cover 2000 maps provided by the European Environment Agency [24], with an approximated horizontal resolution of 3". Again, in order to adapt the roughness maps (raster) to WAsP format (vector-polygon), GIS software has to be used. As regards surrounding obstacles, they are not modeled sensu stricto. Instead, their effect is implemented as equivalent roughness lengths according to the land use. Once PWCs are obtained, the points of the profiles are respectively fitted to potential curves in order to inter- and extrapolate other profile points.

At this point, it is necessary to determine the reference height (z_{ref}) at which both data, WAsP output and the NCEP/NCAR Reanalysis data, can be correlated. Recalling Eq. 1, in the most unfavorable case considered in Sec. 2.2, the average maximum height at which site effects are perceived in WAsP is approximately $h_{max} = 1440m$. According to Troen and Petersen [17], in coastal regions, wind conditions at a pressure level of 850mb (approximately, a height of 1500m) can be considered representative of the geostrophic wind conditions.

One may think that this should be the reference height at which information can be exchanged between both models. Nevertheless, bearing in mind that WAsP profile highest point is by default 200m, at 1500m such profiles may be no longer representative of near-surface conditions. In addition, the geostrophic wind condition is the "site-effect free" wind condition and therefore it cannot be compared to WAsP predicted wind climates (site-effect affected). Indeed, some preliminary studies performed by the authors have demonstrated that larger errors occur when downscaling using $z_{ref} = 1500m$).

For this reason, as lower points (1000mb and 925mb) are often available in the NCEP/NCAR Reanalysis data, the criterion to establish a reference height (at which wind velocities are assumed to be reciprocally convertible, i.e. z_{ref}) is the NCEP/NCAR Reanalysis data lowest available point since, although such point may be out of the WAsP vertical scale, it is generally relatively close.

It is important pointing out that, as such profiles are provided with respect to pressure levels instead of geometric heights, vertical coordinates are not constant from one time step to another. Indeed, the pressure level 1000mB may happen to be below the terrain surface in many cases (especially, at mountainous regions, where surface pressure is always below 1000mB). Therefore, the reference height used is the lowest NCEP/NCAR Reanalysis data point available.

Once WAsP data and the NCEP/NCAR Reanalysis data have been properly processed, the downscaling process itself can take place and Eq. 2 is resolved. The points of the resulting profile $u_k(t_j, z_i)$ are the final results of the downscaling tool. The resulting profiles, as it is done to WAsP-profile points, are fitted to a potential curve in order to compute velocities at points different from those at which profiles are defined.

2.5 Validation

In order to assess the accuracy of the results yielded by the developed downscaling tool, two episodes were tested in two different locations, namely: the period between 17th and 19th of March 2011 in Wideûmont (Belgium) and the period between 22 th and 24 th of July 2011 in Carcaixent (Spain). The necessary field observations are provided by the Institute Royal Météorologique (IRM)[2] and the Agencia Estatal de Meteorología (AEMET)[3], respectively. Recalling the nomeclature of the general scheme of the downscaling tool used in Figure 2, in each case study the selected points are the following:

Test case 1:

- Point A: Saint-Hubert (Belgium).
- Point B: Wideûmont (Belgium).
- Point C: Lat.: 50N - Long.: 5E.

Test case 2:

- Point A: Carcaixent (Spain).
- Point B: Carcaixent (Spain).
- Point C: Lat.: 40N - Long.: 0.

[2] Data available at: http://www.meteo.be/meteo/view/fr/123386-Observations+-+meteo.html

[3] Data available at: \url{ftp://ftpdatos.aemet.es/datos_observacion/

The mast height of the weather stations is 10m and their surroundings are free from obstacles that cannot be modeled as roughness. The distance between points in case number 1 ranges from 15km to 30km, which is within the WAsP computational domain. However in case number 2 points are separated by distances up to more than 100km. The main advantage of the latter is that the station from which the regional wind climate (RWC) is obtained (Point A) and that where the validation data are collected (Point B) match, unlike in case number 1.

3. Analysis of results

3.1 Wind velocity

In order to validate the proposed downscaling tool, wind velocity and direction were estimated for two two-day episodes at two different sites in Europe. Figure 4 shows the wind velocity evolution computed using the downscaling tool and that observed at the meteorological stations of Carcaixent and Wideûmont, respectively.

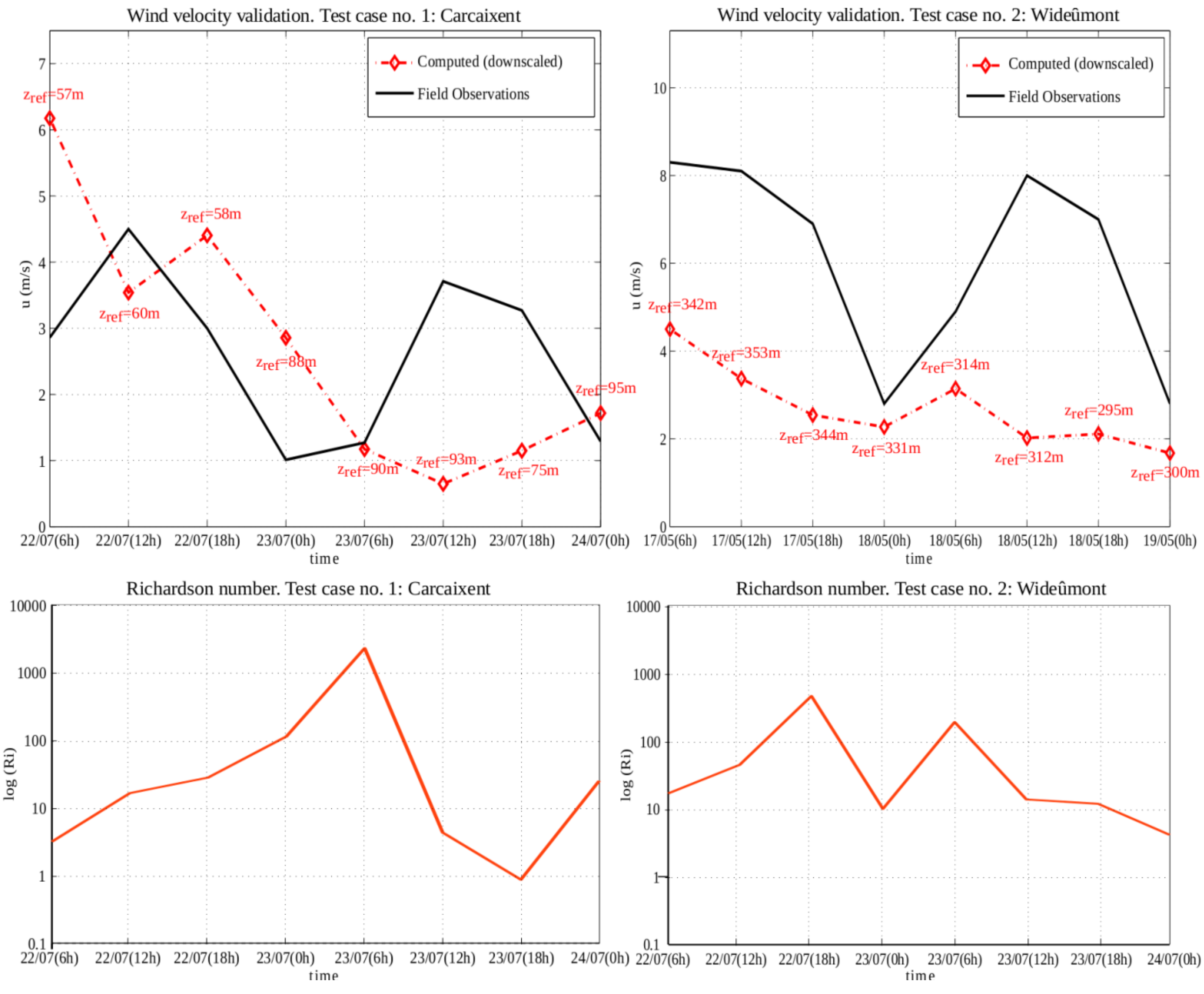

Figure 4. Validation of wind velocities computed by the downscaling tool with 6h-averaged meteorological observations and comparison to Richardson number values

At a first sight, it can be seen that there is a large mismatch between the values obtained by downscaling meteorological data and the field measurements. Nevertheless, in some cases, some trends are followed. E.g.: in both cases, a clear daily pattern of recurrence arises. Therefore, the following step is to find out how the offset and scale factor between computed and observed values can be reduced to the lowest extent (i.e. calibrating the model). In the Wideûmont case, a systematic underestimate of velocities occurs, which may be caused by several reasons; one of them is an overestimate of the terrain roughness length, but also a poor description of the surrounding obstacles of the meteorological station. Nevertheless, other reasons are likely involved in the still large mismatch between computed and

observed values. In this regard, the large scale difference between WAsP and the NCEP/NCAR Reanalysis data may play a paramount role in the lack of accuracy of computations.
The root mean squared error (RMSE) in the Carcaixent case is 2.0m/s, which is approximately 76% of the observed mean value, whereas in the case of Wideûmont, the RMSE is 3.9m/s (37% of the mean observed value).

3.2 Wind direction
As regards the estimate of wind directions, the results are slightly more encouraging. Figure 5 shows respectively the values computed by the downscaling tool and those observed at meteorological stations.
The mismatch is in general very low, especially, if one takes into account that data are treated in a discrete way (in 30º-sectors). That means that two points which, apparently, are separated by 30º may be either almost overlapping or separated by almost 60º. Besides, the height difference may in some cases introduce bias due to the Coriolis forces.
The RMSE comparing downscaled and observed wind directions is in the Carcaixent case 45º, which represents 12% of the complete wind rose (360º). In the Wideûmont case, the RMSE is 34º (9%). Errors up to 30º (one sector) are generally accepted in wind direction predictions. In this case, the results obtained are slightly above that threshold.
As in the case of the wind velocities, a daily pattern of recurrence arises. It is important pointing out that the wind direction is determined by the NCEP/NCAR Reanalysis data (provided at an approximate height of up to 500 or 1000m and different location) and compared to meteorological station observations (measured at a height of 50m or less). This explains the aforementioned pattern: wind directions at different heights tend in general to the same values during periods of atmospheric stability, whereas they diverge when the atmosphere is instable. Indeed, back to the validation of the downscaling tool results, one can see that the highest differences between observed and computed values (provided at different heights) arise by night.

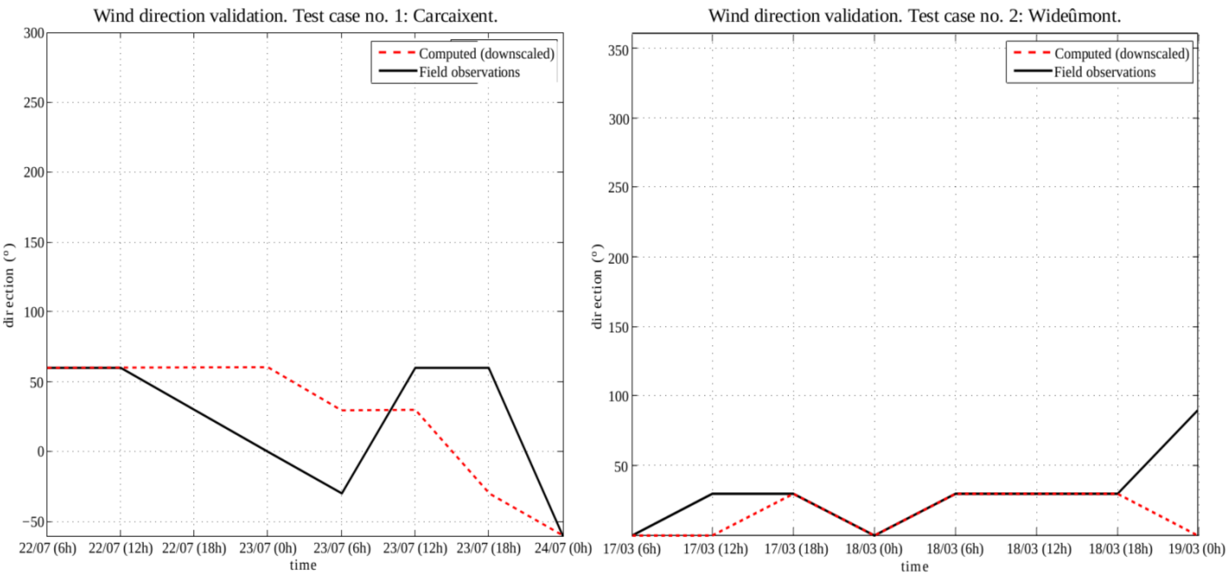

Figure 5. Validation of wind directions computed by the downscaling tool with 6h-averaged meteorological observations

A last attempt to find the causes of the large mismatch between computed and observed values is done by estimating the Richardson number, i.e. the ratio between the potential to the kinetic energy of a flow. It is computed at a given height z as follows:

$$Ri = \frac{g}{\theta} \frac{\frac{d\theta}{dz}}{\left(\frac{du}{dz}\right)^2} \quad (9)$$

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Where g is the gravity, $\theta = T \cdot p/p_0$ is the potential temperature (being p_0 the pressure at on the ground level[4] and p and T the pressure and the temperature at z) and u is the velocity at z.
In atmospheric flow studies, the Richardson number is widely used in NWP as it is also a flow stability indicator. The correspondence between Richardson number values and atmospheric stability is the following: values below zero indicate stable conditions, whereas positive values indicate unstable conditions. When the Richardson number tends to zero the condition is neutral. No significant correlation is found between the Richardson number at a given timestep and the corresponding model-observation mismatch.

4. Conclusions

A method to downscale NCEP/NCAR Reanalysis data using WAsP is developed. This allows to estimate wind energy resources where meteorological data are scarce or not available at all. The downscaling process is validated using observed meteorological data of two meteorological stations in Europe, namely: Carcaixent (Spain) and Wideûmont (Belgium). A large mismatch between the results concerning wind velocities is found, although the main trends are eventually followed by the model. As regards wind direction, better results are achieved.
The development of new downscaling methods, according to several authors, such as Badger *et al.* [4], opens up the possibility to apply global-scale model data in a more sophisticated way and using higher resolutions. In a near future, when computational resources are more powerful, more accurate numerical models and more reliable downscaling techniques can provide good-quality estimates. This is an asset in places where meteorological data are scarce or not available at all. E.g. they can be useful in wind-energy programs in underdeveloped countries. Even in developed countries, the development of this kind of tools is interesting, as meteorological observation time-series have to be generally purchased to institutions.
At last, a future work proposal can be outlined. As mentioned above, a mismatch between computed and observed wind velocity evolution is found, although the main trends are followed in some cases. For this reason, it is important to find out the reason of this mismatch in order to figure out how to reduce it. As regards wind velocity, computed values tend in most cases to underestimate the observed values. Likely, improving the simulations with WAsP would increase the accuracy of the final results. Therefore, better elevation and roughness maps could be used and an in-situ description of the obstacles surrounding the points under study should be performed.
Another action that would likely reduce errors would be refining NCEP/NCAR Reanalysis data by means of WRF or a similar model. In this case, the latter model would be used as an intermediate step in the whole downscaling chain. Under a scheme NCEP/NCAR Reanalysis data → WRF → WAsP a more gradual scale reduction throughout all the scales, both in time and space, would likely improve results.
Also the whole downscaling method may be extended to the use of NCEP/NCAR Reanalysis data from more than one point simultaneously, as other downscaling tools do, e.g. KAMM/WAsP Method [8]. It would be interesting finding out if some statistically-weighted system would yield better results.
In addition, the same approach could be applied to other global datasets. According to Lileo and Petrik [25], the global dataset used in this project (NCEP/NCAR Reanalysis data) show significant time inconsistencies at some grid points of Earth. This can affect drastically the energy production estimates, leading to errors up to 14% with respect to more consistent datasets, such as MERRA-grid data.
As NCEP/NCAR Reanalysis data, the ECMWF Reanalysis Dataset (published by European Center for Medium-Range Weather Forecasts) is also freely available for research purposes, but significantly more consistent. Hence, developing a similar downscaling protocol to refine ERA data using WAsP for wind-energy assessment purposes would be a useful and challenging task.

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