HIGH-RESOLUTION MODEL-BASED WIND ATLAS FOR GREECE

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ABSTRACT

In the frame of this paper a wind climatology has been built for Greece, based on high resolution model simulations performed for a typical year of wind conditions over the area. The methodology followed includes: (a) the development of a typical wind year, (b) the definition of a modeling strategy and the performance of the appropriate simulations, (c) the verification of the 10-m wind speed simulated by the model against observations, (d) the statistical analysis of the wind simulations for the construction of the wind atlas. The analysis is performed at 50 m and includes gridded wind speeds, the parameters of the respective Weibull distributions, the estimated operating hours of wind turbines and the potential power production.

Keywords: model-based wind atlas, weibull parameters

1. INTRODUCTION

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if considerable efforts are made to reduce greenhouse gas emissions and to address the other impediments to increased wind energy deployment (Wiser et al., 2011). During the last decade the wind energy market has expanded rapidly. Thus the identification of potential sites for wind farms is of high interest and therefore the availability of a wind atlas over Greece is of high priority. The production of an accurate wind atlas is a quite complex task especially over Greece that is characterized by a highly complex terrain.

Many wind atlases that have been recently produced for various countries have been based on the use of numerical weather prediction models (NWP) which are accompanied in some cases with the use of diagnostic downscaling models. Indeed, the Swedish wind atlas has been produced based on the simulation of 192 samples of meteorological conditions selected to represent the meteorological conditions governing the wind climate of Sweden with the Meteorological Institute Uppsala University (MIUU) model (Bergström and Söderberg, 2009). Gaston et al. (2008) also presented a wind resource map of Spain that was built using Eta/Skiron NWP model simulations for one year (2006) at a horizontal resolution of 0.1x0.1 deg. Tammelin et al. (2011) prepared the Finnish wind atlas by applying the mesoscale model AROME with 2.5 km horizontal resolution and the diagnostic downscaling method Wind Atlas Analysis and Application Programme (WAsP) with 250 m resolution, the latter only over the areas most favorable for wind power production. The authors produced simulations for a period of 48 months that were selected as representative of the period 1989–2007. Moreover they have also simulated the windiest and the calmest months of the same period. For Greece, the wind atlas produced on 2006 (Foussekis et al. 2006) and updated recently have been based on the use of measured winds from a number...
of wind musts deployed over the Greek territory. Based on the international practice to use NWP models for the construction of wind atlases, the National Observatory of Athens took the initiative to build a wind climatology for Greece based on high resolution model simulations performed for a typical year of wind conditions over Greece. The adopted methodology consists in defining a typical wind year over Greece that then is simulated using a mesoscale model for a domain covering Greece. The simulated wind fields have been verified against surface station observations in order to assess the model ability to reproduce the local wind flow. Finally the model simulated winds at various heights have been statistically analysed for the construction of the wind atlas. The rest of the paper is structured as follows. The next section present the methodology adopted for the definition of the typical meteorological year over Greece. Section 3 is devoted to the presentation of the modeling strategy and the verification of the simulations, while section 4 discusses the results. The last section of the paper is devoted to the concluding remarks of this work.

2. THE TYPICAL WIND YEAR
For the purposes of this study, a typical year based on the wind flow over Greece and the surrounding maritime areas has been defined. For the definition of the typical year the ECMWF meteorological reanalysis fields for the 20-year period 1989-2008 have been used. This ECMWF-Interim database provides data with ~80 km spatial resolution, at 6-hour intervals. The selected area, for which the typical year was built, is bounded from 18 E to 30 E and from 34 N to 42 N. The typical wind year consists of months selected from individual years, concatenated to form a complete year. As for the present application – the development of a wind-atlas- the parameters used from the ECMWF-Interim database are the 10-m wind speed and direction at 6 hours intervals for the aforementioned period. The methodology used in order to define the typical month is similar to the one proposed by Hall et al. (1978) using the Filkenstein-Schafer statistic (Filkenstein-Schafer, 1971). Indeed, the cumulative distribution function (CDF) based on 160 wind bins (20 bins for the wind speed by 8 bins for the wind direction) have been calculated for each month, for each specific year of the 20 year period as well as for the entire 20 year period (long term CDF) for the same month. Then the wind CDF (speed and direction) for each month for each specific year is compared with the respective CDF of the long-term 20 years composite. From the 20 months, the one for which the sum of the absolute differences between the two CDFs is minimal is selected for the typical year. According to the aforementioned methodology the typical year constructed includes the monthly sequence given in Table 1.

<table>
<thead>
<tr>
<th>Month</th>
<th>Year</th>
<th>Month</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1999</td>
<td>July</td>
<td>2008</td>
</tr>
<tr>
<td>February</td>
<td>1996</td>
<td>August</td>
<td>1997</td>
</tr>
<tr>
<td>March</td>
<td>2000</td>
<td>September</td>
<td>2008</td>
</tr>
<tr>
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<td>1995</td>
<td>October</td>
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<tr>
<td>May</td>
<td>1998</td>
<td>November</td>
<td>2007</td>
</tr>
<tr>
<td>June</td>
<td>2006</td>
<td>December</td>
<td>2003</td>
</tr>
</tbody>
</table>

3. MODEL SIMULATIONS OF THE WIND FLOW

3.1 Modeling strategy
The simulations for the wind atlas construction are based on the use of MM5 model. MM5 model is a non-hydrostatic, primitive equation model using terrain-following coordinates.
(Dudhia, 1993). For both the operational chain of MM5 at NOA but also for the model simulations for the wind atlas the following parameterisations have been selected: Kain-Fritsch for the convection, Schultz (1995) for the explicit microphysics, a Hong and Pan for the planetary boundary layer. This model has been verified for its forecast skill over Greece by Kotroni and Lagouvardos (2004).

![Image](image.png)

**Figure 1.** (a) The two nested grids used for the simulations, (b) Location of the surface stations used for the model verification: Alexandroupolis (A), Lemnos (L), Larissa (La), Aktion (Ak), Souda (S) and Heraklion (H).

Two nested grids have been defined and used for the model simulations (Fig. 1). Grid 1 has 10-km horizontal grid increment (230x210 grid points), covering the major part of Southestern Europe, and the Balkans. Grid 2 has 2-km horizontal grid increment (431x436 grid points), covering the Greek territory and all the Greek islands and the adjacent water bodies. The horizontal extension of the defined grids is shown in Fig.1a. In the vertical forty unevenly spaced full sigma levels are selected. For each day of each selected month, four simulations are performed starting at 0000, 0600, 1200 and 1800 UTC with a 6-h duration for each simulation. All data from the 6-hour simulations sequences are stored for further analysis at 1-hour intervals from t+1 up to t+6 hours of simulation. The ECMWF gridded analysis fields and 6-hour interval, at 0.5-degree lat/lon horizontal grid increment, are used to initialize the model and to nudge the boundaries of Grid 1 during the simulation period.

### 3.2. Verification of the model simulations

In order to evaluate the model skill to provide accurate wind forecasts, a verification procedure is undertaken for each month of the defined meteorological year. The observational data include six weather stations distributed across Greece (Fig. 1b). The selected stations are operated by the Hellenic National Meteorological Service. The wind speed value at the model grid point the closest to the observational site has been used for the verification, while the four model points surrounding the observing station were also considered. This procedure permits to reduce the possibility of penalizing the model’s performance due to inconsistencies between model and actual topography.

The initial processing of the data, apart from consistency checking, included reduction of the model 10-m wind speed values, to the height of the observing stations, as well as binning of all data (modeled and observed) to 1m·s⁻¹ intervals. Apart from the original, henceforth “complete” data set, we created a second dataset named “operational” by binning all data below or equal to a cut-in wind speed of 3 m·s⁻¹ into a single bin. The cut-off speed (25 m·s⁻¹) was never reached in the analysed dataset, so no specific treatment was necessary.
The model point closest to the observing station was used for the model performance evaluation. The typical point-to-point comparison is useful in a general case, however it might not be the best choice in the specific context of our work. Since our goal is to provide credible information about the wind energy availability across Greece, it seems appropriate to focus on the comparison of the distributions describing the modeled and the observed wind speed data, rather than the data itself. The first logical step was to compare the empirical distributions of the modeled and the observed wind speeds. However empirical distributions are prone to reflecting the irregularities at the end points of the data, and in other places where the data is sparse, thus increasing the risk of a falsely negative ruling on the similarity of the modeled and the observed distributions. Furthermore, since our entire analysis would be based on the fitted Weibull distributions for the model grid points, we preferred to use those as the basis of the comparison.

An initial comparison using the Pearson correlation coefficients, r, indicated very close agreement (r>0.95 in all cases) between the CDF’s of the distributions fitted to the observed and modeled wind speed. Moreover, the non-parametric Kolmogorov-Smirnov test for the equality of two probability distributions (Sprent, 1993) was applied to the Weibull distributions fitted on the observed and modeled data for each station and for both the complete and the operational data sets. Table 2 presents the resulting D statistics of the Kolmogorov-Smirnov test, as well as the respective critical values for the 5% level of significance. Values of D less than the critical level suggest that at the 5% level of significance, there is not enough evidence to reject the hypothesis that the two samples follow the same distribution. For the original set, at Alexandroupoli and Larissa the Kolmogorov-Smirnov test suggests that the modeled wind speeds do not follow the same distribution as the observed ones. However when the operational data set is examined (wind speeds between 4 and 25m·s⁻¹) this discrepancy is removed and the Weibull distributions fitted on the modeled data are the same as those followed by the respective observed data.

Table 2: Kolmogorov-Smirnov test, D statistic and respective critical values for the 5% level of significance

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>O</th>
<th>D</th>
<th>C</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>corr=0.119</td>
<td>D</td>
<td>corr=0.132</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Alexandroupoli</td>
<td>0.991</td>
<td>0.990</td>
<td>0.193</td>
<td>0.110</td>
<td></td>
</tr>
<tr>
<td>Limnos</td>
<td>0.989</td>
<td>0.955</td>
<td>0.104</td>
<td>0.100</td>
<td></td>
</tr>
<tr>
<td>Larissa</td>
<td>0.986</td>
<td>0.960</td>
<td>0.236</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>Aktion</td>
<td>0.997</td>
<td>0.979</td>
<td>0.077</td>
<td>0.039</td>
<td></td>
</tr>
<tr>
<td>Souda</td>
<td>0.994</td>
<td>0.974</td>
<td>0.067</td>
<td>0.067</td>
<td></td>
</tr>
<tr>
<td>Heraklion</td>
<td>0.997</td>
<td>0.988</td>
<td>0.063</td>
<td>0.063</td>
<td></td>
</tr>
</tbody>
</table>

4. STATISTICAL ANALYSIS OF THE WIND

4.1. Mean wind speed
The Wind Atlas includes monthly wind statistics for seven height levels: 50 m, 75 m, 100 m, 125 m, 150 m, 200 m and 400 m, and for a total of ~190,000 points, each representing an area of 2 x 2 km². The wind field has been analysed at annual and monthly time scales, calculated from the hourly values. The area of the analysis covers Greece and the surrounding waters. In the following, analysis focus is given at the 50 m level winds. Figure 2 presents the monthly average wind speed at 50 m for one representative months. Indeed, during January the mean wind speed is less than 3 ms⁻¹ over the plains of continental Greece while over the medium and high altitudes the mean wind speed increases to more than 6 m s⁻¹ (Fig. 2a). Among the continental areas, Northeastern Greece, Attica and the
adjacent island Evia, southern Peloponissos and the southern Crete present the higher mean wind speeds. Among the maritime areas, the Aegean Sea is much windier than the Ionian Sea, with mean wind speeds ranging from 7 ms\(^{-1}\) up to more than 9 ms\(^{-1}\) locally. Increased wind speeds are also found in the entrance of the Corinthian Gulf, which is a narrow sea-level passage surrounded by a steep complex topography that consists of high mountains, elevated and sea-level gaps/straits. This is in agreement with the findings of Koletsis et al. (2013) who found in their wind climatology of the area that the most intense wind events occur during the winter season. During spring, (not shown) the mean wind speed over Greece presents much less variability than in winter, with winds of the order of 3-4 ms\(^{-1}\) over the plains, increasing to 4-6 ms\(^{-1}\) with height, while over the maritime areas the prevailing wind are of the order of 5 ms\(^{-1}\).

![Average wind speed at 50m - JAN](image1)

![Average wind speed at 50m - JUL](image2)

**Figure 2.** Monthly mean wind speed at 50-m for (a) January and (b) July.

During summer (Fig. 2b), while over land the mean wind speed pattern is quite similar to that of spring, over Attica, Crete and the maritime areas and the islands of the Aegean sea the wind speed is considerably increased. Indeed, during summer northern sector winds are blowing over the Aegean Sea, the Etesian winds, which are mainly north-easterly in the northern Aegean, northerly in the central and southern Aegean and tend to become north-westerly near the southwestern Turkish coasts. The air masses regularly originate from the region of southern Russia and the Caspian Sea and they are dry and relatively cool, contributing to the decrease of surface temperature and the moderation of summer heat and discomfort (Metaxas and Bartzokas, 1994; Kotroni et al., 2001). The sustained wind speed associated with the Etesians often attain near-surface values exceeding 15 ms\(^{-1}\) (Kotroni et al., 2001). Thus, the mean wind speed at 50-m over the Aegean increases to 7-8 ms\(^{-1}\) that locally reaches more than 11 ms\(^{-1}\). Autumn is the rainiest season in Greece which is affected by the passage of low pressure systems associated with southerly winds. The mean wind speed distribution at 50-m is relatively close to that during winter with the windiest areas found over the Aegean, Attica, Evia, the Corinthian Gulf area and Thrace in northeastern Greece (not shown).
4.2 Wind potential
The model simulated winds at hourly intervals at 50-m height have been used in order to
determine the wind potential. If \( f(\nu) \) is the probability density function (PDF) of wind speed \( \nu \),
the wind potential \( P \) can be expressed as:

\[
P(\nu) = \frac{1}{2} \rho \int_{0}^{\infty} \nu^3 f(\nu) d\nu
\]

where \( \rho \) is the air density. This integral can be evaluated over a range of wind speeds and in
the frame of this study it has been evaluated for the range of operation of wind turbines that
usually ranges from a cut-in speed of 4 ms\(^{-1}\) up to the cut-off speed of 25 ms\(^{-1}\) with a step of
0.2 ms\(^{-1}\). The PDF of wind speed is important in numerous wind energy applications. The two
parameter Weibull probability density function is the most widely used and accepted in the
specialised literature on wind energy and other renewable energy sources (Seguro and
Lambert, 2000). Indeed, the wind speed probability density function is given by:

\[
f(\nu) = \frac{k}{c} \left(\frac{\nu}{c}\right)^{k-1} \exp\left[\frac{1}{c^k}\right]
\]

where \( c \) (in ms\(^{-1}\)) is the Weibull scale parameter and \( k \) (dimensionless) is the Weibull shape
parameter that characterizes the asymmetry of the probability function. There are various
methods to determine these two parameters. In the frame of the present work, for the
estimation of the two parameters the least square method has been used (see Carta et al,
2009). Based on the above, once the wind potential is estimated a classification was made
following the Texas State Energy Conservation Office (2011). Indeed, six classes of wind
potential have been used as presented in Table 3.

**Table 3. Classification of wind potential density (adopted from the Texas State Energy
Conservation Office)**

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Wind potential density (Wm(^{-2}))</th>
<th>Commercial Viability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-200</td>
<td>Very Poor</td>
</tr>
<tr>
<td>2</td>
<td>200-300</td>
<td>Poor</td>
</tr>
<tr>
<td>3</td>
<td>300-400</td>
<td>Marginal</td>
</tr>
<tr>
<td>4</td>
<td>400-500</td>
<td>Good</td>
</tr>
<tr>
<td>5</td>
<td>500-600</td>
<td>Very good</td>
</tr>
<tr>
<td>6</td>
<td>&gt;600</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

Figure 3a presents the mean yearly wind potential at 50-m that has been evaluated from a
cut-in speed of 4 ms\(^{-1}\) to the cut-off speed of 25 ms\(^{-1}\) with a step of 0.2 ms\(^{-1}\) based on Eq. 1.
It is clear that in the largest part of the Aegean sea the wind potential is larger than 500 Wm\(^{-2}\),
reaching locally 700 Wm\(^{-2}\). Over the Ionian the wind potential is of the order of \( \sim 300 \) Wm\(^{-2}\).
Locally the wind potential exceeds 400 Wm\(^{-2}\) over the mountain ranges as well as over the
Corinthian Gulf, Thrace, Attica and Evia, southeastern Peloponnisos and Crete. Accordingly
these areas are characterized by wind power class 3 or higher as depicted in Fig. 3b.
Eastern Crete has a higher class wind power that locally is excellent (class 6), and also
southern Crete presents a better wind power class compared to the northern areas. This is
related with the complex topography of Crete island that produces gap winds and acceleration of the wind flow over southern Crete (Koletsis et al. 2009a, b). The wind power
class over Southern Evia island exceeds 5 over a large part, while offshore southern Evia the
wind power class is excellent.
5. Concluding Remarks

In the frame of the present paper a Wind Atlas over Greece has been developed based on simulations performed with the Numerical Weather Prediction (NWP) model MM5 that has been actively utilised at the National Observatory of Athens since 2000. The atlas contains 12 months of weather model simulations where the winds and other variables are calculated for grid boxes 2 x 2 km² in size. The methodology used in order to select the typical months to form the typical wind year was based on the the Filkenstein-Schafer statistical method (Filkenstein-Schafer, 1971) and it is described with details in Section 2. The typical wind year was simulated by MM5 in 6-hour sequences, storing the atmospheric state at 1-hour intervals from t+1 up to t+6 hours of simulation. The initial state of each 6-hour sub-period and the required boundary conditions were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis. The results of the model simulations have been verified against a number of surface meteorological stations while also annually and monthly statistics at various heights are produced over Greece and the surrounding maritime area. At this point it should be mentioned that for wind resource estimation and siting a detailed description of the terrain, namely the surface roughness, orography and obstacles, is required. In that case the Weibull distributions calculated over Greece could be used as input to a microscale model such as WaSP (Mortensen et al., 1993) together with detailed description of the terrain topography in order to estimate local wind climate for wind energy applications. Thus it is in the authors plans to build a web-based interface that could link the current wind atlas result with high resolution topographical data and the WaSP model for siting purposes.

REFERENCES


Figure 3. (a) Wind potential (in Wm⁻²) and (b) wind power class, at 50-m.


