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WIND RESOURCES, PART II: CALCULATIONAL METHODS

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ABSTRACT: The Wind Atlas Analysis and Application Program represents one of several calculational methods or tools that are used routinely in the analysis of wind data and estimation of wind resources. Based on the experience gathered at Risø it is concluded that the program works very well in relatively uncomplicated topography. Less is known about the performance in mountainous terrain, but it is concluded that high-quality wind and topographical data, as well as great attention to detail, are a prerequisite to the succesful application of such models in complex terrain. A case study, using data from an ongoing measuring campaign in very complex terrain in Northern Portugal, is used to illustrate the capabilities and limitations of current models.

1 INTRODUCTION

During the last half a dozen years numerical flow models and other advanced computational tools have become widespread in the wind energy community. One such collection of computer tools is the Wind Atlas Analysis and Application Program (WA^{S}P) which was developed during the investigation leading to the European Wind Atlas. As the name indicates the program is used mainly for two purposes:

1. Establishing of regional wind climatologies, ie wind atlases
2. Micro siting, ie determination of optimum wind turbine sites in specific areas.

Over the years, WA^{S}P has been distributed to several hundred institutions and companies in more than 50 countries around the world. The application of standard tools and common guidelines in the analysis of wind data and wind resource estimation has led to a common frame of reference and a much needed standardization. This paper is a brief report on the status of WA^{S}P, including some observations on the proper use of the program. The limitations of current models in complex terrain are illustrated by a recent example from Portugal and possible future initiatives are touched upon.

2 REGIONAL WIND CLIMATOLOGIES

The European Wind Atlas, or more precisely the EC Wind Atlas, was produced using WA^{S}P and published in 1989. The experience gained from using the regional climatologies is discussed in an accompanying paper (E.L. Petersen: The European Wind Climatology). During the following years wind atlases were produced and published in Algeria, Jordan, Finland, Sweden, Switzerland and Western Australia. Other countries are currently undertaking work using WA^{S}P, which eventually will lead to national atlases in eg Egypt, Syria, Libya, Turkey, Bulgaria, Poland and Israel. Limited regional studies have been performed in India, China, Mongolia, Somalia, Cabo Verde, Chile, Australia and USA.

As discussed in the first part of this paper the reliability of the calculated regional wind climatologies depends strongly on the quality of the data base, the complexity of the topography and the climate of the region. Hence, any published wind atlas should contain a discussion on the representativeness of the statistics based on a proper verification. There are usually three steps in the verification procedure: 1) letting the stations in the data base predict each other, 2) comparisons with measurements from tall masts and 3) comparisons with other types of available information such as voluntary ship reports or power production statistics from wind turbines. As an example, the Swedish Wind Atlas uses the verification to rank the stations of representativeness and actually dismisses a few of them. It is found that especially in Southern Sweden the reliability of the wind atlas statistics is high. On the other hand, in Finland it is found that the quality of the data base is generally not sufficient due to the location of most of the stations in very sheltered surroundings.

3 MICRO SITING

WA^{S}P has been used for siting a large number of wind turbines, single or in wind farms. For countries where a national wind atlas exists the common siting procedure is to select the proper wind atlas statistics and further to acquire a set of meteorological data from the nearest meteorological station. By means of WA^{S}P both data sets are then made representative for the site in question. Ideally, the power production estimates calculated for the two sets of statistics should be close; otherwise it is necessary to look deep into the circumstances under which the two data sets originated – certainly not a trivial matter. In the more general case no wind atlas statistics exist, but data have been collected 'in the neighbourhood' for a few years; often just one year or even shorter. Due to the seasonal and interannual variations of the wind climate use of data series shorter than 3 years should be avoided; the use of short series may add considerably to the uncertainty of the mean power production estimates.

In order to check the mean power production estimates of WA^{S}P it is necessary to pick a number of wind turbines that have produced reasonably continuous over several years. This has been done in Denmark and Southern Sweden with the conclusion that WA^{S}P performs very well in this region of relatively uncomplicated topography. For most of the wind turbines over the world, however, it is necessary to wait some years before sufficient statistics have been collected.

A number of test studies have been performed over the years, largely based on data from two experimental meteorological masts, in order to check whether WA^{S}P was able to predict the measurements from one mast using the data from the other mast. Some of these studies have had rather negative conclusions, but in each case a close look revealed that one or more of the following major errors were committed:

1. the two time series were very short, often only a few months long and sometimes not even covering the same period of time.
2. the orography was not described with sufficient accuracy and detail, especially close to the mast.
3. the position of one, or both, of the masts was entered wrongly to WA^{S}P which make the orography calculations and corrections meaningless.
4. the wind speed and direction series contained serious errors.
5. the author did not understand how to use the program.

There are, however, clear limitations to the use of WA^{S}P: On the micro scale very steep slopes with separating flows are not treated correctly, and on the large scales the dynamics are too simplified by the neglect of the large scale stratification, and also in relation to local, thermally driven flow systems. It should be mentioned, however, that the problems related to large scale flows are alleviated if input data come from a station not too far from the point of application relative to the horizontal scale of the important flow systems.

One of the objectives of the JOULE project "Wind measurement and modelling in complex terrain" is to establish a data base of high-quality wind measurements that can be used in the evaluation and further development of existing models. The project has now come so far as to allow preliminary investigations of this nature.

4 A CASE STUDY IN MOUNTAINOUS TERRAIN

As part of the University of Porto's contribution to the project mentioned above, ten meteorological masts have been erected in the northernmost part of Portugal. A detailed description of the stations and their surroundings, the instrumentation used and the data obtained so far is given by Restivo and Petersen (1993, this volume).

For the purpose of this investigation six stations were selected, representing three different degrees of topographical complexity along a 50-km long profile: from the Atlantic coast in the W to the more than 1000-m high mountains of Arada-S. Macário in the E. In the following we will refer to the stations by the numbers 01, 10, 09, 08, 07, and 06 (going from W to E); a detailed description of the stations, including their names and coordinates, are given by Restivo and Petersen (ibid).

4.1 Station characteristics

Station 01 is situated close to the Atlantic coast in a flat and level area, and the terrain surface close to the station consists of water, farmland and marsh. There are no sheltering obstacles close to the station. Hence, the areas of different roughness are by far the most important topographic influence on the wind measurements.

Stations 10 and 09 are situated approx. 34 km ENE of station 01, in the mountains of Freita. The altitudes of the two stations are 1012 and 1082 m a.s.l, respectively, and the distance between the stations is 3 km. Here the roughness is much more uniform than at station 1, but the height variations around the stations give rise to pronounced orographic effects.

Stations 08, 07 and 06 are situated approx. 14 km further inland, or about 40 km from the Atlantic coast. The three stations are situated a few km from each other in very complex, mountainous terrain, see Restivo and Petersen (ibid). The altitudes of the stations are 1057, 982 and 932 m a.s.l, respectively. Detailed maps of the surroundings of each station are shown in Fig. 1 and some simple orographic characteristics are listed in Tab. I.

Table I: Differences in altitude between the lowest and highest level (Δz) and standard deviations of grid point heights (σ_z) within unit areas of 64 km^2 and 1 km^2 around the six stations. The grid size ($\Delta x = \Delta y$) is 100 m and 10 m, respectively.

	8×8 km^2		1×1 km^2	
#	Δz	σ_z	Δz	σ_z
01	$O(1)$	$O(1)$	$O(1)$	$O(1)$
10	900	187	100	16
09	800	200	92	19
08	718	197	248	51
07	800	178	257	57
06	750	183	260	45

Digital height contour maps covering an area of 8×8 km^2 around each site was used as input to the flow model of WA^{S}P. The altitude differences listed in Tab. I for these maps correspond approximately to the *relative relief* given in the European Wind Atlas. It appears, that neither this measure, nor the standard deviation of 100-m grid point heights seem to differentiate the five mountain stations. The same measures, however, calculated for areas of 1×1 km^2 around each site, show clear differences between the three groups of stations.

4.2 Model calculations and input data

The model used for the wind climate estimations below is version 4.0 of WA^{S}P, which is the latest version of the model that was used for the European Wind Atlas (Troen and Petersen, 1989). The application of this version is described by Mortensen et al. (1993a, 1993b).

The input data to WA^{S}P consist of wind measurements and a detailed topographical description of the surroundings of each station. The instrumentation used for measuring the wind speed and direction is described by Restivo and Petersen (ibid). For the purpose of this study the time-series covering one full year (1992) were used.

The orographic information is contained in digital maps giving the coordinates of height contour lines. In this case, each map covers an area of approx. 8×8 km^2, with a contour interval of 50 m. However, within an area of 1×1 km^2 centered around the stations the contour interval is 10 m. The station levels have been marked with additional height contours in order to get as detailed and accurate a description of the terrain as possible.

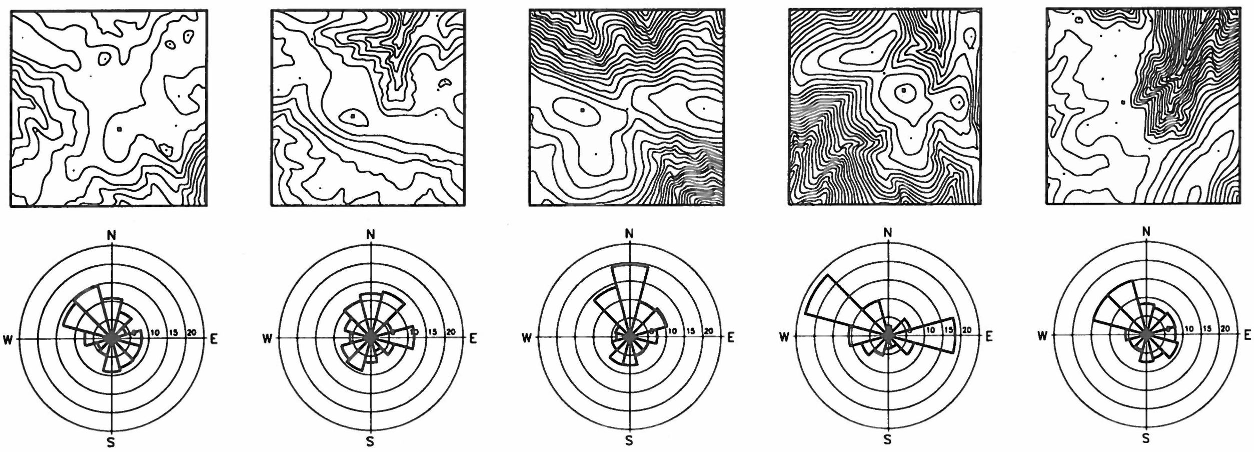

Figure 1: a) Detailed 1×1 km^2 maps of the surroundings of stations 10, 09, 08, 07 and 06 (upper panel). Left to right corresponds to W–E. The contour interval is 10 m. b) Sector-wise distribution of the winds measured at the five stations (lower panel).

The surface roughness at the mountain stations were assumed uniform with a z_0 of 0.05 or 0.03 m. The roughness lengths were estimated from photographs and maps. From the same material it was concluded that neither of the six stations are likely to be influenced by sheltering obstacles. – The roughness classification for station 01 was entered to WAsP as a *roughness map*, ie a digital map of roughness change lines (Mortensen et al, 1993b).

4.3 Results

Using the wind data and topographical information described above, wind atlas data sets were generated for the six stations. These data sets were subsequently used together with the topographical information to predict the wind climate at 10 m a.g.l. at the other five stations. The results are presented below in a so-called score scheme (Troen and Petersen, 1989), see Tab. II. The first column contains the predicted stations and the first row the number of the predictor stations. The diagonal line of bold face figures thus indicates the stations predicting themselves; these values are close to those actually measured, which are listed in the last column.

Table II: Measured and estimated mean wind speeds (ms^{-1}) and mean wind power densities (Wm^{-2}) at 10 m a.g.l. for the six stations. The power densities have not been corrected for the influence of different air densities.

	01	10	09	08	07	06	Meas.
PORT01	**4.2**	4.6	4.6	4.4	3.4	3.4	4.4
	118	137	148	140	58	58	127
PORT10	5.4	**5.5**	5.5	5.2	4.0	4.3	5.6
	262	**227**	233	209	96	115	231
PORT09	5.3	6.0	**5.7**	5.7	4.1	4.3	5.8
	242	321	**272**	293	125	124	279
PORT08	6.7	6.8	6.5	**6.0**	4.6	5.1	6.1
	569	516	398	**313**	191	216	310
PORT07	6.3	7.3	7.2	7.2	**5.3**	5.3	5.4
	354	579	592	653	**216**	229	216
PORT06	5.4	6.2	6.1	6.1	4.4	**4.5**	4.6
	233	354	337	384	136	**139**	139

As one might expect, the picture emerging from Tab. II is not as simple and unambiguous as is often seen in cases of less complex terrain.

Stations 01, 10 and 09 compare fairly well, the differences in mean wind speed and power density being mostly within 10% and 15%, respectively.

The comparisons become difficult, however, when we look at stations 08, 07 and 06. Station 08 predicts stations 01, 10 and 09 reasonably well, but is not predicted well by the same stations. The prediction by station 09 is the closest, possibly because of the orographic resemblance to station 08.

Stations 07 and 06 predict significantly lower mean values at the other four stations than is actually measured. And, conversely, the predictions of 07 and 06 by these stations are significantly higher than the wind climate observed. However, it is noteworthy, that the two stations 07 and 06 compare very well. The reasons for this, as well as for the discrepancies between 07 and 06 and the other stations are not yet clear, but are likely related to the orographic characteristics of these sites – which the model is obviously not able to correct for. Therefore, these stations can be considered representative only of their specific locations and nearby surroundings with similar orographic characteristics.

Finally, it should be mentioned that several different roughness classifications have been employed during the station intercomparisons. It was found, that even though the predictions change somewhat with different roughness descriptions, the overall picture remained essentially the same.

4.1 Comparison with the European Wind Atlas

As mentioned above, only one full years worth of data has been collected so far, hence a comparison with the stations in the European Wind Atlas must be preliminary. The mean wind speeds and mean energy densities for the six stations, at 50 m a.g.l. over roughness class 1 is given in Tab. III.

Table III: Estimated mean wind speeds (ms^{-1}) and mean wind power densities (Wm^{-2}) 50 m a.g.l. over a uniform, flat surface of z_0 = 0.03 m (roughness class 1).

Station	01	10	09	08	07	06
Wind speed	5.1	5.7	5.5	5.4	4.1	4.2
Density	162	209	204	213	80	87

For comparison, the near-coastal stations of the Wind Atlas, Porto and Viana do Castelo, are reported as having mean wind speeds and energy densities of (5.5 ms^{-1}, 198 Wm^{-2}) and (4.7 ms^{-1}, 221 Wm^{-2}), respectively. Coimbra, 60 km to the S and 40 km inland, is reported as (4.8 ms^{-1}, 225 Wm^{-2}). A tentative conclusion is that these (admittedly sparse) observations does not seem to change the picture given in the European Wind Atlas much.

5 CONCLUSION

Comparisons of wind data measured at meteorological stations, as well as actual power productions measured over several years in Denmark and Southern Sweden, have shown that WA^{S}P performs very well in relatively uncomplicated topography. A similar data base of high-quality wind and/or power production measurements is not yet readily available for most areas of complex terrain. Consequently, less is known on the performance of common computational tools in such areas. Furthermore, the application of programs such as WA^{S}P in complex terrain, require great attention to the details of the wind measurements and topographical input in order to get meaningful results.

However, as indicated by the case study above, there are limitations to the use of programs like WA^{S}P. It has long been recognized that in order to do realistic wind climate assessments in mountainous areas there is a need for a solid dynamical model as well. Work along this line has recently been initiated, starting out with the Karlsruhe Mesoscale Model (KAMM). Several goals have to be accomplished:

1. The models are extremely computer time consuming therefore they have to be simplified – if possible – considering the use in relation to wind energy.
2. Establishing methods for the use of such models, which are fundamentally prognostic, for diagnostic wind climate analysis.

The difference between the models in WA^{S}P and KAMM is that the model in WA^{S}P is a local model which can handle very detailed information of the topography out to approximately ten kilometres from the sites. In contrast, the mesoscale models calculate the wind resources over several hundreds of kilometres in squares of one to five square kilometres. Whether the goals are met will be tested by a massive measurement programme in mountainous terrain; employing more than 30 instrumented masts of 30 m height. The masts are currently being put into operation in Crete, Central Italy, Northern Portugal and Southern Germany.

Yet another type of model is necessary for siting in mountainous areas, ie a model which can predict where separating flow occurs. An attempt is currently being made to construct such a model based on the governing equations for the turbulence and using the k-ε closure scheme.

Hence, it is foreseen that future wind climate analysis and siting in mountainous terrain will require the use of all three models mentioned above.

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