Technical University of Denmark

Influence of topographical input data on the accuracy of wind flow modelling in complex terrain

Mortensen, Niels Gylling; Petersen, E.L.

Published in:
European wind energy conference. Proceedings

Publication date:
1998

Document Version
Publisher's PDF, also known as Version of record

INFLUENCE OF TOPOGRAPHICAL INPUT DATA ON THE ACCURACY OF WIND FLOW MODELLING IN COMPLEX TERRAIN

Niels G. Mortensen and Erik L. Petersen
Wind Energy and Atmospheric Physics Department, Risø National Laboratory, Roskilde, Denmark

ABSTRACT

The influence of terrain ruggedness and the characteristics of the topographical input data on the accuracy of WAsP predictions in rugged and mountainous terrain is explored using data from northern Portugal and France. Critical values of site ruggedness index (RIX), map size, height contour interval and accuracy, and digital elevation model grid size are identified through pair-wise station intercomparisons. WAsP may give accurate results outside its operation limits, provided that the difference in ruggedness indices between the reference and predicted site is small and the topographical input data are adequate and reliable.

1 INTRODUCTION

At present, much of the development of wind power in Europe and elsewhere takes places in complex and mountainous terrain; such as the landscapes found in certain parts of Greece, Portugal, Spain, and the United Kingdom. These sites in elevated terrain often favour high wind resources because of the enhancement of the flow by the terrain features. Wind resource assessment and siting, however, becomes increasingly difficult with increasing complexity and ruggedness of the terrain surface – leading to larger-than-usual uncertainties in the wind resource estimates.

The uncertainties in very rugged terrain are mainly caused by the inability of current wind resource assessment models (eg WAsP) to adequately describe the flow. This problem can be dealt with to some extent, as demonstrated by eg [1]. Another important source of error – even in terrain *well within* the operation envelope of the models – is the topographical input data used for the flow modelling; these must be sufficiently detailed and accurate to obtain accurate results.

In this paper we explore the influence of the topographical input data – in particular the characteristics of the digital height contour map or digital elevation model (DEM) – on the accuracy of wind flow modelling results in rugged and mountainous terrain. The sensitivity of the WAsP flow model to different orographical input data are investigated using digitized (standard) topographical maps of varying coverage, detail and accuracy; as well as height contours derived from DEM's with different grid cell sizes.

2 DATA, MODEL AND METHOD

The wind and topographical data presented below were collected in the course of the Joule project "Measurements and modelling in complex terrain" [6, 7] and have been presented in a number of conference papers, eg [9, 10, 3, 11]. The seven sites with meteorological stations are located in the mountains of northern Portugal and near Narbonne, France [12].

The model used for the calculations is the Wind Atlas Analysis and Application Program (WAsP) [14, 4]. Of special interest here is the so-called BZ flow model of WAsP [13, 15] since we focus on the orographic terrain effects. Accurate predictions using the WAsP program may be obtained [1] provided:

1. the reference site (meteorological station) and predicted site (WTG site or met. station) are subject to the same overall weather regime,
2. the prevailing weather conditions are close to being neutrally stable,
3. the reference wind data are reliable,
4. the surrounding terrain (of both sites) is sufficiently gentle and smooth to ensure mostly attached flows, and
5. the topographical model inputs are adequate and reliable.

Since we are investigating the influence of items 4 and 5 on the prediction skill of WAsP, the data were chosen in order to fulfill as closely as possible the first three requirements. The wind and topographical data have been checked thoroughly and are thought to be of high quality; and the station winds compared are very well correlated. We have no information on the stability statistics of the prevailing weather conditions – which may add to the uncertainty of the wind speed predictions – however, the stations compared are at least subject to the same stability regimes.

The data presented here represent pair-wise intercomparisons of two stations or sites: a reference (predictor) site and the predicted site – where all sites may take either role within a given region. For the calculation of a reference wind atlas for each site, the full set of wind and topographical data were used. The complete data sets were also used in the calculation of the site-specific ruggedness indices, see Section 3.

For the purpose of assessing the influence of the topographical input data on the accuracy of the wind flow modelling, only the orographical data of the *predicted sites* were changed. In this way, the different wind climate predictions can be compared to both the measured wind climate at the predicted site and to a 'reference' prediction, using all the available information.

3 TERRAIN RUGGEDNESS

The ruggedness index (RIX) of a given site is defined as the fractional extent of the surrounding terrain which is steeper than a critical slope [1]. The index was proposed as a coarse measure of the extent of flow separation and, thereby, the extent to which the terrain violates the requirement of WAsP, that the surrounding terrain should be sufficiently gentle and smooth to ensure mostly attached flows [1, 8]. The operation envelope of WAsP thus corresponds to RIX $\approx$ 0%.

Figure 1 shows the WAsP wind speed prediction error as a function of the difference in extent of steep slopes (RIX values in %) between pairs of sites. The RIX-value for one site is calculated for each of 72 radii originating at the site, by dividing each radius into line segments defined by the crossing of the radius with the contour lines. The sum of the line segments representing slopes greater than a critical slope, here 0.3 [16], divided by the total sum of the segments (ie the radius) is then the RIX value of the radius in question. The overall RIX value for the site is then simply the mean of the sector-wise RIX values.

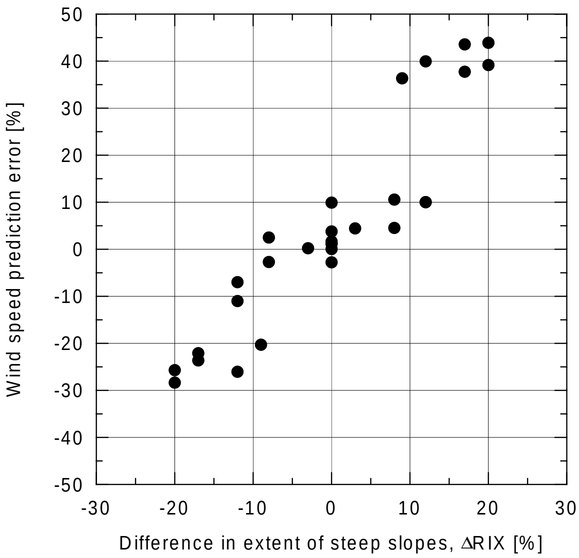

Figure 1: WAsP wind speed prediction error versus the difference in extent of steep slopes (RIX values) between the predicted and the reference site. Data from five Portuguese and two French sites are shown.

The systematic trend in Fig. 1 indicates a strong influence of flow separation on the wind speed prediction error [1]. If the reference and predited sites are equally rugged ($|\Delta\text{RIX}|$ small) the prediction errors are relatively small. If the reference site is rugged and the predicted site less rugged or flat, the overall prediction is underestimated with a significant negative error. Conversely, if the reference site is flat or less rugged than a rugged predicted site, the overall prediction is overestimated with a significant positive error.

Figure 2 shows the same data as Fig. 1, but arranged according to the ruggedness index of the most rugged of the two sites. This figure indicates that accurate wind speed predictions may be obtained – even well outside the recommended performance limits of WAsP – provided that the difference in ruggedness indices between the reference and predicted site

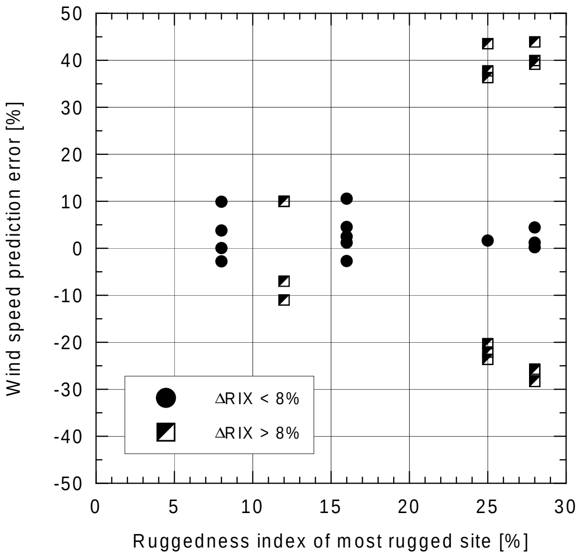

Figure 2: WAsP wind speed prediction error versus the extent of steep slopes (RIX value) of the most rugged of the predictor (reference) and predicted site.

is small. This is obviously the case for the self-prediction at any category of site, but may also occur for neighbouring sites with similar orographical settings and orientation. This represents an important application involving the prediction of wind speeds and power production at adjacent sites along a steep ridge in a wind farm [2].

The ruggedness index can thus be used to judge whether a given situation is inside or outside the recommended operation envelope of WAsP. Furthermore, it may provide the sign and approximate magnitude of the prediction error for situations where one or both of the sites are situated in terrain well outside this envelope.

4 HEIGHT CONTOUR MAPS

The orography of the terrain in the flow model of WAsP is specified as a digital height contour or vector map, containing the (x, y)-coordinates and altitudes of the map contour lines. The map is stored as a file in binary or ASCII format, either in WAsP's own format or in an ASCII drawing exchange format (DXF-file). Three characteristics of the map are particularly important for the wind climate predictions: the size of the map, the contour line interval, and the accuracy of the digitized contour lines.

The influence of the size of the map or model domain on the wind climate predictions has been investigated for two pairs of the Portuguese stations by varying the size of the map pertaining to the predicted sites. One pair is station 8 predicting station 9 (RIX = 8%), the other station 6 predicting station 7 (RIX = 28%). Square maps with a side length of 1, 2, 3, 4, 5, 6, 7, and 8 km were extracted from the original digitized maps and used as input for the predicted sites. The results are shown in Fig. 3. Large wind speed prediction errors are found with the smaller domains, and the errors decrease with increasing map size. With maps of $8 \times 8\,\text{km}^2$ the wind speed estimates seem to be (almost) stable and close to the measured values. The map size seems to be less critical with the

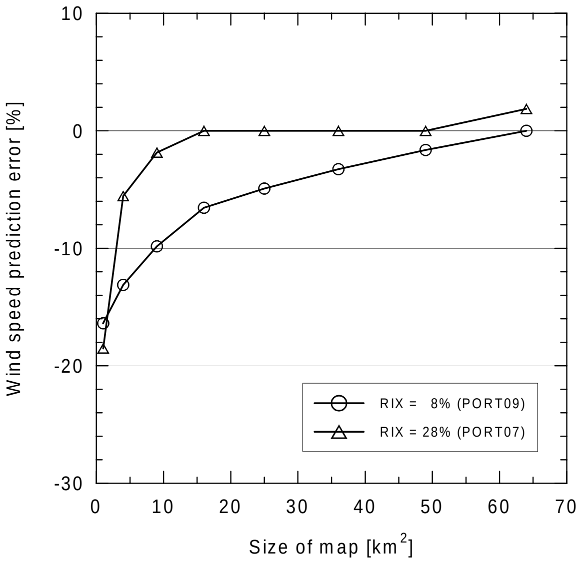

Figure 3: WAsP wind speed prediction error versus the size of the orographical map pertaining to the predicted site.

most rugged of the two cases, where the wind speed estimate becomes stable with a map size of about $4 \times 4\,\mathrm{km}^2$.

The influence of the value of the contour line interval on the wind climate predictions has been investigated for the same two pairs of stations by extracting $8 \times 8\,\mathrm{km}^2$ maps with different contour line intervals: 100, 50, 20, and 10 m, see Fig. 4. As might be expected, a small contour line interval is essential in order to obtain accurate wind speed predictions. Large prediction errors are associated with large contour line intervals and the prediction errors decrease with decreasing contour line interval. In both cases, the two error curves follow each other closely and an interval of 20 m or less provide fairly accurate predictions. The importance of defining the extreme points of the terrain – in particular the hill tops and crests – are evident from the points plotted at "1 m" height contour interval. These points correspond to the original digitized map, where the actual altitude of the sites have been specified by separate contour lines.

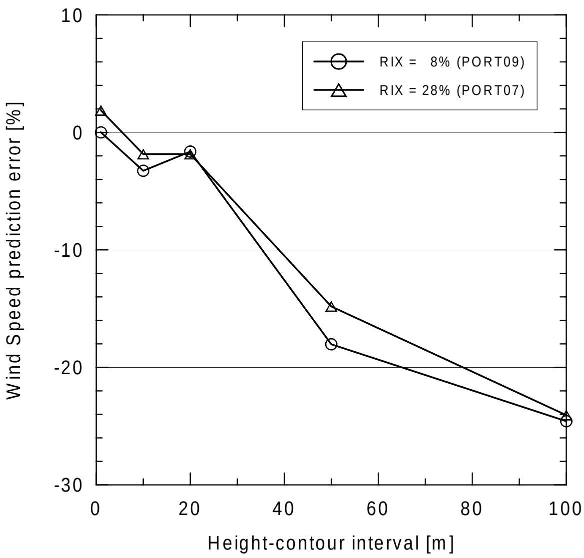

Figure 4: WAsP wind speed prediction error versus the contour-line interval of the orographical map pertaining to the predicted site.

The influence of the (horizontal) accuracy of the contour lines on the wind climate predictions is difficult to assess. Here, we generate maps with a specified accuracy by taking out points in the contour lines that are less than a certain distance ('the accuracy') from the line between the two neighbouring points in the contour line. This 'thinning out' of points is done when loading the map into the WAsP program. The remaining points are thus still accurate, but the number of points in the map decrease as points are deleted. Maps of 600, 300, 100, 50, 10 and 0 m accuracy were used as input to the wind climate predictions and the results are shown in Fig. 5.

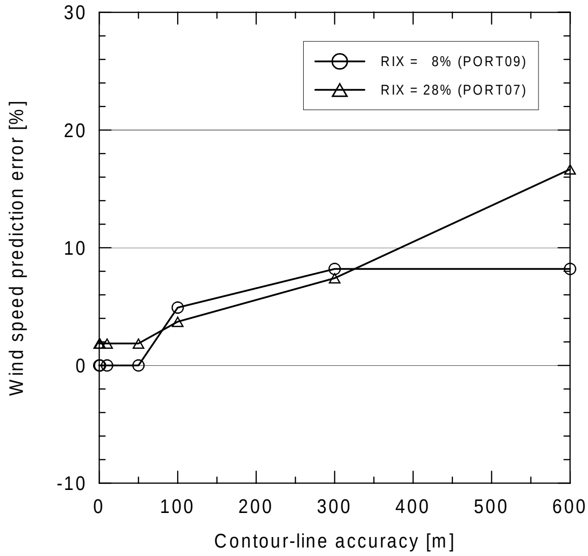

Figure 5: WAsP wind speed prediction error versus the contour-line accuracy of the orographical map pertaining to the predicted site.

The prediction errors decrease with decreasing contour line accuracy, ie more accurate and detailed contours. With an accuracy of 50 m or less the wind speed estimates for the two sites are stable and close to the measured values.

5 DIGITAL ELEVATION MODELS

A digital elevation model (DEM) consists of the spot heights of nodes in a (usually) regular grid. Digital elevation models cannot be used directly by WAsP, but must be transformed to height contour or vector maps. Several commercial programs (eg Surfer) can perform this transformation; here we have used the program `GRD2MAP`, which is included in the WAsP Utility Programs [5].

Digital elevation models of varying grid cell size are not readily available for northern Portugal, but had to be established from the original digitized height contour maps. Several regular DEM's with grid sizes of 250, 200, 150, 125, 100, 75, 50, 25 and 10 m, respectively, were calculated using the WAsP utility program `MAP2GRD` [5]. These DEM's were subsequently used to the generate contour maps with 20-m contour intervals; one map for each grid cell size. Finally, the nine maps were used as inputs in the prediction of the wind climate at the two predicted sites; the results are shown in Fig. 6.

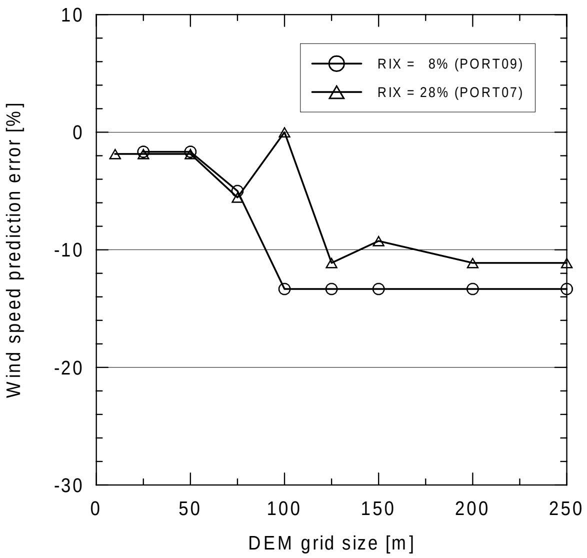

Figure 6: WAsP wind speed prediction error versus the grid size of a digital elevation model (DEM) pertaining to the predicted site.

The prediction errors are large when the maps based on grids with large grid cell sizes (>75 m) are used, and decrease with decreasing grid cell size for the finer grids (≤ 75 m). Incidentally, the error is $\approx 0\%$ for the rugged site with a grid cell size of 100 m; however, this is probably caused by the fact that coordinates of the site happens to coincide with a specific point of the 100-m grid. With a grid cell size of 50 m or less the prediction errors are identical to the errors obtained with the 20-m contour original map, see Fig. 4. A combination of a $2 \times 2\,\text{km}^2$ hand-digitized map around the site with any of the nine maps based on DEM's gives results that are as accurate as using the original digitized map.

6 CONCLUDING REMARKS

The most important factor for the accuracy of WAsP predictions in rugged and mountainous terrain is the ruggedness of the terrain, described by the ruggedness indices (RIX) of the reference and predicted sites. In general, if both indices are close to 0%, we are within the operation limits of WAsP. If one or both of the two indices is larger than 0%, prediction errors must be expected. The difference in RIX values between the two sites is a fairly coarse measure of the significance of the problem, but it may provide estimates of both the sign and approximate magnitude of the prediction error. WAsP may give accurate results outside its operation limits, provided that the difference in ruggedness indices between the reference and predicted site is small and the topographical input data are adequate and reliable.

An adequate height contour map should cover an area of at least $10 \times 10\,\text{km}^2$, with a height contour interval of less than ≈ 20 m. The extreme points of the terrain – hill tops and crests – should be specified as well. Contours may be 'thinned' to obtain a manageable map/map file. If a digital elevation model is available only, the grid size should be less than ≈ 50 m. The grid size is not critical if the terrain within 1 km of the site is digitized in detail.

ACKNOWLEDGEMENTS

The wind and topographical data reported were collected in the Joule project "Measurements and modelling in complex terrain", contract JOUR–CT90–0067.

REFERENCES

[1] Bowen, A.J. and N.G. Mortensen (1996). Exploring the limits of WAsP: the Wind Atlas Analysis and Application Program. Proceedings of the *1996 European Union Wind Energy Conference*, Göteborg, Sweden, May 20–24, 584–587.

[2] Bowen, A.J. and N.G. Mortensen (1997). WAsP prediction errors due to site orography. Risø–R–995(EN). Risø National Laboratory, Roskilde. In preparation.

[3] Mortensen, N.G., E.L. Petersen and L. Landberg (1993). Wind resources, Part II: Calculational methods. Proceedings of the *European Community Wind Energy Conference and Exhibition 1993*, Lübeck–Travemünde, March 8–12, 1993, 611–614.

[4] Mortensen, N.G., L. Landberg, I. Troen and E.L. Petersen (1993). Wind Atlas Analysis and Application Program (WAsP). Vol. 2: User's Guide. Risø–I–666(v.2)(EN). Risø National Laboratory, Roskilde. 133 p.

[5] Mortensen, N.G., L. Landberg, I. Troen and E.L. Petersen (1996). Wind Atlas Analysis and Application Program (WAsP). Vol. 3: Utility programs. Risø–I–666(v.3)(ed.2)(EN). Risø National Laboratory, Roskilde. 42 pp.

[6] Petersen, E.L., L. Landberg and N.G. Mortensen (1996). Measurements and modelling in complex terrain. Report to the Commission of the European Communities, 361 pp.

[7] Petersen, E.L., N.G. Mortensen and L. Landberg (1996). Measurements and modelling in complex terrain. Proceedings of the *1996 European Union Wind Energy Conference*, Göteborg, Sweden, May 20–24, 580–583.

[8] Rathmann, O., N.G. Mortensen, L. Landberg and A. Bowen (1996). Assessing the accuracy of WAsP in non-simple terrain. Wind Energy Conversion 1996. Proceedings of the *18th British Wind Energy Association Conference*, Exeter, England, 25–27 September 1996, 413–418.

[9] Restivo, A. (1991) Resource assessment in regions of Portugal with complex terrain. Wind energy Technology and implementation. Proc. *European Community Wind Energy Conference*, Amsterdam, Holland, 797–801.

[10] Restivo, A. and Petersen, E.L. (1993). Wind measurement and modelling in mountainous regions of Portugal. Preliminary results. Proc. *European Community Wind Energy Conference*, Lübeck–Travemünde, March 8–12, 603–606.

[11] Rodrigues, A.H. (1994). Wind resource estimations in the northern mountains of Portugal. Proc. *5th European Wind Energy Association Conference*, Thessaloniki, Greece, October 10–14, Vol. 1, 244–249.

[12] Sacré, C. (1994). Climatological analysis of wind measurements on a hill near Narbonne (France) 1991–93. EN–CLI 94.18 C, CSTB, Nantes, 10 pp.

[13] Troen, I. (1990). A high resolution spectral model for flow in complex terrain. *Ninth Symposium on Turbulence and Diffusion*, American Meteorological Society, Risø National Laboratory, Roskilde, Denmark, April 30 – May 3, 417–420.

[14] Troen, I. and E.L. Petersen (1989). *European Wind Atlas*. Risø National Laboratory, Roskilde. 656 p. ISBN 87–550–1482–8.

[15] Walmsley, J.L., Troen, I., Lalas, D.P., and Mason, P.J. (1990). Surface-layer flow in complex terrain: Comparison of models and full-scale observations. *Boundary-Layer Meteorology* **52**, 259–281.

[16] Wood, N. (1995) The onset of separation in neutral, turbulent flow over hills. *Boundary-Layer Meteorology* **76**, 137–164.