

## ASSESSING THE ACCURACY OF WASP IN NON-SIMPLE TERRAIN.

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**SYNOPSIS:** The influence of rugged terrain on the accuracy of predictions by the Wind Atlas Analysis and Application Program (WASP) is investigated using two case studies of field measurements taken over 3½ years and 1 year, respectively, in rugged terrain. Using the first case study the parameters that could cause substantial errors in a prediction are identified and discussed. In particular, the effects from extreme orography are investigated. A suitable performance indicator is developed which predicts the sign and approximate magnitude of such prediction errors. This procedure could provide a means of correcting for rugged terrain effects. The second case study is used as an independent set of data for comparison.  
**Keywords:** Resources, complex terrain, models (mathematical), siting.

### 1. INTRODUCTION

The Wind Atlas Analysis and Application Program (WASP) has been shown to give accurate climatological predictions over low, smooth hills of small to moderate dimensions with sufficiently gentle slopes to ensure attached flows, such as typically found in northern Europe. WASP has been used recently to develop the European Wind Atlas (1,2) and for wind-energy assessments in other countries. Out of necessity, WASP is increasingly used for situations that do not lie within its recommended operational envelope. In particular, the program is being used for the investigation of candidate sites in rugged, complex terrain which may also be subjected to intense solar radiation or stratified atmospheric conditions (3,4).

This paper utilises full-scale wind data from a previous field programme in the rugged hills of northern Portugal and in eastern Crete to investigate the accuracy of WASP under such extreme conditions. The goals of this work are to gain a better understanding of the causes and extent of the prediction errors, to develop a practical performance indicator which will enable users to correct for orographic effects if necessary, and to facilitate future improvements to the WASP program.

### 2. THE WASP PROGRAM

WASP is a PC program used extensively to estimate wind energy resources and is described in detail by (5). The program can generalise a long-term meteorological data

series at a (reference) site into a so-called *Wind Atlas*, referring to a fictitious plane site subject to the same meteorological forcing. The Atlas may then be used to estimate conditions at other (predicted) sites. Accurate predictions using the WASP package may be obtained provided that both the reference and predicted sites are:

- a) subject to the same weather regime,
- b) the prevailing weather conditions are close to being neutrally stable,
- c) the surrounding terrain is sufficiently gentle and smooth to ensure mostly attached flows, and
- d) the reference data are reliable.

The orographic model used by WASP is similar to the MS3DJH family of models. Briefly, a linearised set of flow equations are used in connection with a grid zooming in on the terrain closest to the site. The flow perturbation created by the terrain gradients are represented by a modified potential flow. The method is described in detail by (6). The linear model is limited to neutrally-stable wind flows over low, smooth hills with attached flows. WASP predictions over simple isolated hills compare well with the measured field data from the two bench-mark field measurements of Askervein and Blasheval (6,7).

However, when, out of necessity, it is used for steep, rugged terrain outside its application envelope, WASP typically overpredicts the terrain induced speed-up as reported in literature (4-8).

### 3. FACTORS IN THE PREDICTION PROCESS

The combined WASP Analysis and Application procedures may be considered as a transfer function model linking the wind speeds at the reference site with those at the predicted site. WASP assumes that there is a unique speed-up factor between the two sites for each wind direction sector which is determined by the roughness field and local terrain heights at both sites. This speed-up factor is assumed to be independent of climatic conditions.

A significant category of errors are those associated with the terrain surrounding both sites. Such errors are influenced by extensive flow separation, the degree of turning in each sector and the map size. These effects from orography will be discussed later in detail.

Errors in the prediction due to non-standard atmospheric conditions affecting the flow behaviour can also be very significant. Such climatic influences include; atmospheric stability, stratification, diurnal sea breezes, downslope winds, and blocking or channelling in valleys. The cross-correlation coefficient for mean wind speeds between the two sites is assumed by WASP to be unity, signifying that both sites are subject to the same weather regime. A high correlation between the reference and predicted sites is therefore an essential but not exclusive condition for an accurate prediction by the WASP model.

A longer averaging time of say, 1 hour, may be more appropriate than the 10 minute averages used here in order to allow a particular wind event to envelope physically the two sites. However, only a small improvement in the cross correlation coefficients was achieved with 1 hour mean wind speeds. Field observations also indicate that monthly, seasonal and even yearly variations significantly affect the correlation values if the record length is relatively short.

The generalised wind data of the Atlas file is created by forcing the measured data to fit a standard Weibull frequency distribution. The magnitude of any prediction error is affected by the degree of transformation applied by the Analysis procedure in order to create the Atlas file. The direction rose is typically divided into 12 equal direction sectors. Steep, oblique ridges affect the direction of the incident flow and may cause the wind direction at the predicted site to fall into an adjacent direction sector to that occurring at the reference site.

### 4. ACCUMULATION OF PREDICTION ERRORS.

The size of any error by WASP is dependent on the degree that the operational limits are violated by factors associated with the atmospheric conditions and the terrain. Consider here, only the effects from orography on the accuracy of the WASP prediction model.

Application of WASP to estimate the mean wind-speeds ( $U_{pe}$ ), at the predicted site using measured data at the reference site ( $U_m$ ) involves creation of a generalised Atlas file valid within a region defined by the extent of the wind regime at the reference site and which must include the predicted site. The Atlas file represents the distribution of wind-speeds and directions for the whole area around the

reference site with all local obstacles, surface roughness and orographic effects either removed or standardised. Both when creating the Atlas file and when generating wind estimates for the predicted site, the effects from local obstacles, roughness and orography are determined for each direction sector using 3 built-in physical models for the reference site and the predicted site, respectively.

In the Atlas generation as well as in the prediction procedure WASP relates wind speed at an actual site ( $U_{rm}$  and  $U_{pe}$ , respectively) to the Atlas value  $U_A$ . The accurate speed-up correction for orographic effects has an accompanying error ( $E_1$  and  $E_2$ ). The error will normally have a positive sign in line with the tendency for WASP to overpredict rugged sites relative to flat sites. Steep terrain promotes flow separation, particularly on the lee side of a ridge lying at an obtuse angle to the wind flow. When the flow is detached from the ground, the effective terrain is modified to something that is less rugged than the actual terrain. Linear numerical models such as WASP that assume attached flows, could therefore be expected to overpredict consistently flow speeds over rugged terrain.

The tendency for over-prediction of rugged sites should hold equally well for the Analysis and Application procedures as the Atlas file represents a fictitious reference site which is flat and featureless. Thus, in general for a site 'x' ( $x=1$  for a reference site,  $x=2$  for a predicted site) a site-value is related to the atlas value by  $U_A + (\Delta U_x + E_x) = U_x$ . The overall prediction process utilises both the Analysis and Application procedures in succession. Therefore, combining the equations for the reference and the predicted site to eliminate  $U_A$ , one obtains  $(U_{rm} - \Delta U_1 + \Delta U_2) + (E_2 - E_1) = U_{pe}$ . Here the first parenthesis on the left hand side is identified as the true value at the predicted side,  $U_{pm}$ , so that the overall prediction error ( $U_{pe} - U_{pm}$ ) is determined by the difference in the two individual WASP procedure errors, ( $E_2 - E_1$ ). The magnitudes of the individual procedure errors depend on the degree that each site contravenes the orographic limits of the WASP prediction model. Both errors as defined, share the same sign as both the reference and predicted sites are invariably more rugged than the featureless site represented by the generalised data in the Atlas file. The sign of the overall prediction error may be positive or negative (signifying over- or under-prediction) depending on the relative magnitudes of the two individual procedure errors. A certain degree of cancellation between the two procedure errors is therefore likely to occur.

The relative sizes of the two procedure errors which may be assumed to be roughly proportional to the individual site ruggedness, thus determine the accuracy and bias of the overall prediction by the WASP model.

### 5. CASE STUDIES

The wind speed data used here are taken from the Joule programme project (9,10,11,12) based in Northern Portugal over a period of 3½ years, and from the Cretan data in the European Wind Atlas Vol.2 (2), in which also the Portuguese data are used. The Portuguese region of interest lies in Northern Portugal just north of latitude 40° N on the coastal ranges of the mountains, some 50km SW of the

coastal city of Porto. Site 01 is located on the coastal plain, sites 06, 07, 08 are within 5km of each other on a ridge some 45km away to the east, while sites 09, 10 are situated on an adjacent ridge about 15km to their west. The five hill sites have similar elevations between 932 and 1082m. The terrain is mostly steep with smooth, barren hillsides leading into a number of deep valleys that run down to the coastal plain. The hill sites clearly lie outside the operational terrain limits for the WAsP program. For all sites 8x8 km contour maps with height resolution of 50 m and within the closest 1km<sup>2</sup> with resolution of at least 10 m.

The mean wind measurements were taken at 10m a.g.l. as consecutive 10 minute averages, 3s gust speeds and instantaneous wind directions. The data were collected over a period of 3½ years from July 1991 to April 1995. The measured wind-speed statistics and climatologies of the 6 sites were generated by the WAsP Analysis procedure and processed by the Utilities packages.

The prevailing winds blow persistently off the sea from the north-west. The coastal-plain site is frequently in a different wind regime to the high-level hill sites. Wind speeds are higher over the summer months at the coastal site due to the prevailing sea breezes, in contrast to the hill sites which have their peak wind speeds during the winter months. Frequent winter storms occur at the hill-top sites but with significantly weaker winds at the sea-level, coastal plain site. Only the strong wind events are reasonably well correlated between the coastal plain and hill sites.

The instantaneous speed-up ratio of the measured wind-speeds in any direction sector varies widely, especially for the coastal plain-hill site pairs. Significant variations are also evident between the summer and winter owing to the different climatic conditions prevailing during each season. Average cross-correlation coefficients at zero time lag (3m/s threshold) for various site pairs were calculated from the wind-speeds measured throughout the 3½ years of records. The resulting coefficients are not high (61-86%) for any site pair and are lowest (35-45%) for pairs involving the coastal-plain site 01.

Predictions by WAsP of the mean wind-speeds and energy densities for all site pair combinations are shown in Table 1. The errors vary in sign and are sometimes large. However, good predictions are obtained between site pairs involving combinations 06-07 and 01-09-10, including all the self-prediction cases. Some sector-wise prediction errors are also large and may exceed those for all-directions. WAsP consistently overpredicts at most hill sites when using the flat, coastal-plain site 01 as reference.

The second case study involves 5 Cretan sites, code names 43, 45, 47,48 and 49. All sites are situated in the Lasithi county in the eastern part of Crete, station 43 about 14 km NE of Ay.Nikólaus, while the others are situated about 16 km SE of Ay.Nikólaus and further on to the easternmost end of Crete. All sites are inland hill sites surrounded by complex terrain, with heights above sea level from 185 to 793 m and with distances from the sea from 3 to 8 km. The data from these sites consists of 1-year time series (April 1993 to April 1994) with records of 10 min. average wind speed and wind direction taken at 18.5 m a.g.l (site 43) and 30 m a.g.l. (remaining sites). Similar data from sites closer to the sea were available, but were

excluded because sea- and land-breezes found exclusively here would essentially mean that they are not in the same wind regime as the hill sites. The prevailing wind direction for the selected sites is northerly, from ENE to NW. The cross-correlation coefficients between the pairs of time series are, as for the Portuguese hill-hill site pairs, only medium, ranging from 63% (the 43-45 pair, about 30km apart) to 91% (the 47-48 pair about 9 km apart). For all sites 12x12km height contour maps were used, supplemented by a coast contour line of the entire eastern part of Crete, ranging from 20 km W of site 43 and eastwards. The height contour maps available for the sites 43 and 45 had only low resolution (z-resolution 200 m, with supplementary 100 m contours), while for sites 47 to 49 medium resolution maps were available: the closest 1.5 km with a z-resolution of 40 m, with supplementary 20 m and 8 m contours where necessary, and further out with 100 m z-resolution with supplementary 50 m contours. The Atlas wind speed statistics corresponding to the 5 sites were created by the WAsP analysis procedure, and all site-pair combinations were used to create predictions as reported in Table 2. The prediction errors vary in sign and are for many cases large.

## 6. PERFORMANCE INDICATORS

### 6.1 Cross correlations

The cross-correlation coefficient of mean wind-speeds at both sites is a commonly used measure of the sites' suitability for prediction techniques such as WAsP and the Measure-Correlate-Predict method (MCP). A high level of cross-correlation in wind speeds will ensure that both sites lie within the same weather regime but does not ensure neutral stability. However, for sites which lie within the WAsP performance envelope for both terrain and atmospheric stability, a high correlation is the only essential pre-requisite for an accurate prediction.

As indicated by Fig. 1 there is no apparent relationship between the size of the prediction error and the cross-correlation coefficient for any of the Portuguese site pairs considered here. Furthermore, the cross-correlation coefficient is unable to indicate the sign of the prediction error. It can only be assumed that these large prediction errors are due to the fundamental limitations of the orographic model and to a lesser extent, the prevailing atmospheric conditions. It may be concluded that a high level of cross-correlation is not by itself, always a good indication of the potential for WAsP to make an accurate prediction. An additional orographic indicator is also needed for sites situated in rugged terrain.

### 6.2 Orographic indicator

A practical site parameter is therefore required which quantifies the extent to which the terrain at a particular site exceeds the limits implied in the derivation of the orographic model. Such a parameter should be a measure of site ruggedness and if possible, be derived directly from the site height contour data. The ability to predict whether or not the flow will separate is fundamental to the estimation of the performance of the orographic model and other linear numerical models, which assume the presence of

attached flows. As discussed in section 4, the possible high-ruggedness error in the atlas generation procedure from a meteorological station on the one hand, and in the site prediction procedure on the other hand, will have negative and positive effects, respectively, on the total prediction procedure. In search for a performance indicator only differences in terrain properties between the two sites should therefore be considered.

The difference in relative relief (relative relief = difference between highest and lowest level within a 10-by-10 km area) was tested as a candidate for a performance indicator but with no success.

Instead, the fraction of the surrounding terrain which is over a critical slope of say, 0.3 was proposed as a *ruggedness index I* to provide a coarse measure of the extent of flow separation (12), and consequently the natural choice for an orographic performance indicator to predict the overall error ( $E_2 - E_1$ ) is the difference in the ruggedness-indices between the predicted and reference sites. This hypothesis was tested using the set of data from the Portuguese stations. The steep-terrain fractions for sites considered here were estimated using a calculational procedure which considers the slopes along the centre radius of each of the 12 sectors across each cell in a 250m rectangular grid within 4 km from the stations.

The resulting orographic performance indicator ( $\Delta I = I_2 - I_1$ ) provided encouraging results when plotted against the percentage WAsP prediction error (E) as shown in Fig. 2. The success of the indicator to correlate the prediction error was tested to be insensitive to variations in the details of the method used for estimating its magnitude, including changing the grid size. In view of the approximate nature of the analysis, the above analysis can be used to propose a linear relationship between the percentage prediction error and the orographic performance indicator based on the well correlated hill-hill site pairs (solid circles). Using trend lines through the origin one gets  $E = 3.3 \cdot \Delta I$  for  $I > 0$ , and  $E = 2.3 \cdot \Delta I$  for  $I < 0$ . However, the data might also be interpreted to suggest a vanishing error ( $|E| \leq 5\%$ ) for  $-3 < \Delta I < 3$ , and off-origo trend lines:  $E = 4.2 \cdot (\Delta I - 3)$  for  $\Delta I > 3$ , and  $3.2 \cdot (\Delta I + 3)$  for  $\Delta I < -3$ . Both interpretations are indicated in Fig. 2. Independent of the detailed interpretation the systematic trend confirms the strong influence of flow separation on the orographic prediction error.

In the Portuguese data set those data points involving the flat coastal-plain site 01 (open squares) are marginalised due to their low correlation caused by the prevailing atmospheric stability. It is proposed that the magnitude of the prediction error for a certain value of the orographic indicator is affected further by the prevailing atmospheric conditions between each site pair. Prevailing stable conditions such as might occur between the coastal plain and hill sites, would reduce the error by a significant amount. Unstable conditions are likely to increase the error by a relatively small amount. These climatic effects would be less prevalent for the hill-hill site pairs which share the same approximate location and elevation. The details of this analysis and the ideas behind them are reported in more detail in (13).

As an independent test of the orographic performance indicator to correlate the prediction error as proposed

above, the same procedure was applied to the wind data sets from the five Cretan hill sites. Although, in most cases, only low-resolution height contour maps were available for the sites, it was thought that these data might give an indication of the applicability of the orographic performance indicator in general. The ruggedness indices were determined as for the Portuguese sites, but using a 100m x 12sectors polar grid. The results are shown in Fig. 3.

Although containing a lot of scatter, for which especially the sites with low-resolution maps are responsible, there seems to be a weak indication of large wind speed overprediction in case of performance indicators larger than 3. However, the overpredictions are much higher than expected from the tendency lines derived from the Portuguese wind data. The site pairs involving only sites with medium resolution maps have performance indicators within or close to the proposed "orographic range for accurate prediction", with prediction errors, which are limited, but clearly larger (up to 20%) than for the Portuguese wind data set (5%). The large scatter in the Cretan results is probably due to the low-resolution height contour maps available, both due to uncertain estimates of performance indicators and due to uncertain overall WAsP prediction processes. The present Cretan results are clearly too uncertain to allow a comparison with the tendency lines for  $|\Delta I| > 3$ . In order to be really useful for an independent evaluation of the orographic performance indicator to correlate the prediction error of WAsP as proposed by the Portuguese data, the Cretan wind data - or similar sets of wind data from complex terrain - must be supplemented with height contour maps of an extension and a resolution matching those from the Portuguese sites.

Provided the performance indicator shows out to hold more generally, most areas in UK, falling between the gentle terrain of Northern Europe and the more complex and rugged terrain of Southern Europe, should be well suited for application with WAsP in combination with the proposed high-ruggedness correlation method.

## 7. VERTICAL WIND SPEED PROFILES

In a recent study of the wind climate at a site in the Mediterranean region, wind data from a 40m mast in very rugged terrain (ruggedness index = 16%, using the evaluation procedure described in the preceding section) was analysed. As this is outside its application envelope, one might suspect WAsP to misrepresent the vertical wind speed profile for this site. However, as indicated by Table 3, the modelled profile is close to reality, as both the mean wind speed and the wind energy at 40m height is predicted very accurate by measurements in the three lower measuring heights of the mast.

## 8. CONCLUSIONS

WAsP prediction errors may be significant if the local climate or terrain lie outside its normal operational envelope. A high level of cross-correlation between wind speeds at the reference and predicted sites is essential in

assuring the two being within the same weather regime, but it is certainly not an exclusive pre-requisite for an accurate prediction. The value of the correlation does not indicate the sign or magnitude of the prediction error.

The sign and approximate magnitude of the prediction error due to orography is proportional to the difference in ruggedness between the predicted and reference sites. An approximate estimate of this error may therefore be made with a performance indicator based on site ruggedness. One suitable indicator developed here is the difference in the fractional extent of the terrain with slopes greater than a critical value between the predicted and reference sites. This indicator also provides a means of defining in quantitative terms, the orographic limits for accurate WASP predictions and a suitable correction if those limits are exceeded.

A test case with wind data from a number of Cretan sites indicated the same general trend, but could not, due to insufficient resolution of the available height contour maps, be used as an independent test of the performance indicator correlation method.

Further test cases, supplied with height contour maps with resolutions at least as those of the Portuguese site maps, are needed before the reliability of the indicator can be confirmed and the method can be used for correcting for the effects of rugged terrain.

However, contrary to the aforementioned error in wind speed prediction for a certain height in rugged terrain, the vertical wind speed profile is modelled closely to reality by WASP, as indicated by recent data from the Mediterranean area.

## 8. ACKNOWLEDGEMENTS

A major part of this work was performed by A.Bowen while working as a guest scientist at Risø National Laboratory August 1995- June 1996. The opportunities and financial assistance afforded by the Risø National Laboratory and the University of Canterbury made this project possible and both are gratefully acknowledged.

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**Table 1:** Score tables for WASP predictions of Portuguese site wind-speed and wind energy density from 3½ years of data.

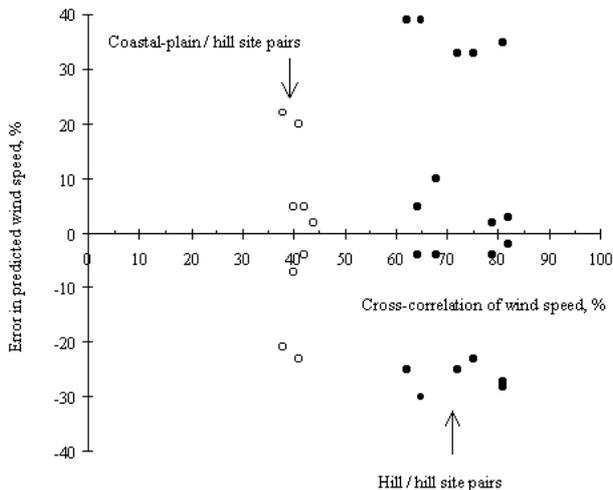
Pred. sites	Ref. sites	01	06	07	08	09	10	Measured
01	U m/s	4.2	3.4	3.3	4.4	4.5	4.5	4.3
	E W/m <sup>2</sup>	112	52	53	129	136	126	120
06	U m/s	5.6	4.6	4.4	6.1	6.1	6.4	4.6
	E W/m <sup>2</sup>	254	137	135	355	333	366	134
07	U m/s	6.5	5.5	5.3	7.3	7.3	7.5	5.4
	E W/m <sup>2</sup>	387	230	217	627	572	596	214
08	U m/s	6.3	4.8	4.5	6.2	6.4	6.8	6.2
	E W/m <sup>2</sup>	457	176	181	329	387	467	325
09	U m/s	5.7	4.6	4.4	6.0	6.1	6.4	6.1
	E W/m <sup>2</sup>	293	137	144	325	326	380	324
10	U m/s	5.5	4.3	4	5.5	5.5	5.6	5.7
	E W/m <sup>2</sup>	256	111	90	236	232	227	225

**Table 2:** Score tables for WAsP predictions of Cretan site wind-speed and wind energy density from 1 year of data.

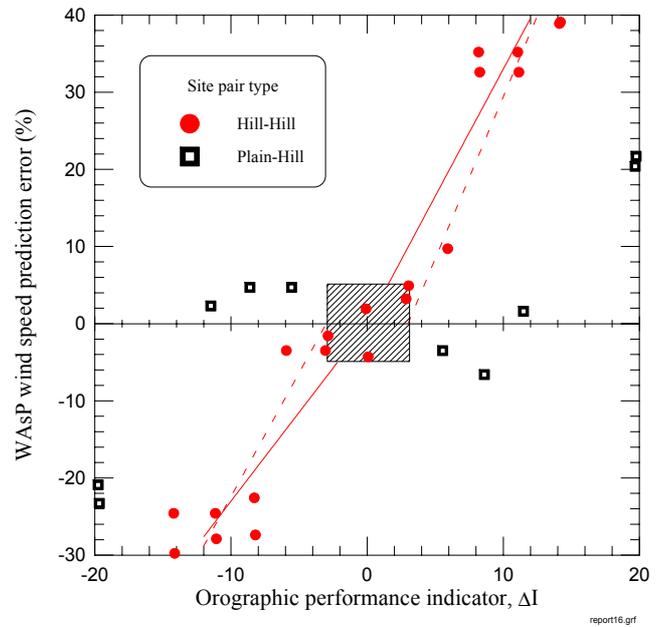
Pred. sites	Ref. Sites	43	45	47	48	49	Measured
43	U m/s	7.9	13.7	10.9	11.9	9.6	7.8
	E W/m <sup>2</sup>	708	3444	1925	2144	1233	714
45	U m/s	3.0	7.4	5.4	5.3	4.3	7.3
	E W/m <sup>2</sup>	51	505	252	220	137	494
47	U m/s	7.2	10.3	8.5	9.5	7.5	8.5
	E W/m <sup>2</sup>	548	1816	854	1045	569	865
48	U m/s	7.6	10.8	8.9	9.7	7.5	9.6
	E W/m <sup>2</sup>	627	2184	965	1075	585	1062
49	U m/s	7.6	9.4	8.3	10.0	7.9	7.9
	E W/m <sup>2</sup>	605	1455	836	1249	622	632

**Table 3:** Wind climate at 40m height at a very rugged (16%) Mediterranean site as estimated from measurements in the same and three lower heights. The Weibull parameter A, the mean wind speed U energy E are normalised by the measured value (index  $m_{40}$ ), while the Weibull k-parameter is given directly. The measured mean wind speed  $U_{m40}$  is about 10 m/s.

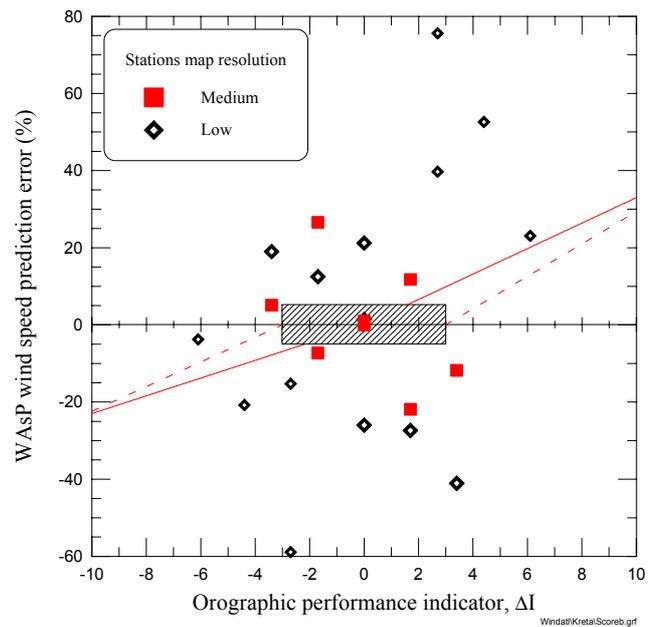
	z [m]	A/A <sub>m40</sub>	k	U/U <sub>m40</sub>	E/E <sub>m40</sub>
Predictor	10	1.02	3.28	1.08	1.09
	20	0.99	3.07	1.04	1.03
	30	1.01	3.06	1.05	1.08
	40	0.99	3.11	1.03	1.01
Measured	40	1.00	3.38	1.00	1.00



**Fig. 1:** Predicted wind speed error vs. the average annual cross-correlation coefficients (10-minute-mean wind speed) for the Portuguese sites.



**Figure 2:** Plot of the WAsP prediction error E and the proposed orographic performance indicator  $\Delta I = I_2 - I_1$  for the Portuguese site pairs. An “Orographic range for accurate prediction” and tendency lines for the correlation between  $\Delta I$  and E are indicated.



**Fig. 3:** Plot of the WAsP prediction error E and the proposed orographic performance indicator  $\Delta I = I_2 - I_1$  for the Cretan site pairs. The “Orographic range for accurate prediction” and tendency lines for the correlation between  $\Delta I$  and E proposed by the Portuguese data are shown.