

## EXPLORING THE LIMITS OF WASP THE WIND ATLAS ANALYSIS AND APPLICATION PROGRAM

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**ABSTRACT:** The influence of rugged terrain on the accuracy of predictions by the Wind Atlas Analysis and Application Program (WASP) is investigated using a case study of field measurements taken over 3½ years in rugged terrain. 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 allows the user to assess the consequences of using WASP outside its operating envelope and could provide a means of correcting for rugged terrain effects.

**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. 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 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 which 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 and 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].

### 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 often 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 therefore 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.

When applied to estimate the mean wind-speeds ( $U_{pe}$ ), at the predicted site using measured data at the reference site ( $U_{rm}$ ), WAsP first creates a generalised Atlas file by means of its Analysis procedure. 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. The effects from local obstacles, roughness and orography are determined for each direction sector using 3 built-in physical models. The Atlas file is assumed to be universal within a region defined by the extent of the wind regime at the reference site. The predicted site is assumed to lie in the same regime so that the same Atlas file may then be used to predict its conditions. The Atlas file generated from measured data at the reference site is then used to estimate the wind-speeds and energy at the predicted site, taking into account the local obstacles, surface roughness and orographic effects at the predicted site, using the WAsP Application procedure.

Consider first the WAsP Application procedure applied using generalised wind-speed data from the Atlas file ( $U_A$ ) to estimate the sector-wise wind-speeds at a particular (predicted) site ( $U_{pe}$ ). The accurate speed-up correction for orographic effects has an accompanying error ( $E_2$ ). The error will normally have a positive sign in line with the tendency for WAsP to overpredict rugged sites when using a flat reference site. 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. Supporting evidence for the over-prediction of sites in rugged terrain is available in the literature [4,8].

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, for the Application procedure,

$$U_A + (\Delta U_2 + E_2) = U_{pe}$$

Conversely, when (previously) analysing the reference site measured data ( $U_{rm}$ ) to create the corrected speed in the Atlas file ( $U_A$ ), a further accurate speed-up correction ( $\Delta U_1$ ) with its associated error ( $E_1$ ) is involved. This Analysis procedure involves the orographic model in the opposite sense such that,

$$U_{rm} - (\Delta U_1 + E_1) = U_A$$

The overall prediction process utilises both the Analysis and Application procedures in succession. Therefore, combining both equations to eliminate  $U_A$ ,

$$(U_{rm} - \Delta U_1 + \Delta U_2) + (E_2 - E_1) = U_{pe}$$

The estimated speed at the predicted site ( $U_{pe}$ ) is made up of the correct (measured) speed ( $U_{pm}$ ) and the overall prediction error which has accumulated from the two stages of the prediction process. The measured speed at the predicted site is assumed to involve no errors and is,

$$U_{pm} = U_{rm} - \Delta U_1 + \Delta U_2$$

The overall prediction error ( $U_{pe} - U_{pm}$ ) is therefore 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 STUDY

The wind speed data used here are taken from the Joule programme project [9,10,11] based in Northern Portugal over a period of 3½ years. The results are also used in the European Wind Atlas Vol.2 [2]. The 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.

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.

**Table 1:** Score tables for WAsP predictions of 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	4.3	4.5	4.5	4.3
	E W/m <sup>2</sup>	112	52	53	122	136	126	120
06	U m/s	5.6	4.6	4.4	6	6.1	6.4	4.6
	E W/m <sup>2</sup>	254	137	135	358	333	366	134
07	U m/s	6.5	5.5	5.3	7.2	7.3	7.5	5.4
	E W/m <sup>2</sup>	387	230	217	615	572	596	214
08	U m/s	6.9	5.2	4.7	6.2	6.7	7	6.2
	E W/m <sup>2</sup>	604	214	196	331	440	514	325
09	U m/s	5.7	4.6	4.4	6	6.1	6.4	6.1
	E W/m <sup>2</sup>	293	137	144	341	326	380	324
10	U m/s	5.5	4.3	4	5.1	5.5	5.6	5.7
	E W/m <sup>2</sup>	256	111	90	194	232	227	225

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.

## 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

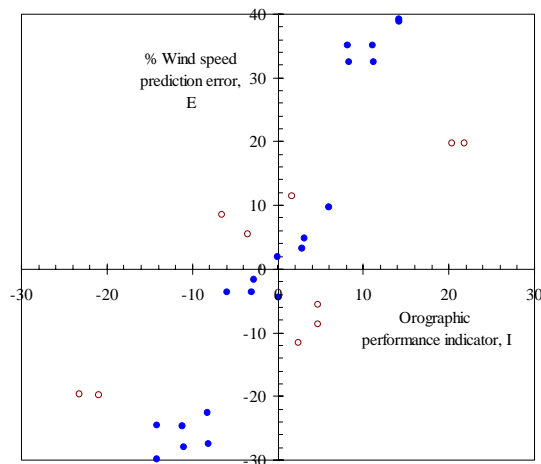
WAsP performance envelope for both terrain and atmospheric stability, a high correlation is the only essential pre-requisite for an accurate prediction.

There is no apparent relationship between the size of the prediction error and the cross-correlation coefficient for any of the 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 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. The fraction of the surrounding terrain which is over a critical slope of say, 0.3 is therefore proposed as a coarse measure of the extent of flow separation [12].

An orographic performance indicator to predict the overall error ( $E_2 - E_1$ ) can now be defined as the difference in these percentage fractions of steep terrain between the predicted and reference sites. The steep-terrain fractions for sites considered here were estimated using a sub-routine which considers the slopes along the centre radius of each of the 12 sectors across each cell in a 250m rectangular grid. The resulting orographic performance indicator (I) provides encouraging results when it is plotted against the percentage WAsP prediction error (E) in Fig. 1. The success of the indicator is insensitive to detailed variations in the method used for estimating its magnitude. In view of the approximate nature of the analysis, a linear relationship between the percentage prediction error and the orographic performance indicator can be made through the origin for the well correlated hill-hill site pairs (solid circles) eg;  $E = k \cdot I$ , where  $k=3.3$  for  $I>0$  and  $k=2.3$  for  $I<0$ . The systematic trend confirms the strong influence of flow separation in determining the orographic prediction error.



**Figure 1:** Plot of the WAsP prediction error and the proposed orographic performance indicator. Solid circles are hill-hill site pairs. Open circles are plain-hill site pairs.

Those data points involving the flat coastal-plain site 01 (open circles) 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.

## 7. 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 an essential but not 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. However further test cases are needed before the reliability of the indicator can be confirmed. The ideas described in this paper are reported in more detail in [13].

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