WIND PREDICTION DEVIATIONS IN COMPLEX TERRAIN

Paulo Pinto[1], Ricardo Guedes[2], Miguel Ferreira[2,3], Álvaro Rodrigues[4,5]

[1] IPB – Instituto Politécnico de Bragança
Quinta de Santa Apolónia, Apartado 134 5300 Bragança - PORTUGAL
phone +351 273 303 154 email: pp@ipb.pt

[2] MEGAJOULE – Consultoria em Energias Renováveis
Rua Eng. Frederico Ulrich, 2650 4470-605 Moreira da Maia - PORTUGAL
phone +351 220 915 480 email: megajoule@megajoule.pt

[3] UMP – Universidade Moderna do Porto
Rua Augusto Rosa, 24 4000-098 Porto - PORTUGAL
phone +351 222 073 230 email: mvferreira@netcabo.pt

[4] INEGI – Instituto de Engenharia Mecânica e Gestão Industrial
Rua do Barroco, 174 4465-591 Leça do Balio - PORTUGAL
phone +351 229 578 716 email: ahr@inegi.up.pt

[5] FEUP – Faculdade de Engenharia da Universidade do Porto
Rua Dr. Roberto Frias 4200-465 Porto - PORTUGAL
phone +351 225 081 763 email: hrodrig@fe.up.pt

ABSTRACT: The Portuguese experience in wind farm development has been mainly focused on mountainous regions. The installed capacity of about 450 MW and the more than 300 measuring stations, planned specifically for wind resource assessment, allowed a solid experience in all aspects involved in this kind of projects.

The evaluation of the wind regime follows consolidated procedures whose knowledge is already generalised in wind energy field. These studies make use of local measurement of wind characteristics followed by calculations using simplified micro-climatology models. The quality of the predictions is obviously dependent on the accuracy and representativity of local measurement but also on the model's liability. Both factors can be strongly affected by singularities being the terrain complexity, in general, the main factor. Wind measurements in complex terrain are often representative of only small areas and predictions face typical, but sometimes severe, deviations.

The problems associated with wind predictions with WA^{S}P models in complex terrain were already the target of several studies in the last decade. The Risoe National Laboratory attempted to characterise terrain complexity by its parameterisation (through the Ruggedness Index, RIX) and pointed reference values for the deviations induced in flow simulation, but results were somewhat inconclusive and did not present a practical method. On the other hand, the use of specific interpolation techniques in regular climatology is a common practice and several approaches are known, although its use in wind resource assessment is not often explored.

The present work suggests and tests a simple combined procedure to adjust wind speed predictions, obtained from WA^{S}P models, by use of the ruggedness concept, at first, and following the interpolation of predictions from different local measurements. The procedure was tested with several sample cases, in moderately to extremely complex terrain, for which more than one measurement points were available.

Results are conclusive for the tested sites. The adjustment method proposed results in relevant improvements on predictions in the majority of the cases, and the prediction error reduction is in average 38 %. Although the extrapolation of these conclusions for other cases must be made with care, they are a good indicator of the merit of this approach and of how it can permit to decrease the uncertainty of resource assessment in places were few measurements sites are available. In future, results can be further verified with the analysis of more sample cases.

Keywords: Complex terrain, ruggedness index, cross predictions, spatial interpolation

1 Introduction

The atmospheric flow behaviour is of complex nature and its simulation is bound with uncertainty. The irregularity of the terrain surface and the atmospheric instability are factors that push numerical models, and wind energy meteorology, to their limits. The fame of linear models like WA^{S}P are unmatched due to their simple use and fast results. This family of models neglects the surface layer instability, and the terrain shape is one of the major sources of uncertainty.

Particular changes in the atmospheric flow may be caused by steep slopes and rocky eruptions, among other aspects. Phenomena like flow separation, stratification and unsteadiness are not easily measured by regular equipment and linear models are not able to reproduce them. The sources of flow complexity, in cases were orography is dominant, can occur over small distances resulting in a huge variability of the wind resource over a given area.

While the installation of as many measurement sites as necessary to assess the wind regime over the area would be unfeasible, the modelling of the wind regime is also difficult. Generally, the compromise solution is to install meteorological stations spread over the area and, afterwards, modelling the wind regime using a combination of the results.

The work developed used simple techniques for adjustment of wind speed predictions, taking into account basic aspects of resource assessment in complex terrain: the terrain's complexity or ruggedness and the combination of results from different predictors. The methods are already presented in literature but this work intends to confirm their usefulness in wind resource assessment, more specifically when made throw WA^{S}P calculations.

The methodologies were tested in four sample cases, from moderately to extremely complex terrain. Results of the analysis are presented and seem to be conclusive, within the limits of the representativity of the cases studied.

2 Methodology

In WA^{S}P case, the deviations of simulation results seem to follow a typical behaviour when compared with a relation between the ruggedness of predictor and predicted sites. This relation is well illustrated by the ruggedness index of the terrain, RIX, as proposed by Risoe National Laboratory, or by the ΔRIX, (difference between RIX from predictor and predicted sites).

The RIX coefficient is described as the percentage of the terrain around a given site that is more complex than a reference terrain in which the slope is critical, in a way that it induces the flow separation (typically a 30 % slope). This index is a measure of the wind flow separation and, because of that, of the extension in which the terrain violates the requirements of prediction linear models, as the ones used by WA^{S}P. If RIX is close to zero the terrain is clearly inside the WA^{S}P limits utilization, while big differences from zero can lead to significant errors. The WA^{S}P envelope is usually associated with the RIX bellow 20 to 30 %. The relationship between ΔRIX and the percentage prediction error of the previsions was already referred in other works and can be illustrated by figure 1 [1]. The wind speed data used was taken from meteorological stations sited in mountainous terrain in Northern Portugal over a period of tree and half years, whose data are part of the European Wind Atlas project [2].

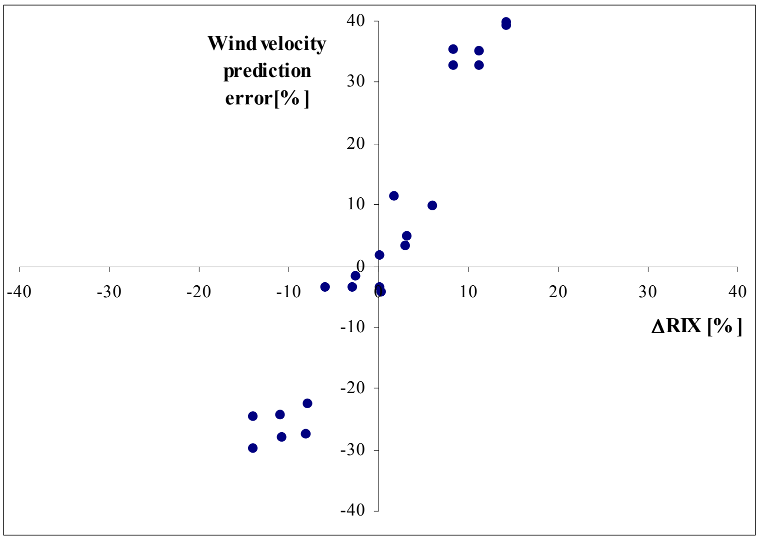

Figure 1 – WA^{S}P prediction error *versus* orographic performance indicator, ΔRIX [1]

The conclusions point to the existence of an almost linear correlation, which could prove that the prediction error is proportional to the predicted site "additional" ruggedness, when compared to the predictor one. In other words, despite of the terrain complexity, if the RIX coefficients of two sites are similar, WA^{S}P should in fact give good results. More explanation about this effect and its fundaments can be found in other works [1, 3].

If the proportional character of the relation between ΔRIX and wind speed prediction error can be assumed, then the absolute value of WA^{S}P estimations can be adjusted in a simple manner. The linear regression on the points in figure 1 could give a *ΔRIX-calibration* transfer function relating WA^{S}P adjusted and non-adjusted predictions.

Significant improvements in the assessment of a site's wind resource can be achieved when several local measurements are considered. Results of each predictor site only need to be combined in order to allow a single, more accurate, final result. The use of interpolation schemes for meteorological fields has been extensively discussed and several techniques are available. The technique used in this work, is the gravity method [4]. This method weights, for a predicted site, the estimations from each predictor with the distance between the two sites. This is a classic approach many times used in wind energy assessment.

$$V_i = \frac{\sum_{K=1}^{n} \left(V_{ki} \frac{1}{d_{ki}^{2}} \right)}{\sum_{K=1}^{n} \left(\frac{1}{d_{ki}^{2}} \right)} \qquad (3)$$

Where V_i is the interpolated wind velocity for site *i,* V_{ki} is the preliminary wind velocity estimation for site *i* according to predictor site *k* and d_{Ki} the distance between predicted site *i* and predictor site *k*.

These two techniques, *ΔRIX-calibration* and *gravity method interpolation*, can be used in combination to adjust wind speed estimations. That is to say, when more than one predictor site can be used, results can be firstly adjusted with *ΔRIX-calibration* and next *interpolated*. For simplicity, this modification on WA^{S}P estimations is herein called *adjustment*.

3 Sample cases

The *adjustment* methodology was tested with four real cases. All areas are located in mountainous regions, three of them in Portugal's mainland and one in Madeira island. Figure 2 shows its approximate locations.

The Meadas (2 met stations), Coelheira (4 met stations) and Montemuro (3 met stations) sites are all located in northern Portugal, just south of Douro river, at latitudes of around 41º North. All areas are along mountain tops in typical complex terrain. Altitudes above sea level are between 1000 and 1400 m and the distance to Atlantic Ocean is less than 100 km. Annual average temperatures are within 10-12 º C. All areas are typically served by the Atlantic climate regime, with prevailing Northwest winds and higher intensities during winter season, and marked diurnal cycles.

Madeira island is situated around 700 km west from the mainland at a latitude of 32 º North, in the Atlantic ocean. The Paúl da Serra site (3 met stations) is located in the top of an extremely rugged mountain. It lays only about 20 km from the sea coast at altitudes of near 1500 m above sea level. The climate here is distinct from the continental sites. At a regional level, the synoptically cycles are more important, opposed to the diurnal ones, related to the fluctuations on the Azores anticyclone, and there is no marked prevailing wind direction.

Together, all sites include 12 meteorological stations and at least one year of simultaneous wind data for each site. All measurement were conducted in the scope of wind resource assessment campaigns, for local wind farm projects. All wind data was validated and a good representativity is to be expected.

The following tables, 1 through 4, present the cross relations between meteorological stations in each area under study. Predictions of wind speed were made using the WA^{S}P models and refer to average values for periods of at least one year.

A total of 26 cross predictions were made. When compared with measurements, results show deviations between -28.6 % and 20.6 % (positive deviations meaning under-prediction and negative deviations meaning over-prediction). In average, the absolute errors in cross predictions are of 9.1 %.

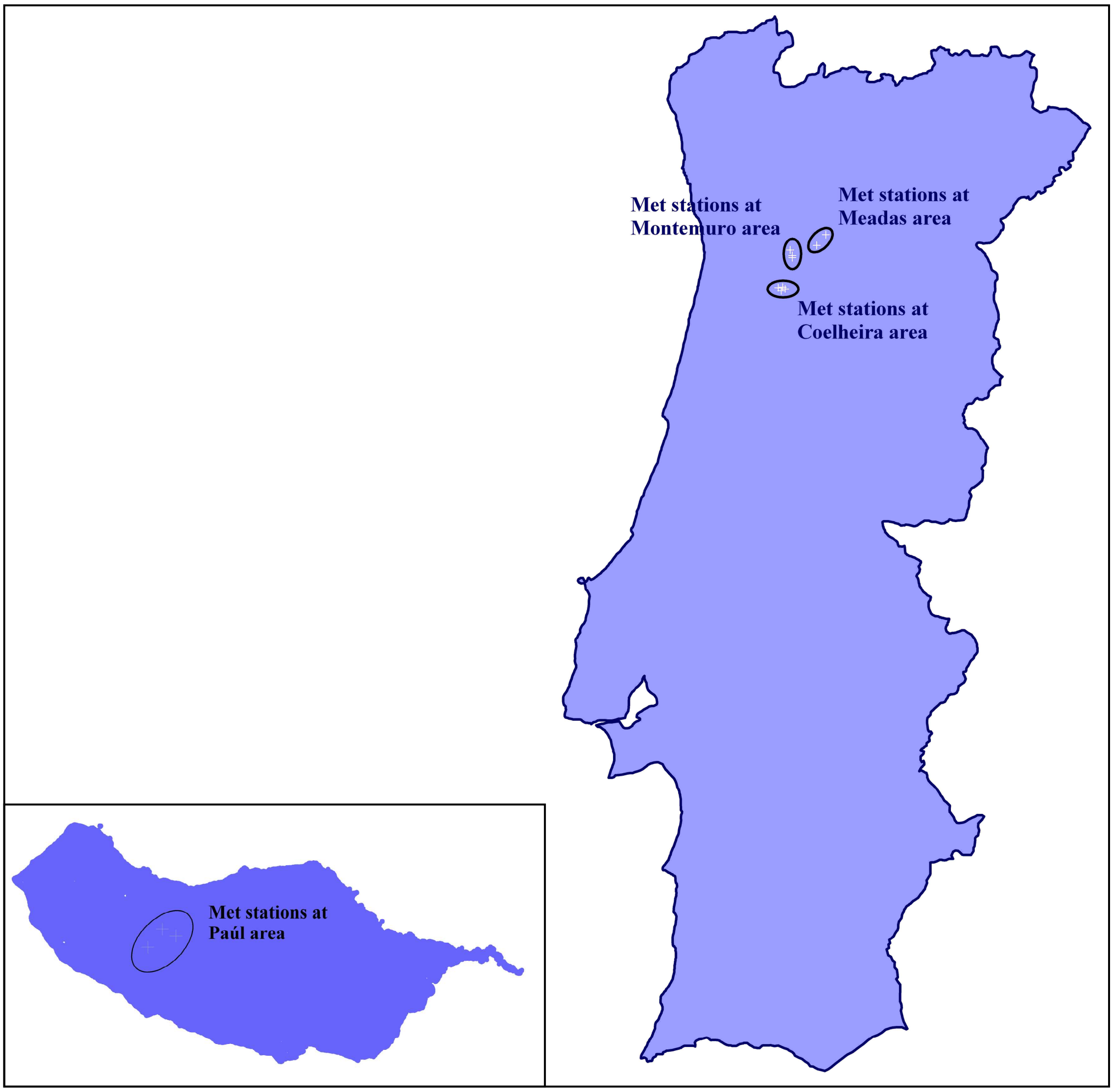

Figure 2 – Studied areas approximate location

Table 1 – Cross relations between met stations in Coelheira site.

Stations	Measured wind velocity [m/s]	Distances [m]				ΔRIX [%]				Wind velocity predictions [m/s]			
		20	100	101	102	20	100	101	102	20	100	101	102
20	**7.7**		1694	2269	2554		-6	-13	-4		8.0	8.8	8.3
100	**7.1**	1694		2431	3922	6		-7	2	7.1		8.3	7.5
101	**7.6**	2269	2431		2415	13	7		9	6.8	7.0		7.2
102	**7.7**	2554	3922	2415		4	-2	-9		7.7	7.8	9.0	

Table 2 – Cross relations between met stations in Montemuro site.

Stations	Measured wind velocity [m/s]	Distances [m]			ΔRIX [%]			Wind velocity predictions [m/s]		
		185	183	120	185	183	120	185	183	120
185	**6.5**		3320	4300		6	6		6.2	6.0
183	**7.3**	3320		1135	-6		0	8.0		7.2
120	**7.2**	4300	1135		-6	0		8.0	7.5	

Table 3 – Cross relations between met stations in Paúl da Serra site.

Stations	Measured wind velocity [m/s]	Distances [m]			ΔRIX [%]			Wind velocity predictions [m/s]		
		P1	P2	P3	P1	P2	P3	P1	P2	P3
P1	**6.3**		3396	1720		-2	-6		6.7	8.1
P2	**6.1**	3396		2615	2		-4	5.7		6.9
P3	**6.8**	1720	2615		6	4		5.4	5.8	

Table 4 – Cross relations between met stations in Meadas site.

Stations	Measured wind velocity [m/s]	Distances [m]		ΔRIX [%]		Wind velocity predictions [m/s]	
		18	21	18	21	18	21
18	**7.3**		3396		-8		7.3
21	**7.2**	3396		8		7.2	

The relation found between prediction errors and differential ruggedness is shown in figure 3 together with the best fit regression on the plotted values. The regression is similar to that found in previous works by Risoe (see figure 1).

The "transfer function" derived from the linear regression, here called *ΔRIX-calibration*, will be used to adjust the presented cross predictions [1].

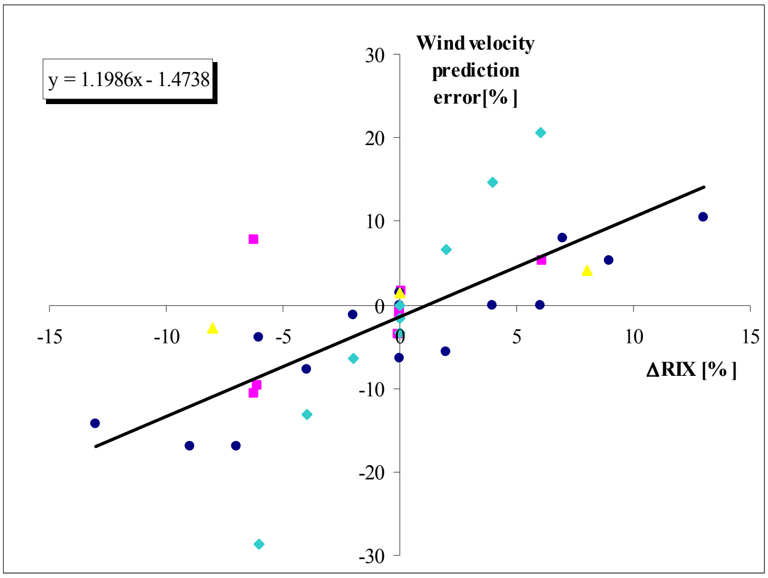

Figure 3 – WA^{s}P prediction error *versus* orographic performance indicator, ΔRIX, for the sample cases.

The application of the gravity interpolation method on the cross predictions is based on the set of weights presented in table 5 through 8. The weighting applies for each predictor and the set of weights varies according to the predicted site. Note that for the Meadas case only 2 meteorological stations are considered, thus no interpolation method can be applied on the cross predictions, since for each prediction only one predictor site is available.

[1] - To be precise and maintain the analysis completely independent, one *ΔRIX-calibration* function would have to be found for each of the four cases. In each case the pairs *Prediction Error vs ΔRIX*, derived from that same case, would have to be excluded from the fitting process, and another *ΔRIX-calibration* function would be found. Differences found between the linear regressions, and therefore in the overall final results and conclusions, were, however, very small and, for simplicity in analysis and presentation, a single *ΔRIX-calibration* is used - the one shown in figure 3.

Table 5 – Weighting for gravity method in Coelheira site

Stations	Weighting			
	20	**100**	**101**	**102**
20		59.8%	36.3%	39.3%
100	50.1%		31.6%	16.7%
101	27.9%	29.0%		44.0%
102	22.0%	11.2%	32.1%	

Table 6 – Weighting for gravity method in Montemuro site.

Stations	Weighting		
	185	**183**	**120**
185		10.5%	6.5%
183	62.7%		93.5%
120	37.3%	89.5%	

Table 7 – Weighting for gravity method in Paúl da Serra site.

Stations	Weighting		
	P1	**P2**	**P3**
P1		37.2%	69.8%
P2	20.4%		30.2%
P3	79.6%	62.8%	

4 Wind speed adjustment

Three different processes were tried for adjusting the cross predictions already presented: using the *ΔRIX-calibration* function on the cross predictions (one *calibrated* prediction for each predictor site), applying the gravity method interpolation (one *interpolated* prediction for all predictor sites) on the cross predictions, and, finally, interpolating the *ΔRIX-calibrated* cross predictions.

The following graphics, figures 4 to 7, present the results of the three forms of adjustment in terms of the wind velocity predictions, compared with the real value of the predicted site from the meteorological stations at Coelheira site. The percent error from each prediction is also shown. In order to avoid an exhaustive presentation, the results for the other areas are condensed on table 8.

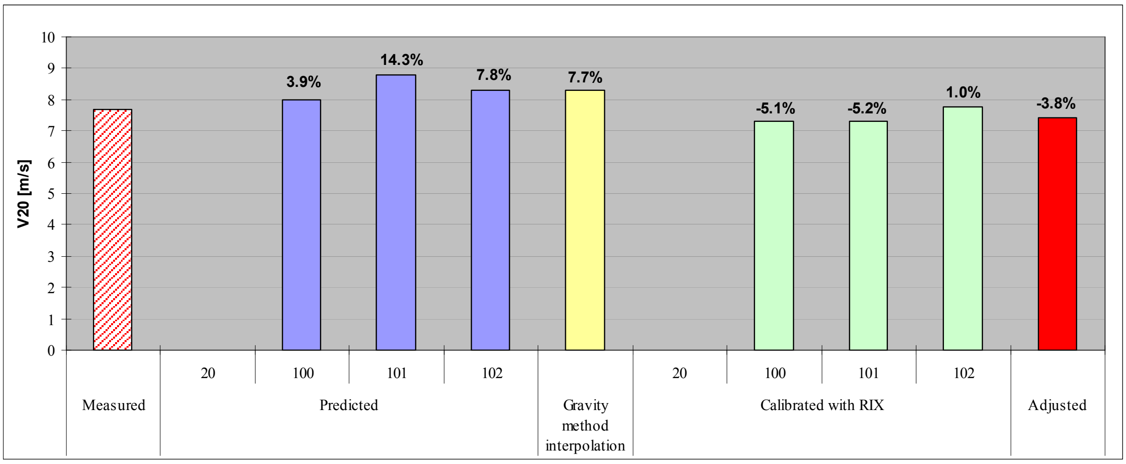

Figure 4 – Predictions for met. station 20 at Coelheira site

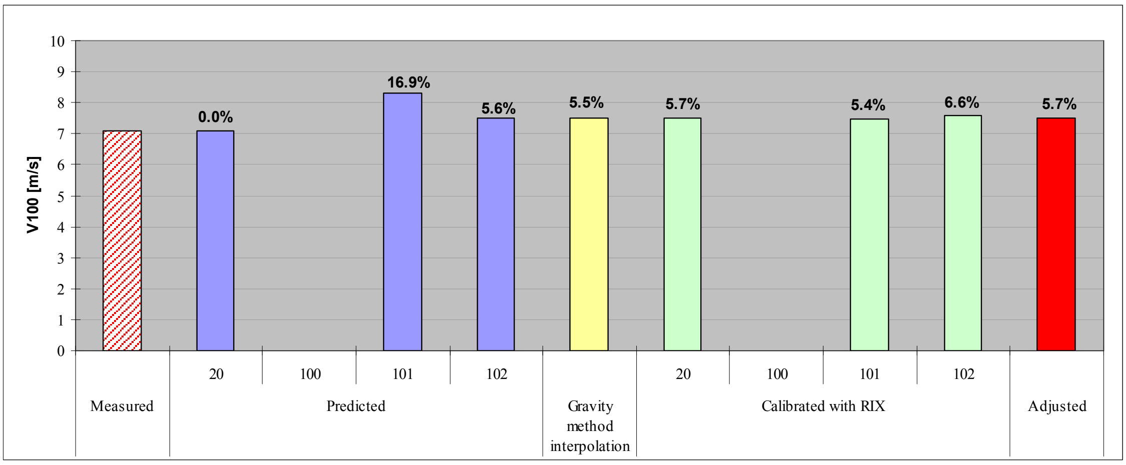

Figure 5 – Predictions for met. station 100 at Coelheira site

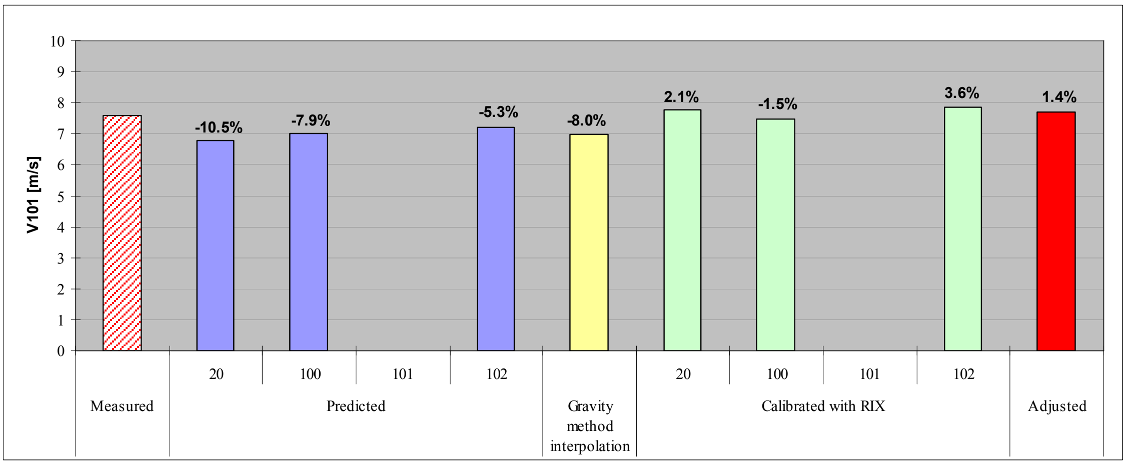

Figure 6 – Predictions for met. station 101 at Coelheira site

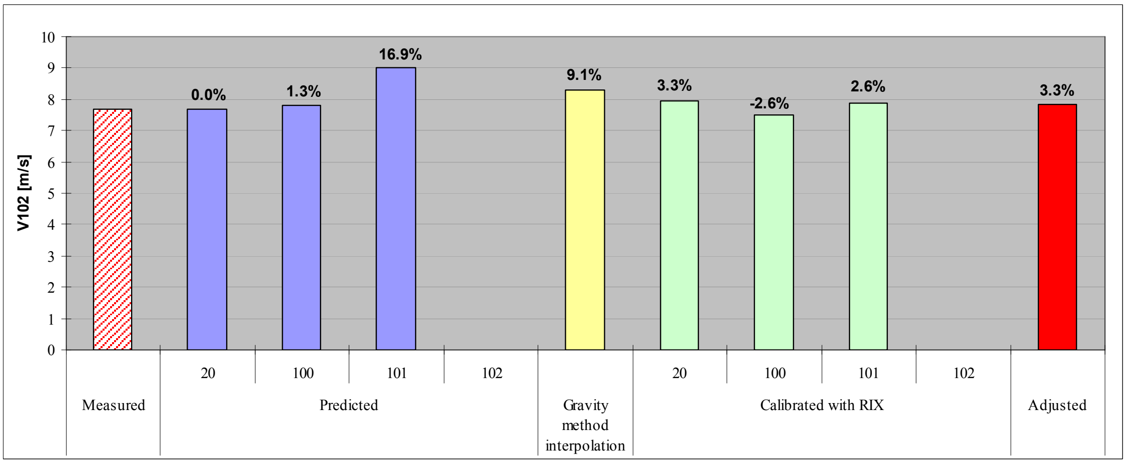

Figure 7 – Predictions for met. station 102 at Coelheira site

Table 8 – Predictions percent errors for Montemuro and Paúl sites

Stations	**Errors [%]**							
	non-adjusted predictions			**interpolated predictions**	**ΔRIX-calibrated predictions**			**Adjusted predictions**
185		-5.2	-7.7	-6.1		0.3	-15.9	-5.5
183	9.6		-1.6	-0.4	0.0		-3.0	-2.7
120	10.7	3.6		4.1	0.8	2.0		1.9
P1		6.3	28.6	24.0		2.2	17.4	14.3
P2	-6.6		13.1	5.8	-5.7		6.0	1.7
P3	-20.6	-14.7		-18.8	-16.0	-11.9		-14.8

The application of the gravity interpolation method on the simple predictions has the merit to smoothen the deviations but it is not an adjustment in itself. The average absolute error for the *interpolated* results, 9.0 %, is smaller than the average error for the cross predictions, even if improvement is not significant.

It is not possible to conclude that *ΔRIX-calibrated* predictions are significantly improved when compared with the non-adjusted estimations. Although, in average, there is an enhancement of estimations - average absolute error for *calibrated* predictions is of 5.3 % (against 9.1 % for non-adjusted predictions) and 71 % of the cases show improvement – the quality of results is, nevertheless, more variable. *ΔRIX-calibration* is many times pernicious and for a few cases results show even unreasonable deviations from measured values.

For the *adjusted* results, the large majority of cases show a notorious improvement in the quality of predictions. The average error of the *adjusted* predictions is of 5.5 % and about 80 % of the cross prediction are improved by this method.

Figure 8 compares the absolute error for each *adjusted* predictions (*Eadj*) and the absolute error for the simple cross predictions (*E*). It can provide an idea of the degree of improvement in each case given by the *adjustment* of the cross predictions.

For the sample cases *Eadj/E* has an average value of 0.62, which means that adjusted predictions standard errors are, in average, 38 % smaller. The standard deviation for *Eadj/E*, of 0.53, shows some dispersion of the results, which leads to more difficulty when trying to conclude about the real benefits of this kind of approach. However, only 2 results fall outside the merit interval, with values of 6.35 and 1.65 [2]. The greater value refers to cross prediction between met stations at Paúl da Serra, the most rugged site from those studied and, furthermore, the most prone to be influenced by thermal stratification effects due to the proximity to the sea and to the high altitude (more than 1500 meters). If one decides to exclude this case, considering that it falls clearly outside the WA^{S}P envelope, the results would be much more conclusive.

[2] - Although, in fact, four results show worst predictions after adjustment, only two can be considered in *Eadj/E* because cross predcitions for those cases are exact and so *E*=0, giving infinite values to *Eadj/E*.

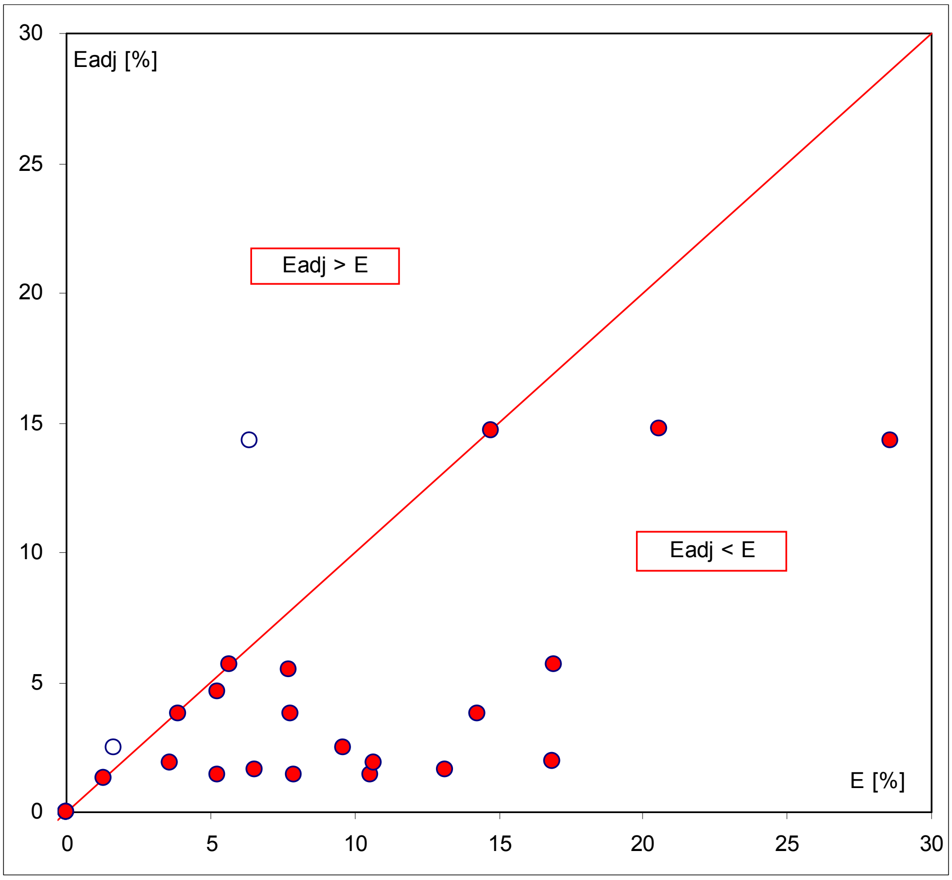

Figure 8 – Comparison between the absolute errors for *adjusted* (*Eadj*) and *non-adjusted* (*E*) predictions

5 Conclusions

Results for the trial cases show quite well that the adjustment of predicted average wind velocity made by linear flow model WA^{S}P, with the proposed combined methodology, results, for the majority of cases, in significant reduction of the errors from initial estimations, that is to say, better predictions.

Standard errors for the *adjusted* results were in average 38 % lower than those for the simple, *non-adjusted*, cross predictions. Only few (about 20 %) of the sample cases didn't show improvement by the *adjustment*. Nevertheless, some results included in the analysis seem to be outside this general trend, what could be explained with the higher complexity of the terrain and, by that reason, excluded from the analysis, permitting an enhancement on the merits of the methodology.

Isolated *ΔRIX-calibration* gives very variable results and great care must be taken on its use. The application of the gravity interpolation method smoothens the deviations of initial predictions and gives less variable results, but improvement in estimation is small.

The representativity of this conclusions can be argued. All areas are located in the Northern Atlantic region, and so subjected to its relatively moderate climate, both in wind intensity and air temperatures. Nevertheless, places are independent from each other, being similar only on the complexity of the orography. The use of this conclusions in regions with very different climates and wind regimes must be considered in a case by case basis, but still they do provide a very good start. On this matter, the knowledge of the terrain characteristics against the understanding of the wind flow model limits is, probably, the most important asset in any studied case.

Further improvements can, and will, be made on this prediction adjustment method. The more comprehensive analysis on the results, namely the filtering from less significant cases, will, in first hand, give more precise outcomes. The expansion of the sample cases "database" will be extremely useful to define with more precision the *ΔRIX-calibration* regression, and globally confirm once more the results that were stated. The investigation of different interpolation schemes, introducing more geo-climate variables will also be, most surely, of significance.

REFERENCES

[1] Anthony Bowen and Niels Mortensen, "Exploring The Limits of WASP – The Wind Atlas Analysis and Application Program". European Wind Energy Conference and Exhibition, 1996, Goteborg, Sweden.

[2] N. Mortensen, L. Landberg, I. Troen, Erik Petersen. Wind Atlas Analysis Program (WASP), 1993.

[3] Niels Mortensen and Erik Petersen, "Influence of Topographical Input Data on the Accuracy of Wind Flow Modelling in Complex Terrain". European Wind Energy Conference & Exhibition, 1997, Dublin, Ireland.

[4] Mireille Lefevre et al, "Study of effective distances for interpolation schemes in meteorology". European Geophysical Society XXVII Annual Assembly, 2002, Nice, France.

[5] Álvaro Rodrigues et al, "Improving Techniques for Statistical and Physical Modelling of Wind Resource in Complex Terrain". European Wind Energy Conference and Exhibition, 1996, Goteborg, Sweden.