Validation and challenges of CFD in complex terrain for real world wind farms

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Summary

GL Garrad Hassan (GL GH) considers that the development of real-world wind speed predictions using CFD models is arriving at a tipping point where consistently improved wind speed predictions can be provided, when compared to linear models. This represents a new and exciting step forward for CFD modelling. Until recently GL GH did not consider it possible to universally state that a real contribution to wind resource assessment could be gained by employing CFD modelling for real wind farm sites. Although there are still limitations, GL GH now considers CFD modelling to be a valuable and permanent part of the wind resource assessment "toolkit".

Here a sample validation of a CFD-based wind speed prediction methodology is presented using measurements from three real wind farm sites. The conclusions of this study illustrate this tipping point of adding value has been reached and are in general agreement with the conclusions of the Bolund modelling comparison.

It is important to note that CFD models require careful consideration both in setup and when interpreting the results to ensure that the best possible outputs are obtained. Neglecting this consideration may result in highly erroneous values.

Introduction

The recent Bolund blind test presented wind speed predictions from a wide variety of modellers; the predictions were compared to wind speed measurements made at a number of masts situated across the Bolund Hill, which is located near to Risø DTU National Laboratory for Sustainable Energy in Roskilde, Denmark [1]. The comparison showed that non-linear RANS models (CFD) employing two-equation turbulence closure methods had the potential to provide improved agreement with measurement. However, whilst this potential improvement is noted, a wide spread of results was also observed, as seen in Figure 1, even though these models were theoretically very similar to each other. This scatter presents a serious concern for users of this type of modelling results, as it indicates that there is a high sensitivity to user input.

Recent work within GL GH has led to the same conclusions. An excerpt from this work is presented here.

These findings are significant as GL GH has spent a number of years investigating and developing CFD-based modelling methodologies. Until recently, although the theories applied within CFD codes have shown great potential, it has not been possible to practically apply them in a way that consistently provides improved agreement with wind speed measurements in complex terrain, here defined as in [2]. Instead, GL GH has historically provided CFD analysis with great care and highlighted the caution to be used when interpreting the results. The results of these analyses have been applied mainly in a qualitative fashion.

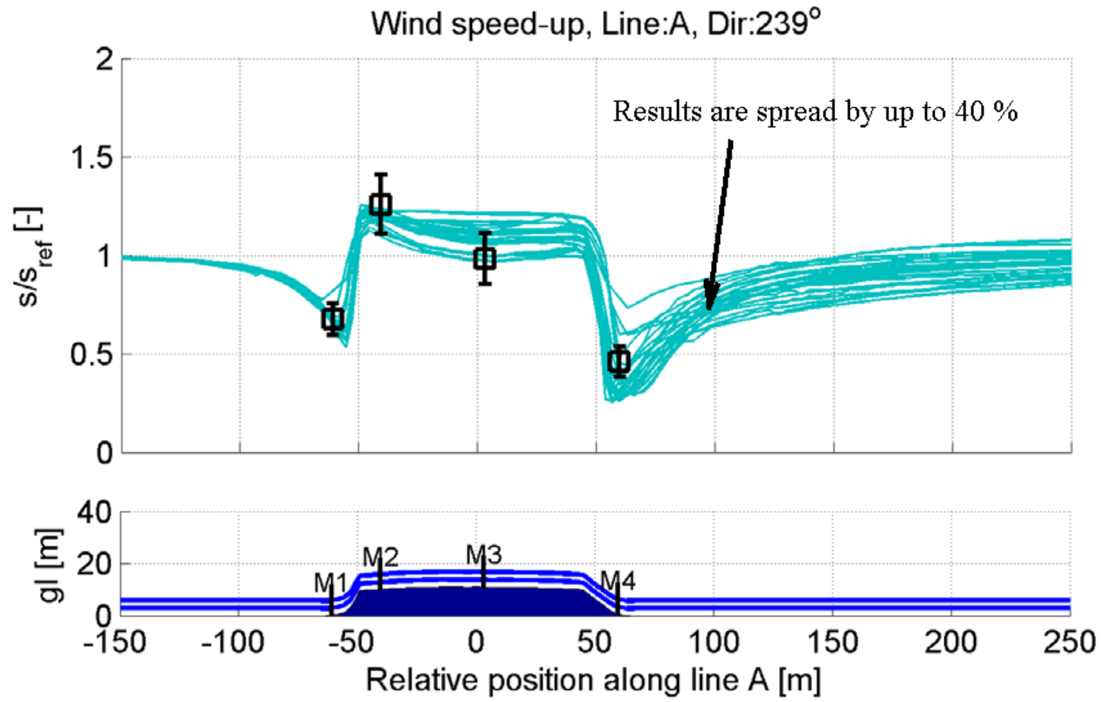

Figure 1 **Wind speed predictions made by CFD models (2-equation closure methods) at 5 m above ground level in the Bolund experiment. This figure is reproduced from A. Bechmann, et.al., "Results of the Blind Comparison" [1].**

The best way to improve confidence in the application of CFD techniques is to validate the modelling results against measurements. A lot can be learned from considering theoretical situations such as 2D hills etc. especially if the results can be compared to wind tunnel measurements. In fact, consideration of simple validation cases is essential in the early stages of development to ensure that a model is behaving correctly. An example of such a validation study carried out for another CFD-based modelling technique can be found here [3]. However the final purpose of applying a CFD model to wind resource assessment is to improve the prediction of wind speed across real wind farm sites, which requires full-scale quality data measured at real sites [4].

Wind speed measurements for masts pairs situated at three real wind farm sites are presented here to illustrate the modelling performance. For each mast pair, a prediction of the long-term mean wind speed is made at one mast location using the measured data available from the other mast location. This modelling prediction can then be compared to the measurements made at the second mast in order to examine the deviation from measurement. When doing this, it is important to remember that, although measurements are the most reliable method of predicting the wind speed at a specific point, the measurements themselves are subject to uncertainty. In order to minimise the effect that measurement uncertainty has on this study, the quality of the measurements has been considered to ensure that the uncertainty lies within acceptable bounds.

This work is specifically aimed at improving wind speed predictions in areas featuring steep slopes. As a result, the presented sites all feature complex terrain. However, in order to focus on the ability of the model to consider this type terrain, only sites where the flow can be reasonably approximated as neutrally stable were considered. Additionally, sites featuring any significant areas of forestry have not been included here. Although consideration of both non-neutral flows and forested regions is possible within CFD models, it is considered prudent to robustly validate each flow condition separately, with this paper dealing with the complex terrain case.

Due in part to the conclusions drawn here, GL GH now considers CFD to be a valuable and permanent part of the wind resource assessment "toolkit". It remains important to note that despite the value CFD can provide, this is not a panacea; CFD calculations are sensitive to user-defined parameters and careful consideration and interrogation of results is required to produce the most reliable predictions. Considerable investment in computer resources is also required to achieve the necessary mesh resolutions for mesh independence on large sites (high memory requirements) and also to provide results within commercially acceptable timescales (high computer performance).

Modelling Methodology

In order for a CFD based modelling methodology to provide value as a commercial tool, it is paramount that no post-simulation 'tuning' of the model is carried out. In addition to this the spread of results as observed in the Bolund test must be minimised, or in other words, the modelling process must be repeatable. This can be achieved both by minimising the sensitivity to user defined meshing parameters, i.e. by achieving mesh independence, and also by applying universal settings for each simulation. The nature of CFD modelling and the diversity of real wind farm sites will frustrate the definition of a completely universal set of modelling parameters that will produce the best possible results in every scenario. It is likely that universal parameters will be available for categories of sites only. However, as the investigation carried out here is focussed entirely on improving wind speed predictions in close proximity to steep slopes, the modelling parameters are the same for all the sites presented here. Some of these parameters are outlined briefly in Table 1.

Modelling setting	**Value applied**
Turbulence closure model	k-ε
No of iterations completed	800
Convergence criteria	Sum of consistency residuals < 1 x 10^{-4}
Solver	Coupled
Numerical scheme	2nd order upwind

Table 1 A summary of the model settings

When setting up the mesh for each site the following guidelines are followed:

- All mast locations must be situated at least 10 km from any edge of the domain
- The cell base size is 20 m. The settings in the meshing algorithm are configured such that in areas where there are large changes in terrain gradient, cells as small as 10 m may be inserted.

Preliminary tests were carried out to ensure that the mesh has an acceptable level of independence.

Site Details

Figures 2 - 4 illustrate the terrain at each of the sites.

The most relevant properties of the considered sites are shown in Table 2, below.

Site number	No. masts	Mast heights (metres)	Approximate distance between masts (kilometres)	Length of concurrent data period (years)	Measurement quality	Characteristic height of local terrain features[1] (metres)
1	2	50	0.7	1.5	Good[2]	450
2	2	50	2	1	Good[2]	200
3	2	65	13	1	Good[2]/satisfactory[3]	500

Notes

1. The typical height of the main hills/ridges above the valley floor
2. Fully compliant with IEC guidelines
3. Not completely compliant with IEC guidelines so subject to additional uncertainty but still considered to be valid for use in this study.

Table 2 Properties of the sites considered in the work presented here

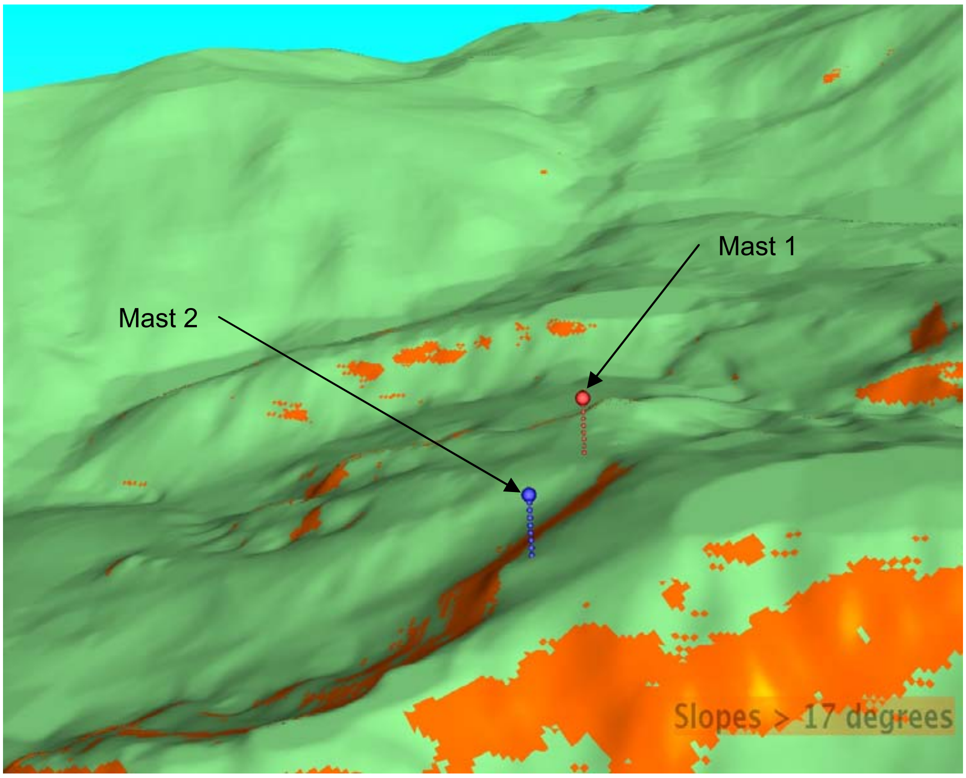

Figure 2 A view of the terrain at Site 1 indicating the measurement mast locations

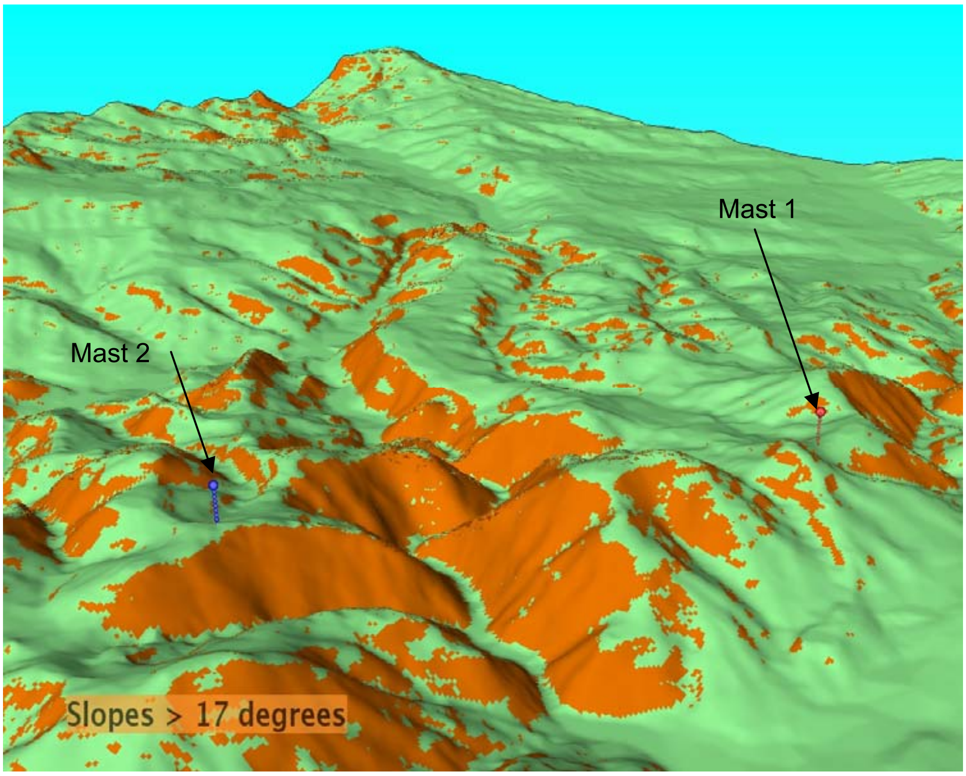

Figure 3 A view of the terrain at Site 2 indicating the measurement mast locations

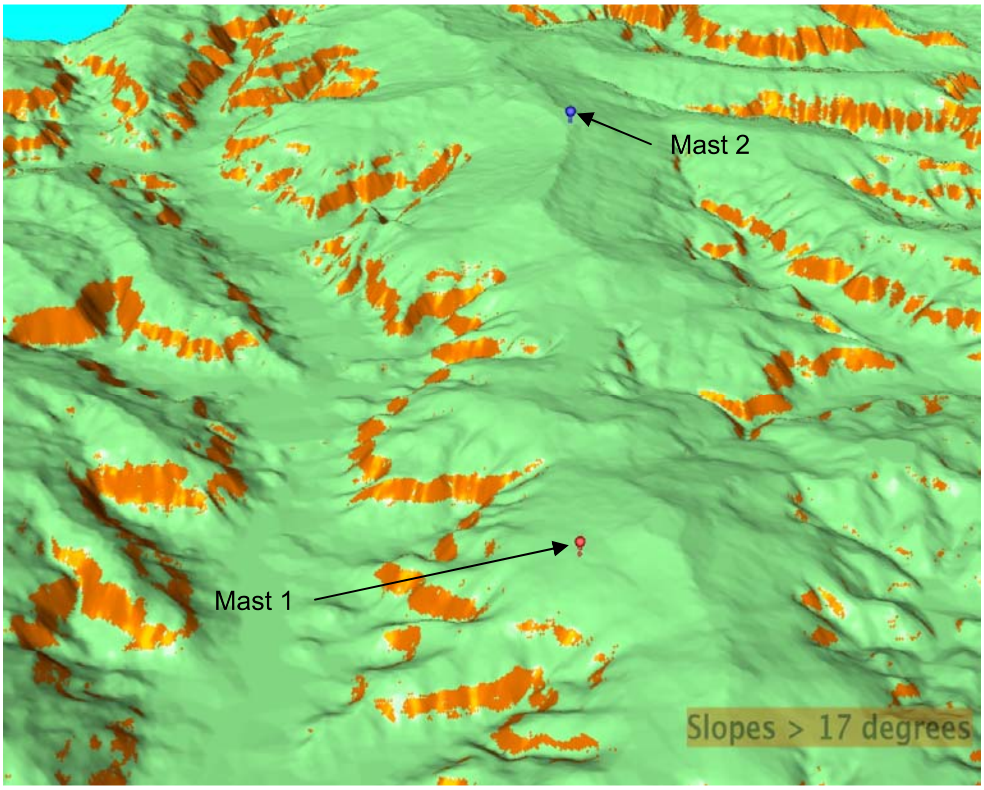

Figure 4 A view of the terrain at Site 3 indicating the measurement mast locations

Results

The results of the comparison with measurement for each of the sites considered here are presented alongside results from a linear modelling technique in Figure 5. The deviation from measurement is calculated as the difference between the measured long-term mean wind speed and the same value predicted by the model for the identical location.

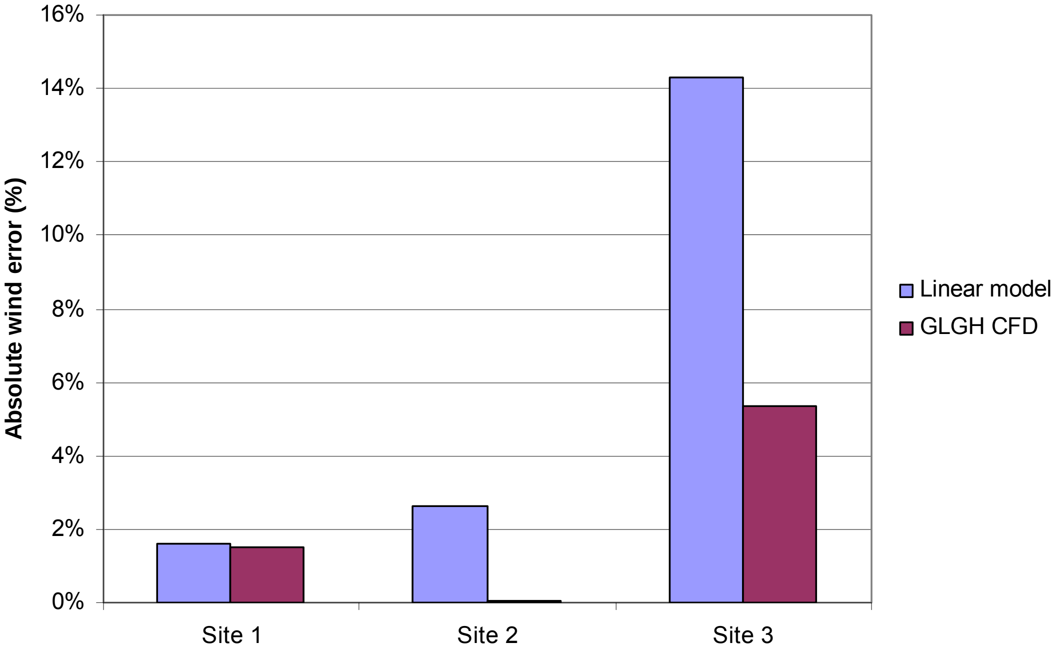

Figure 5 **A comparison of the agreement between measurements and both a linear model and a CFD based modelling technique**

Concluding Remarks

It is clear that for all three sites presented here, the CFD-based modelling technique provides improved agreement with measurement when compared to the linear flow model. The results also suggest that this improvement is greatest when the terrain is most complex.

The ability of CFD to predict flow separation contributes to the improved agreement with measurement at sites with steep slopes. Figure 6 shows a region of flow separation predicted near to Mast 1 at Site 2. The linear modelling technique considered in the results presented in Figure 5 assumes that the flow remains attached for all locations so that the streamlines of the flow travel more or less parallel to the terrain surface. When flow separation occurs in the real flow this results in this type of linear model producing an over-prediction of wind speed near to the separated flow region. As the CFD model is able to simulate flow separation the streamlines travel over the separation ‘bubble’ and improved agreement with measurements is observed.

Most linear models decompose the terrain into spectral components. The amplitude of the flow perturbation caused by any given spectral component of the terrain is assumed to be linearly proportional to the amplitude of that terrain component. This approximate relation does indeed hold when the flow perturbation is small i.e. for shallow slopes, but as slopes grows steeper, non-linear effects cause the proportional relation to break down. At hill crests, the actual positive perturbation grows more slowly than the terrain amplitude, while the actual negative perturbation in concavities grows more quickly than the amplitude, ultimately resulting in flow separation and recirculation. The assumptions made in order to linearise the underlying flow equations are clearly broken in such conditions.

The CFD model makes no such assumption and as such does not suffer from the same intrinsic limitations as linear models. It is thus able, in theory, to model regions of flow separation and recirculation, and to account for the non-linear effects that cause the flow perturbation to deviate from what is predicted by linear models.

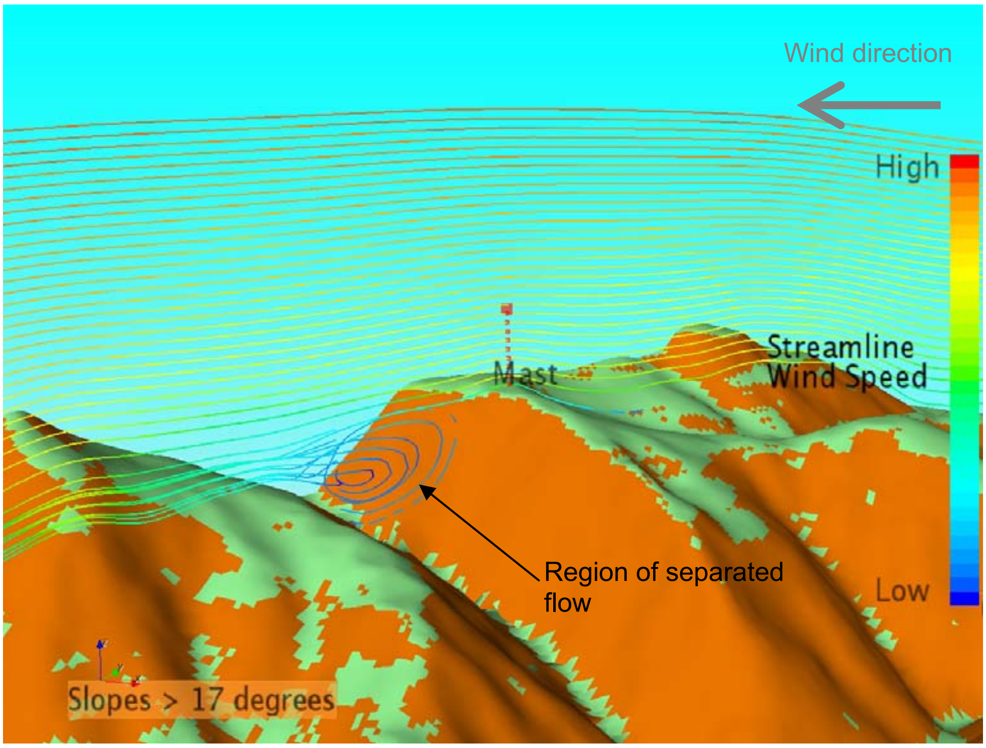

Figure 6 **A view of Mast 2 from Site 2 including streamlines for the predominant wind direction as they pass over the mast. NB - the background terrain has been removed from the plot for visualisation purposes only.**

Following many years of CFD development at GL GH, the results presented here show that the hardware and software now available as state-of-the-art is able to consistently provide value above linear flow models in complex terrain and can be considered to be a permanent part of the wind resource ‘toolkit’.

However, great care and expertise are still required, and engineering judgement is essential to ensure value added is maximised. The scatter demonstrated by the Bolund Blind Test highlights the importance of these points.

References

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4. IEC 61400-12-1, "Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, Annex G". 2005.