Met Office

Virtual Met Mast™

Version 1
Methodology
and Verification

January 2010

Contents

1. Background

Wind energy is proportional to the third power of the wind speed. This makes establishing a high quality wind climatology at a prospective wind farm site a vital requirement. Very often there is no alternative to going from a crude map based assessment straight into expensive on-site monitoring to evaluate wind energy potential. The Met Office Virtual Met Mast™ fills this gap by providing a very reliable site and hub height specific estimate of the wind climatology.

2. Introduction

In addition to its archives of wind speed and direction monitored at conventional sites, the Met Office and the European Centre for Medium Range Forecasts (ECMWF) have gradually been building up archives of wind data produced by forecast models. Since 2006 these winds have been produced by the Met Office on a 4km grid covering the UK (UK4). Interpolation techniques have been developed to produce an hourly time series of wind data for any location, and any height above ground.

This document explains how these model winds are used to produce wind frequency analyses and statistics comparable with those that are generated from on-site monitoring; what we are calling a Virtual Met Mast™ (VMM). Comparisons with on-site monitored data, loaned to the Met Office by various organisations, are presented as a means of verifying and giving confidence in the VMM when on-site observations are not available.

3 Method

Creating a Virtual Met Mast™ involves the following stages:

a) Extract wind speed and direction data from the Met Office UK4 model archive, commencing in January 2006, then interpolate to the required location and proposed hub height.
b) Remove the model representation of land use and topography and replace with values more representative of the actual land use and topography at the site. This is known as downscaling. If the hub height is above a calculated roughness reference height then no roughness calculation is applied. Currently no corrections are applied over the sea and no specific corrections are made to take into account eddies, sheltering or complex flows that occur in complex terrain. See Annex 1 for more detail.
c) Extract wind speed and direction data from the ECMWF 80km grid spacing (ERA) model

archive, commencing in 1989, and then interpolate to the required location and proposed hub height.

d) Merge the UK4 and ERA data together using the matrix method of Measure-Correlate-Predict (MCP). See Annex 2 for more details. This gives a 21-year climatology based upon the UK4 model.

e) Produce the wind frequency analysis and associated derived parameters appropriate for wind energy assessments.

A VMM assessment can be produced for onshore and offshore sites. Near-shore sites may be affected by rapid changes in terrain (cliffs) and the boundary-layer transition at the coastline, in ways that VMM does not currently pick up. However, the verification results presented here show levels of agreement that make a VMM assessment valuable even in this challenging environment.

This report documents the verification of VMM winds against wind observations from wind farm sites across the UK. Comparisons made both for onshore and near-shore sites are presented in section 4. Conclusions are drawn in section 5.

4 Comparison of results with hub-height observations

4.1 Data

The forecast model data archive for the operational UK4 model extends from January 2006 to the present day. The UK4 model utilises a wide range of observations to produce the best possible wind fields from which the forecasts are taken forwards. Sources include: conventional anemometers on land and on buoys at sea, satellite profiles, ground based profiles, radiosondes and aircraft reports. Many man-years of effort have been employed in optimising the mix of these data, with improvement continually taking place.

For verification purposes, only on site observations made since January 2006 can be compared with the VMM predictions, as before that date the VMM data are in frequency analysis format. Most on site data are in the form of ten minute means. The model data are spot winds (though not gusts) calculated on the hour. To gain correspondence, only ten minute means leading up to the hour are used for verification.

Wind observations from nine locations have been acquired. They cover a range of terrain complexity; three are near-shore. The measurements from seven sites were made using mast-mounted anemometers and wind vanes at heights of between 20m and 80m. A further set of data comes from a wind farm with several turbine mounted anemometers and one set of data are from a LIDAR[1]. Note that for all the datasets, little is known about either the quality of the measurements, instrument calibration or the suitability of the measurement sites.

The bias comparisons between VMM and observed data over the entire verification periods are summarised in Table 1. For onshore sites the impact of downscaling is shown. Monthly and daily comparisons are shown graphically in the following sections.

Site ID	**Site Type**	**Verification Period (months)**	**Height (m)**	**Uncorrected Model - Observed (m/s)**	**Downscaled Model - Observed (m/s)**
NS1	Near-shore	7	25	**-1.3**	N/A
NS1	Near-shore	7	48	**-1.0**	N/A
NS1	Near-shore	7	70	**-0.8**	N/A
NS2	Near-shore	2	68	**0.2**	N/A
NS3	Near-shore	2	30	**0.7**	N/A
OS1	Simple	10	70	1.0	**0.7**
OS2	Simple	44	50	-0.2	**0.2**
OS3	Hilly	44	50	0.2	**-0.3**
OS4	Hill summit	2	47	-3.0	**0.8**
OS4	west facing slope	2	47	-1.5	**-0.1**
OS4	east facing slope	2	47	-1.5	**0.4**
OS4	Leeward	2	47	-1.0	**0.4**
OS5	Hilly	2	60	-2.0	**1.5**
OS6	Hilly	15	60	-2.0	**1.2**

Table1: Summary bias figures for each verification site

4.2 Verification for Near-Shore Sites

As no downscaling corrections are applied over the sea; the results presented here are identical to the uncorrected UK4 data.

For two of the sites only two months of data are available. One (coded as NS3) gave a bias (defined throughout as the model minus the measured mean wind speed) of 0.7 m/s (at 70m height) the other, NS2, a bias of 0.2m/s (at 30m height). In both instances the model over predicted the wind speed (positive bias).

Measurements at the third near-shore site, are available for four heights and this allows a more detailed investigation of the VMM accuracy. The results for 25, 38, 48 and 70m above sea level

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[1] A land based remote sensing system that gives wind speed profiles by measuring the Doppler shift of reflected laser beams

are shown in Figures 1 to 4. At 25m the model consistently under predicts the monthly mean wind speed by -1.3 m/s on average. The bias reduced at 48m, to -1.0 m/s, and reduced again at 70m to -0.8 m/s. Note that the behaviour at 38m is quite different to that at the other heights, perhaps raising questions about the quality of the observations at this height.

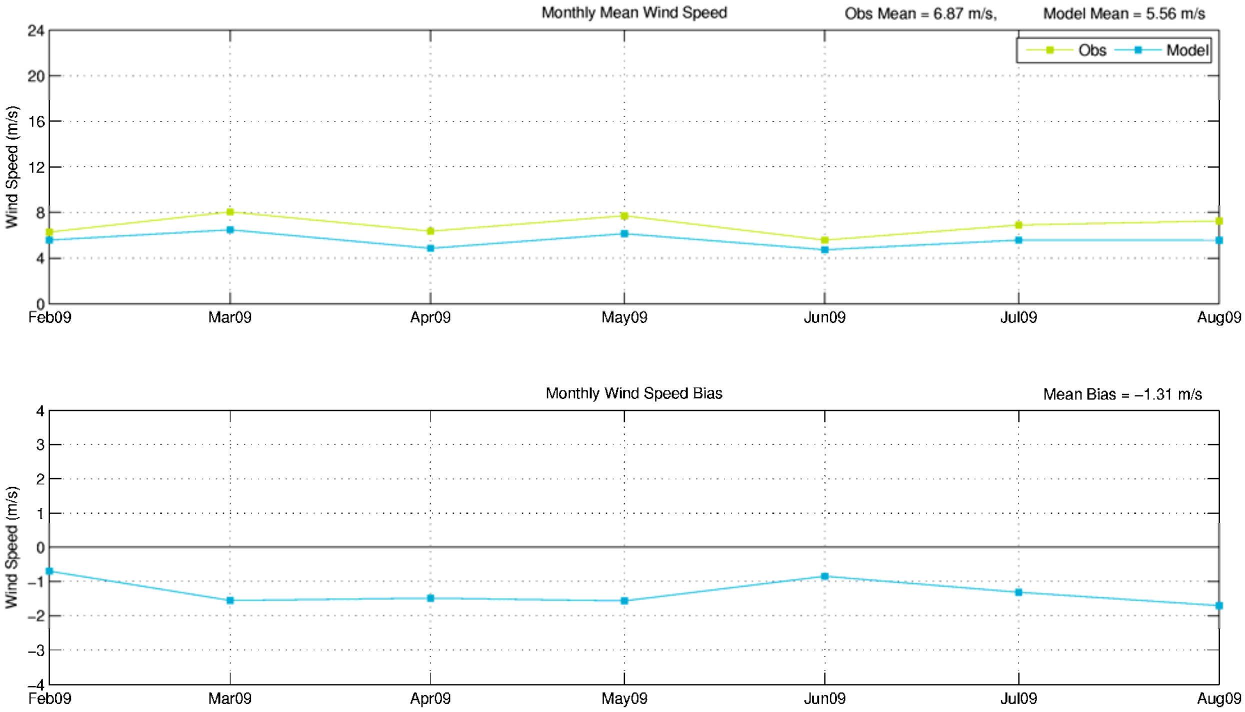

Figure 1: Near-shore site (NS1) at height of 25m

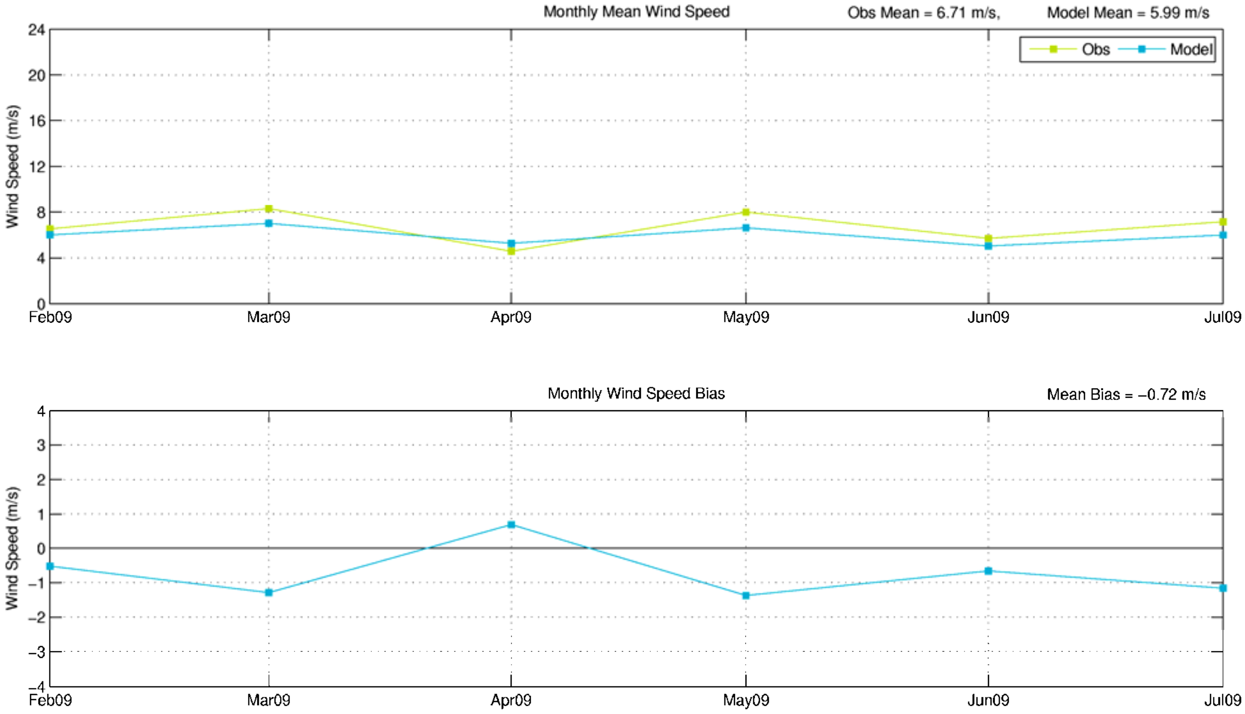

Figure 2: Near-shore site (NS1) at height of 38m

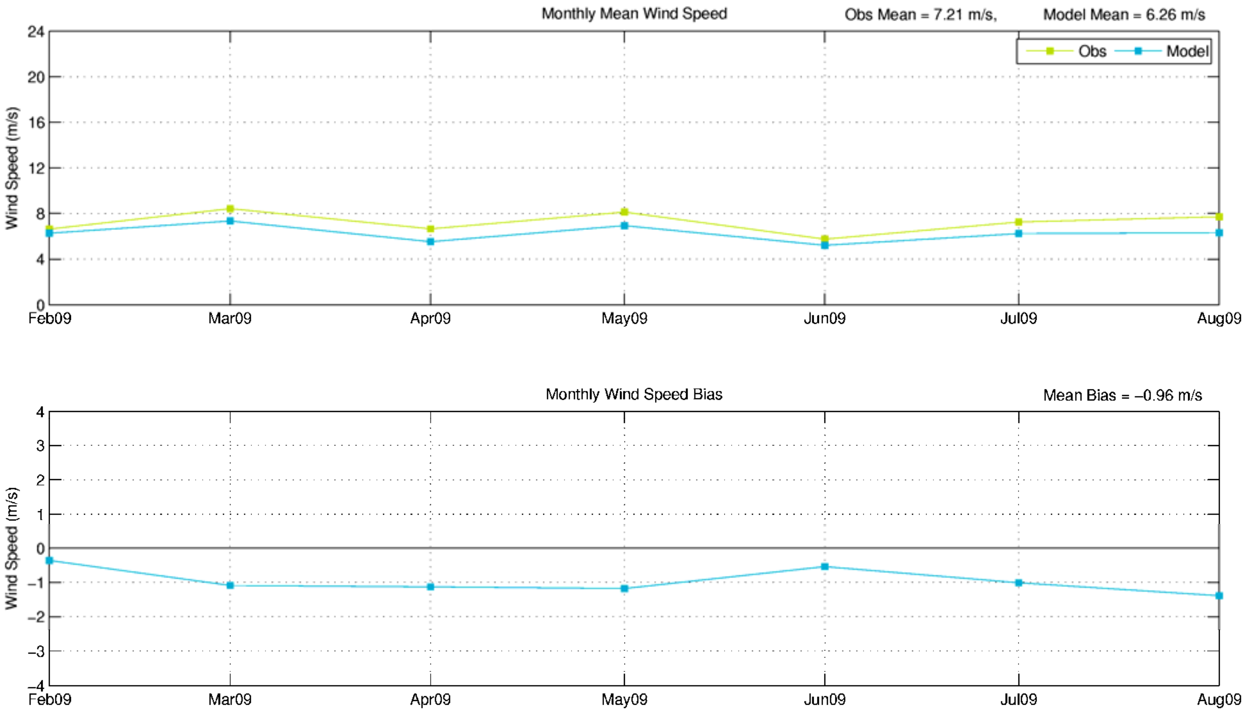

Figure 3: Near-shore site (NS1) at height of 48m

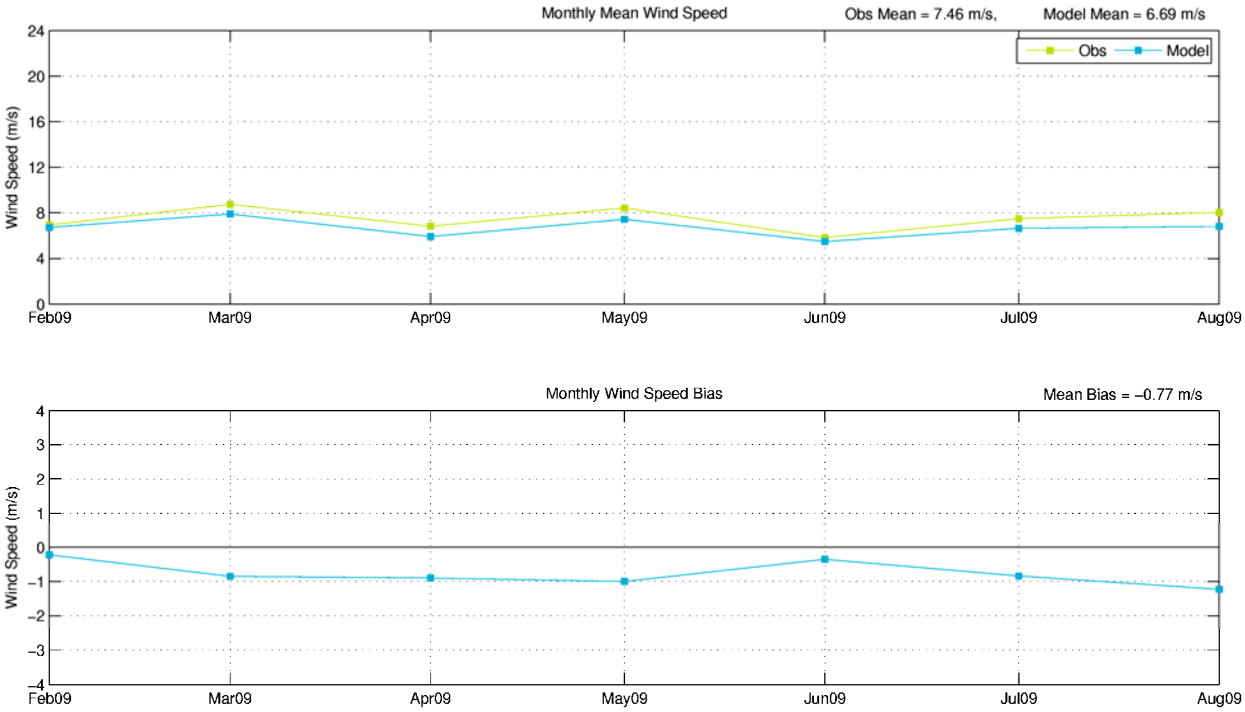

Figure 4: Near-shore site (NS1) at height of 70m

Overall, for the three near-shore sites considered here, the model appears to provide a reasonable prediction of the measured monthly average wind speed. Further investigation would be required to identify the causes of the biases at each site. However, a few plausible, if tentative, conclusions can be drawn.

- This reduction in bias error with height at site NS1 is what would be expected, as local effects that may not be modelled become less important as height increases.
- The relatively small 0.2 m/s bias at site NS3 is consistent with it being located upwind (climatologically) of the coast, and is therefore relatively unaffected by the boundary-layer transition across the coastline. Issues with the way the model handles the adjustment of the flow at the coastal boundary are therefore unlikely to have a major influence on the results for this site, but could contribute to the larger biases found at the other sites.

4.3 Verification for Onshore Sites

4.3.1 Hilly Terrain

No particular definition has been used to differentiate hilly terrain from that which is less complex; a merely subjective assessment has been made. We begin by considering the accuracy of the VMM predictions for the hilliest site for which we have data. The measured and VMM predicted monthly mean wind speeds and bias are shown in Figure. 5. This is the only site where the full set of roughness and altitude corrections were made to the UK4 data. The uncorrected UK4 model under-predicted the wind speed at this site, with the monthly bias of typically around −2 m/s. The roughness correction reduces this negative bias significantly, consistent with the idea that the enhanced effective roughness used in the model is largely responsible for the under-prediction. The bias obtained with the roughness correction is typically around +1.0 m/s. Applying the orographic height correction increases the wind speed further, simply because the UK4 model orography is lower than the actual height of the site, with a resulting bias of around +1.2 m/s. Note that given the position of the wind farm, we should not be surprised by the failure of the height correction in this case. The presence of significant terrain immediately to the west of the site suggests that a more refined correction scheme is necessary.

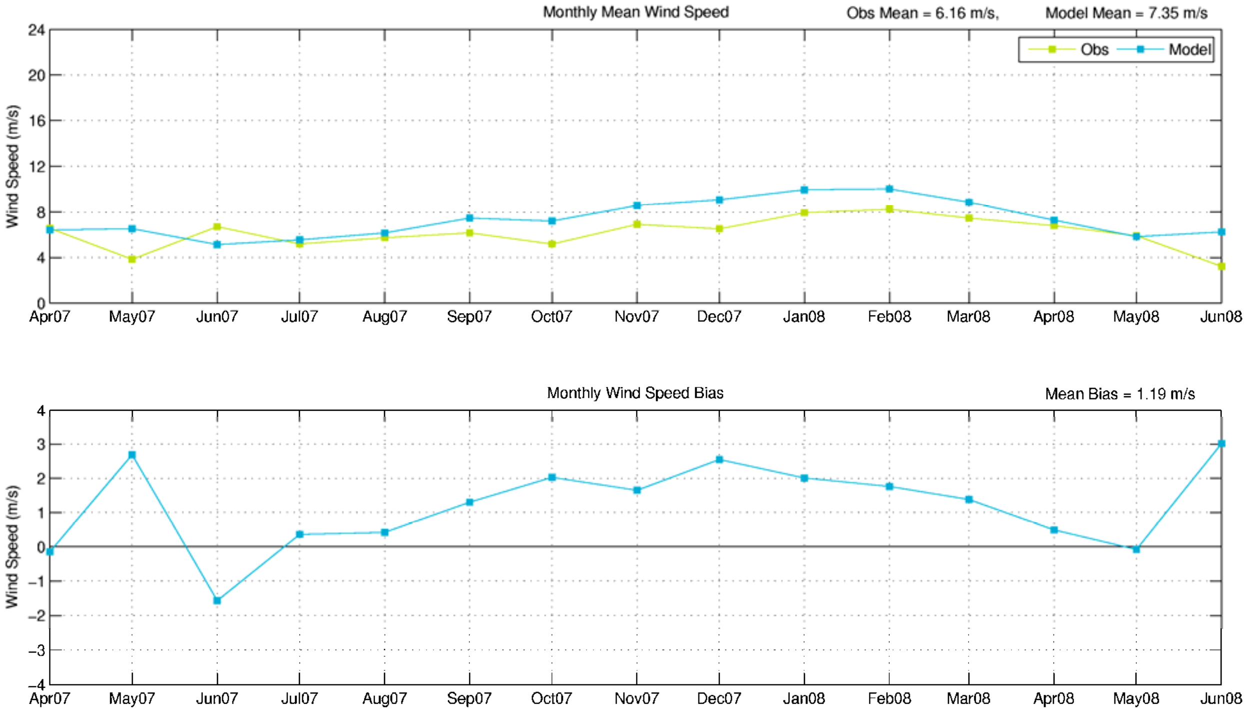

Figure 5: Most hilly site (OS6) at a height of 60m

For all of the remaining sites the roughness reference height lies below the measurement height and thus no roughness correction is applied.

In the next example observations from turbine anemometers (coded OS4) on an existing wind farm have been used, albeit for only two months. This gives an opportunity to consider variations across a typical upland wind farm site. Observations from five of the turbines have been selected for comparison with the VMM predictions. Turbine 1 is located at the north-west edge of the array, on the west facing slope. Turbine 2 is situated at the north-east corner, on the east-facing slope. These turbines are respectively on the upwind and leeward slopes of the hill for westerly flow. Turbines 3 and 4 are located near the summit, in the centre of the array. Turbine 5 is at the eastern edge of the array and is on the leeward slope for westerly conditions.

Comparisons between the VMM predictions and the turbine measurements are presented in Figures 6 to 10. Note that due to the short data series, daily averages have been presented. These are by nature more variable than monthly means. Only when daily mean wind has an impact on some aspect of the wind farm, is the daily bias of interest.

For all turbines the uncorrected model wind speeds are lower than those observed. When using uncorrected UK4 data, turbines 3 and 4, on the summit, give the largest negative bias at around

−3 m/s. The height corrections appear to do a reasonable job in reducing the differences, with a tendency to over compensate. For turbines 3 and 4, the large negative bias is replaced by positive biases of 0.8 m/s. For turbines 1 and 2 the biases are reduced to less than 0.5 m/s. For turbine 5, on the leeward slope, the bias is 0.4 m/s. This is perhaps because the scheme does not account for sheltering effects on the leeward side of the hill. Overall, these biases are in line with what would be expected given the simplicity of the scheme; the height corrections are reasonable and in all cases provide corrections with the appropriate sign.

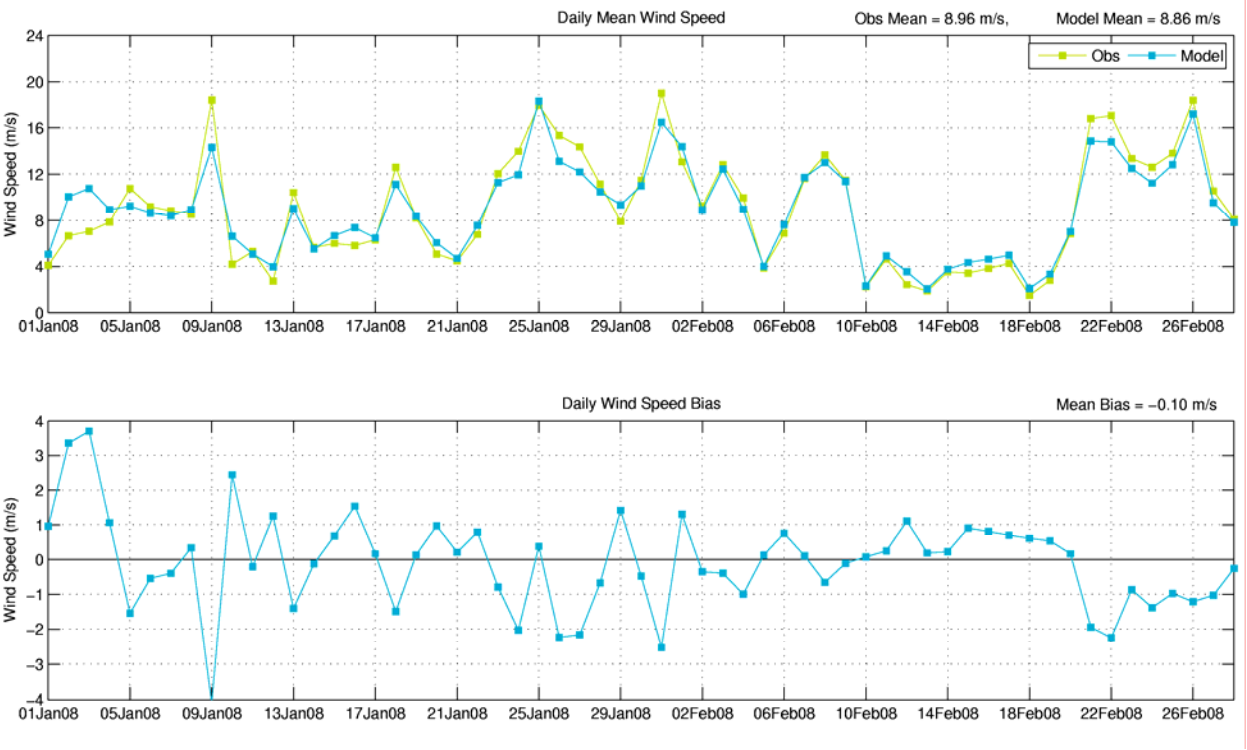

Figure 6: Hilly site OS4, turbine 1, west facing slope at a height of 47m

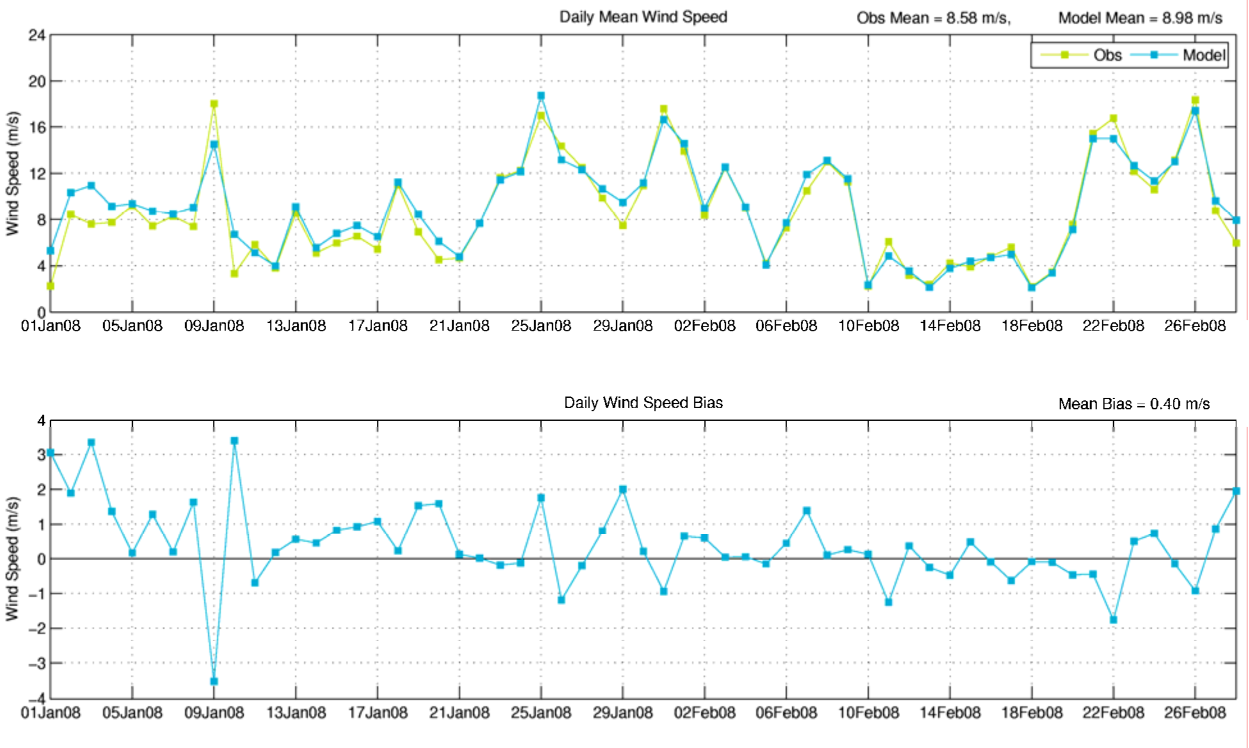

Figure 7: Hilly site OS4, turbine 2, east facing slope at a height of 47m

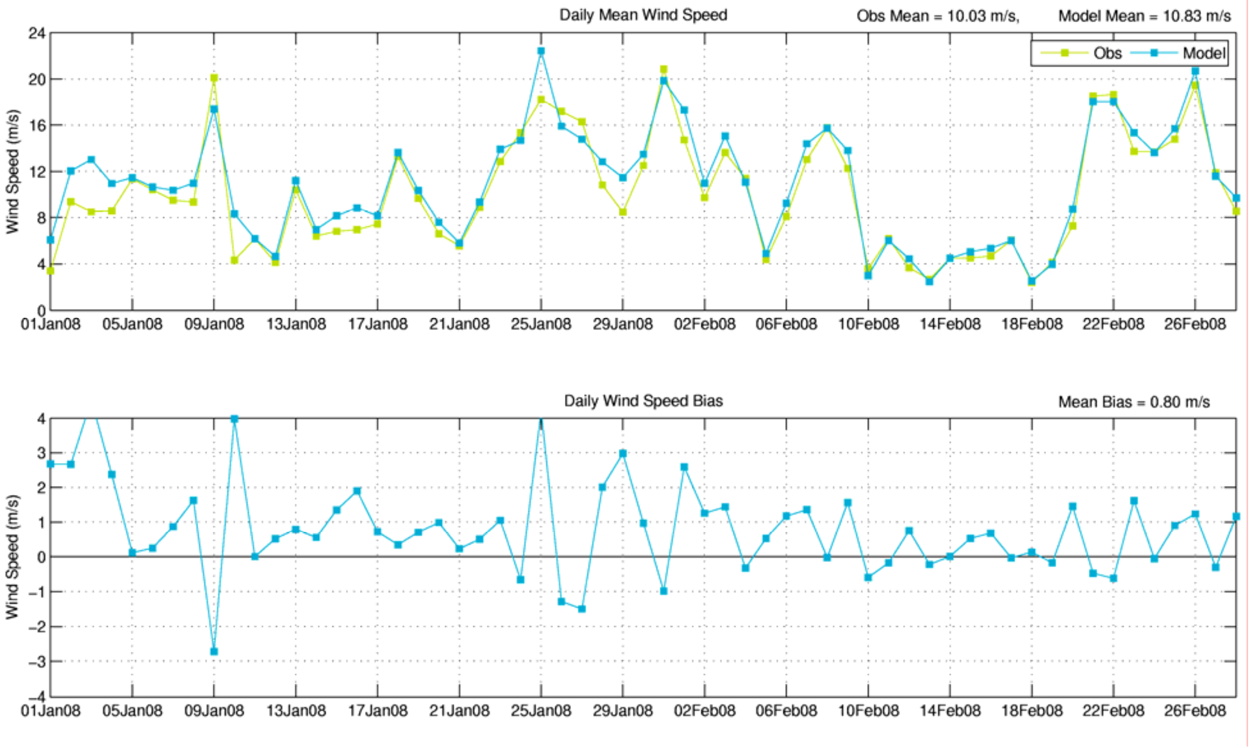

Figure 8: Hilly site OS4, turbine 3, summit location at a height of 47m

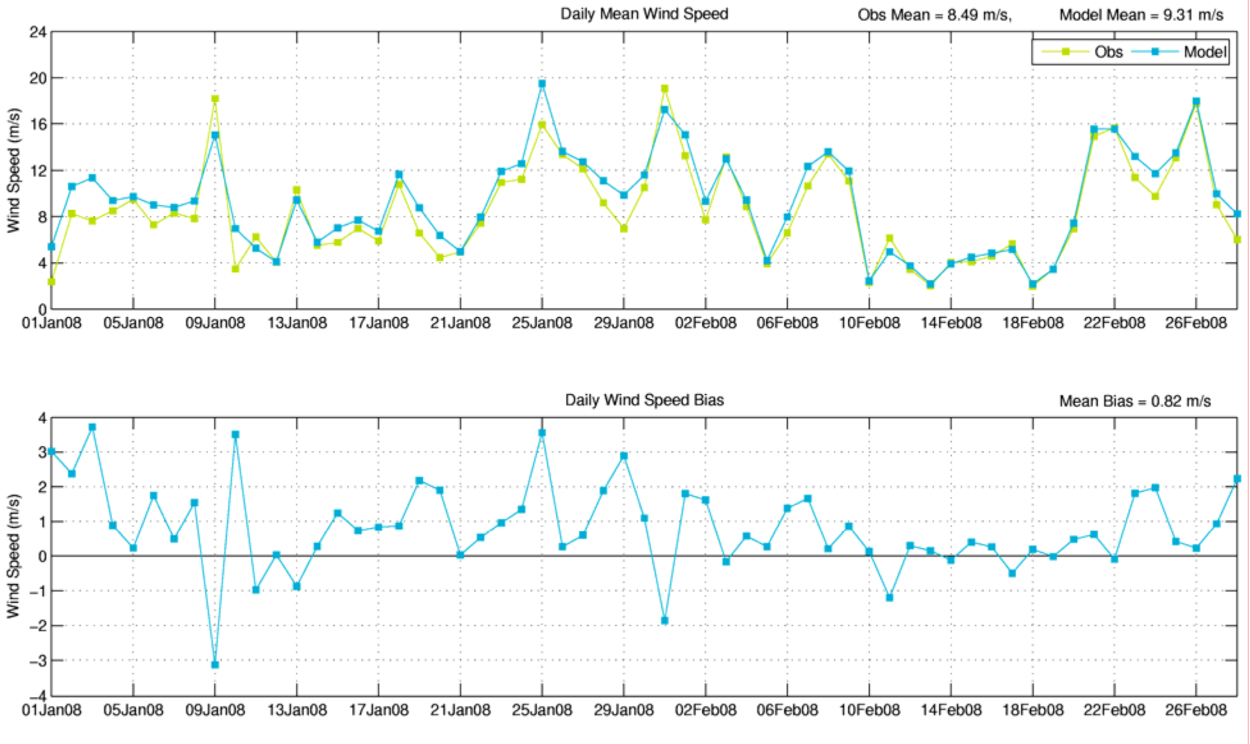

Figure 9: Hilly site OS4, turbine 4, summit location at a height of 47m

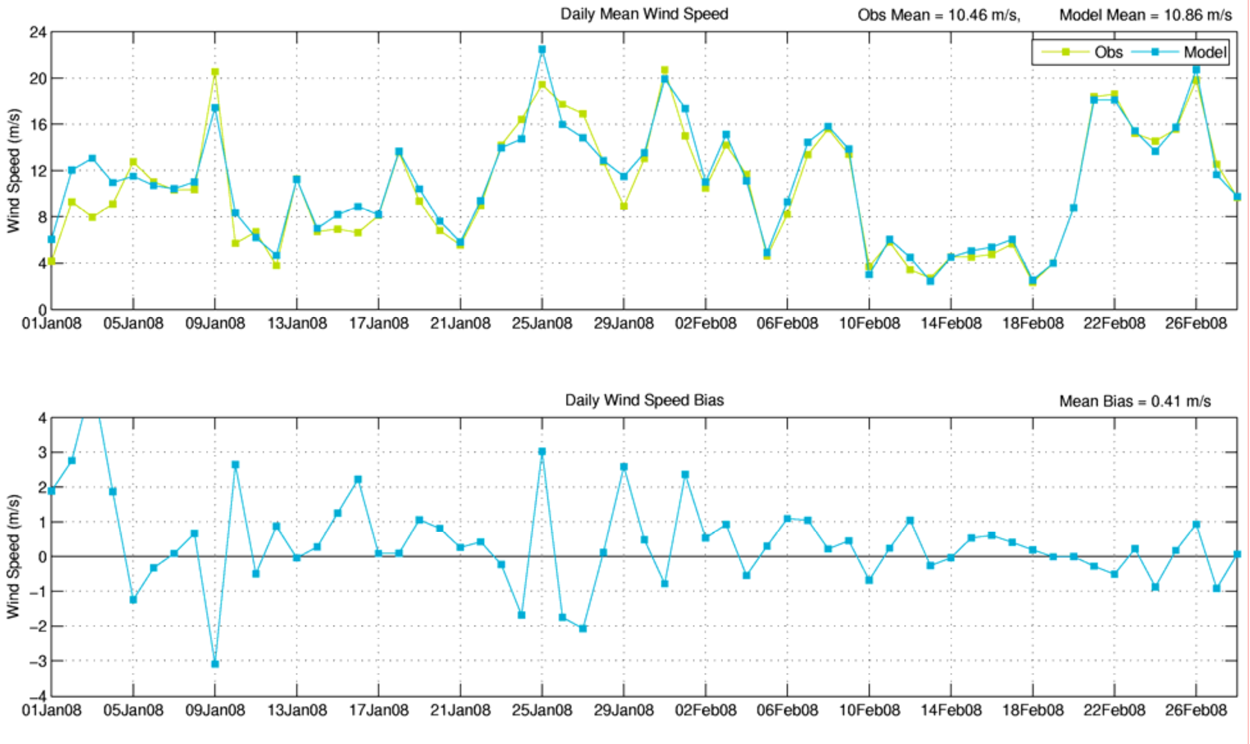

Figure 10: Hilly site OS4, turbine 5, leeward slope at a height of 47m

Results for another hilly site are presented in Figure 11. In this case the uncorrected model data are in reasonable agreement with the observations (see Table 1), the height correction turning a small positive bias into a small negative bias. Nevertheless, both the uncorrected and corrected predictions are in very close agreement with the observations.

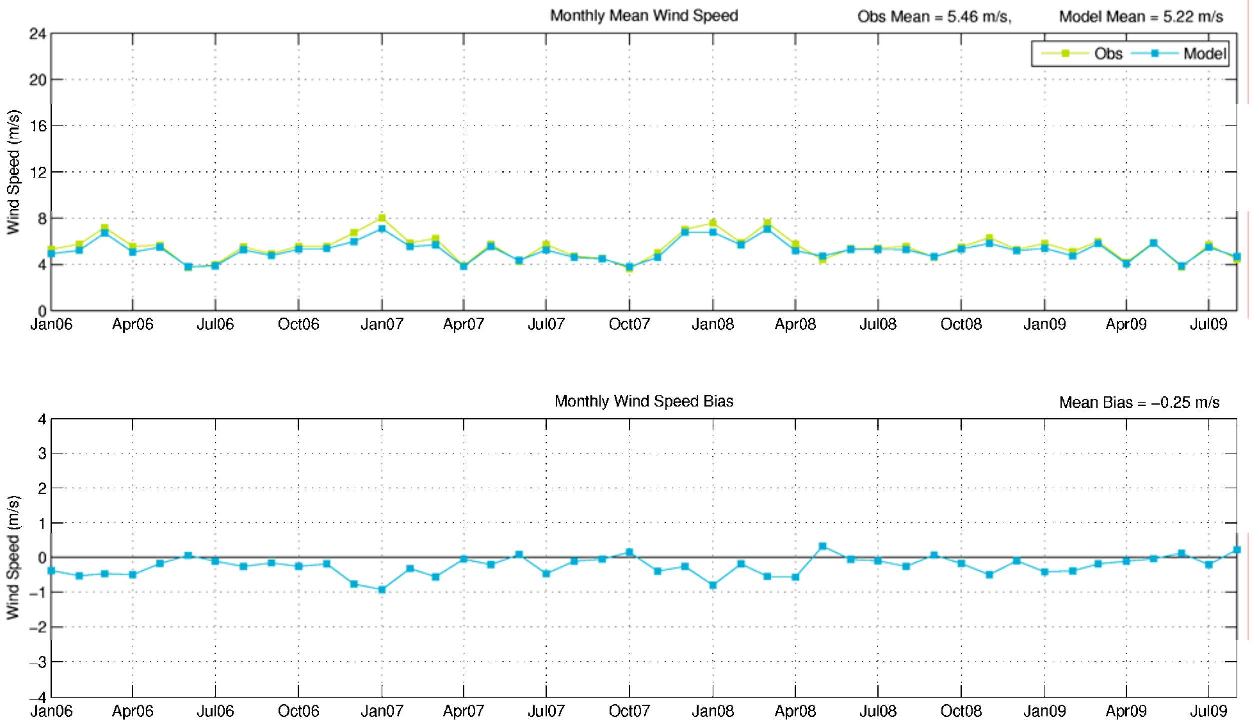

Figure 11: Hilly site OS3, at a height of 50m

One further hilly site (OS5), with only two months of on site observations at 60m, gave an uncorrected bias of -2 m/s. Application of the height correction over compensates (see Table 1). The individual monthly biases are +1 and +2 m/s.

4.3.2 Simple terrain

The final two onshore sites considered here are for relatively flat, simple terrain. Figure 12 shows the VMM predictions and observations for one of the sites. The height correction has no real impact on the results, just changing the sign of the 0.2 m/s bias (see Table 1). The magnitude of the monthly bias is typically less than ±0.5 m/s, although there is one month in particular, December 2008, where the difference is much larger. It is possible that a problem with the on site data quality is being highlighted here.

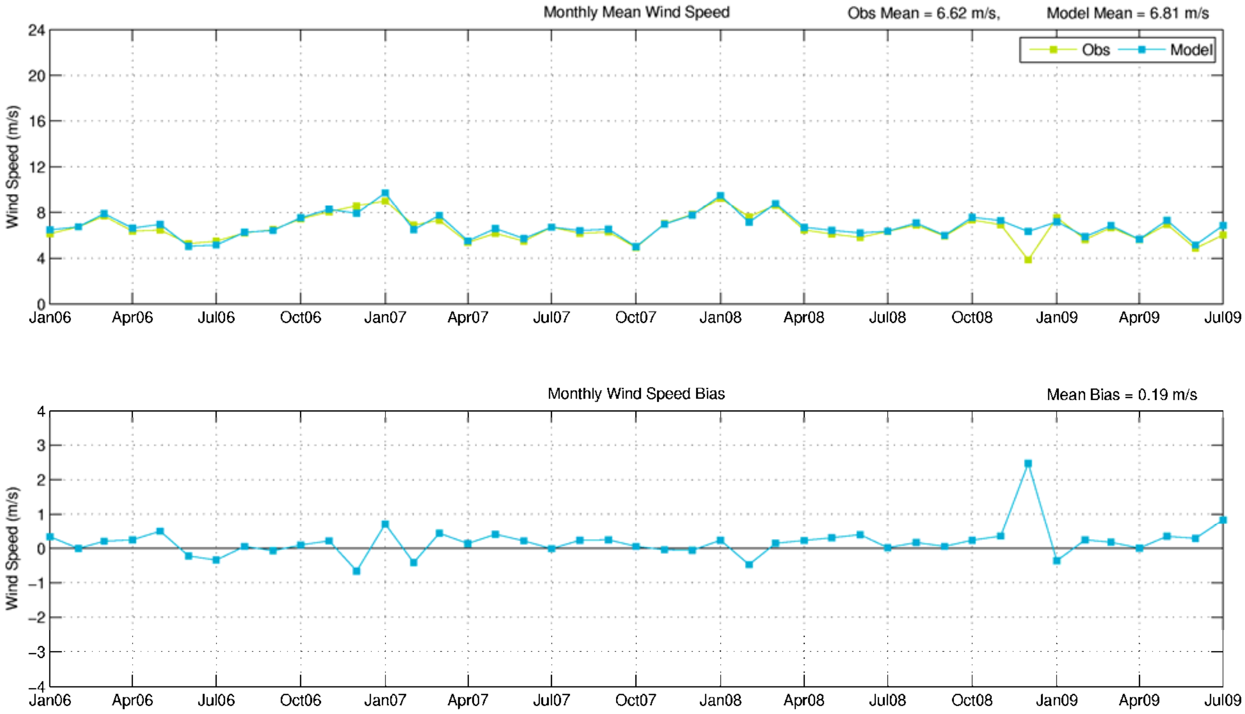

Figure 12: Flat site OS2, at a height of 50m

Results for the other site are presented in Figure 13. For this site the model appears to over-predict the measured winds, resulting in positive monthly biases between 0.3 and 1.1 m/s, with an overall mean of 0.7 m/s. The height correction reduces the bias slightly, but is not large enough to significantly improve the quality of the predictions. The results perhaps suggest that there may be insufficient drag in the model in this locality, possibly because the grid-box aggregated roughness length in the model is too small. For example, increasing the roughness length by a factor of almost 4 (from the value of 0.11m, derived from the 1 km gridded data, to 0.4m) causes only a very slight reduction in the winds at 70m. This suggests that the cause of the positive bias is probably not the model roughness, but is more likely due to some peculiarity of the site or other deficiency of the model.

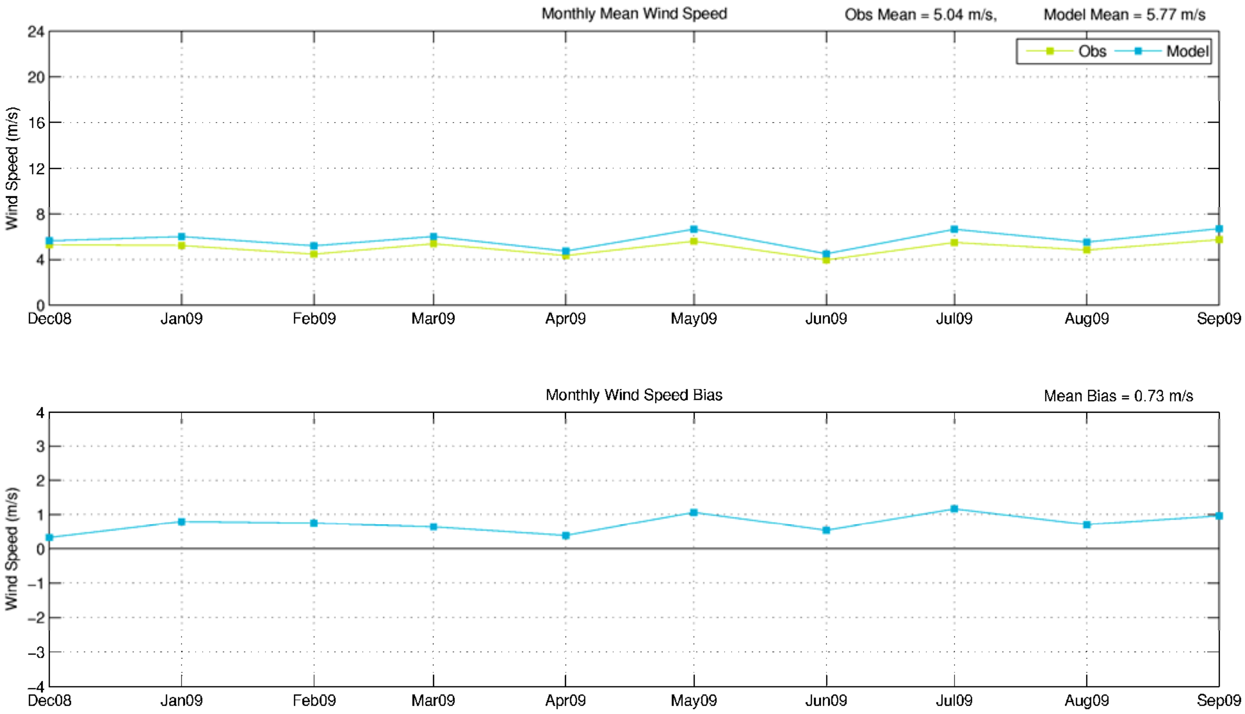

Figure 13: Flat site OS1, at a height of 70m

5 Discussion and Conclusions

Overall, the results presented here suggest that version 1 of the Virtual Met Mast™ provides reasonably accurate estimates of monthly mean wind speeds at typical hub heights. Of the sites tested against, greatest accuracy is achieved for near-shore sites which lie upwind (in a climatological sense) of the coast or where coastal land which is relatively flat and homogeneous, and for the higher hub heights. The results suggest that further improvements might be obtained via a near-coast correction scheme. This is currently planned for VMM version 2.

For onshore sites, the current tuning of the roughness reference height calculation is such that the roughness correction stage is applied only for sites where the surrounding terrain is most complex. For simpler sites no roughness correction is applied. For the sites considered so far, this tuning appears to be close to optimal. In general, the orographic height correction provides a correction of the appropriate sign, if a little strong, and offers an improvement over the uncorrected model data. Tentatively, given the very few sites used, it can be said that a typical accuracy for simple, flat onshore sites is better than ±0.5 m/s. For hilly terrain the accuracy is reduced but is generally as good as ±1 m/s.

Annex 1 – Downscaling

In version 1 of the VMM, corrections are applied to remove the effect of the sub-grid turbulent form drag (effective roughness) parameterisation scheme and to account for model height error. These corrections are based on those developed by Howard and Clark (2007).

The downscaling applied in VMM version 1 closely follows that described by Howard and Clark (2007). The corrections consist of a two-step process which is designed to correct for deficiencies in the NWP model characterisation of local roughness and the terrain:

1. Correction for the NWP model effective roughness length (which is enhanced in order to parameterise the turbulent form drag due to sub-grid orography) and replacement by a local vegetative value.
2. A further correction to the wind profile to account for local acceleration due to sub-grid orography.

The details of the implementation are described in greater detail by Clark (2009) and Howard and Clark (2007). They are presented schematically in Figure A1.

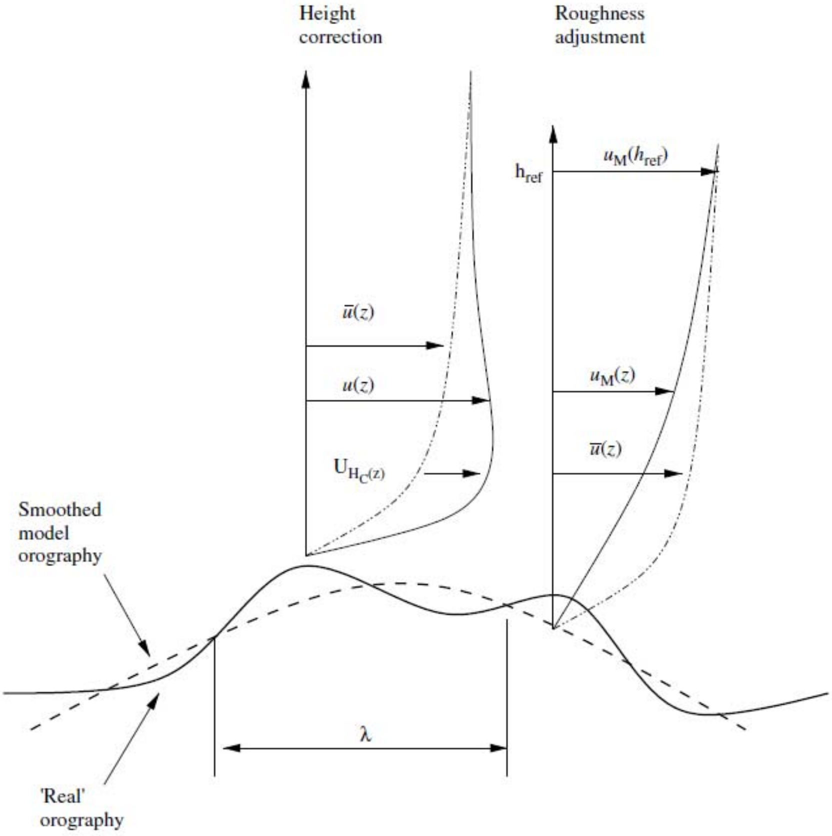

Figure A1: A schematic of how the roughness adjustment and altitude correction are applied.

The above corrections are applied sequentially and it is possible to verify the VMM predictions against observations at each stage. The first step (the roughness correction) involves estimating a reference height, z_{ref}, above which the effect of the sub-grid orography or, equivalently, the effective roughness length, is small. The wind profile below z_{ref} is then assumed to vary logarithmically with height and to be in local equilibrium. A vegetative roughness length is then used to define the wind profile below z_{ref} :

$$U(z) = U(z_{ref}) \frac{\ln[(z - d)/z_0]}{\ln[(z_{ref} - d)/z_0]} \qquad (1)$$

where z_0 is the local vegetative roughness length, d is the displacement height (both calculated at present on a 1km resolution grid) and U(z) is the wind speed profile. Note that if z_{ref} is deemed to lie below the height for which wind predictions are required (e.g. the wind turbine hub height) then no roughness correction is applied. The reference height itself is estimated by assuming that perturbations to the flow arising from the sub-grid orography will decay exponentially with height, with a decay scale of k^{-1}, where k is a characteristic horizontal wave number for the sub-grid orography. This assumption is consistent with linear solutions for flow over hills. If we then require that the perturbations have decayed by a fraction z then z_{ref} is defined by

$$z_{ref} = -\ln(\varepsilon)k^{-1} \qquad (2)$$

The parameter ε can be used as a tuning parameter to adjust z_{ref} . Larger values (below unity) will reduce z_{ref}. Tests for the sites considered here indicate that near-optimal results are achieved with a value of ε = 0.12, suggesting that the appropriate value of z_{ref} is the height at which the flow perturbations have decayed to 12% of their surface values. Smaller values of z (implying greater z_{ref}) typically resulted in winds which were too high compared with observations. Note that for all sites considered here, apart from one, the resulting values of z_{ref} are below the hub (or measurement) heights. Therefore, for all but one site, the roughness correction is not applied.

The second step (the orographic height correction) involves determining the error in model terrain height, Δh, for the site and estimating the corresponding acceleration (deceleration) which would occur when the site is located on an unresolved hill (in a valley). The correction makes use of linear theory for turbulent flow over hills (using Mason and King's (1985) model D solution[2]) but the crude representation of the error in the model orography (via a single

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[2] The VMM code includes the option to neglect inner-layer effects in the Mason and King solution. However, tests have shown that this has little impact on the results, presumably because the measurement heights considered are typically above, or comparable to, the inner

parameter, Δh) means that it should be regarded only as a first approximation. Effects due to terrain aspect, wind direction or sheltering by nearby hills are not accounted for. However, as shown in section 3 of the report, despite its simplicity the orographic height correction generally improves the VMM predictions and to a large extent removes model bias.

Note that in version 1 of the VMM downscaling is applied only over land. No corrections are applied for offshore sites.

References

Clark, P. (2009): UK Climatology - Wind Screening Tool. Met Office internal document. Available from: http://www-rdg/˜appc/documents/Documents.html

Howard, T. and Clark, P. (2007): Correction and downscaling of NWP wind speed forecasts *Meteorol. Appl.*, **14,** 105–116.

Mason, P.J. and King, J.C (1985): Measurements and predictions of flow and turbulence over an isolated hill of moderate slope. *Q. J. R. Meteorol. Soc.*, **111,** 617–640.

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layer depth

Annex 2 – Measure-Correlate-Predict Matrix Method

Woods and Watson (1997) describe a technique that aims to produce better estimates of the wind direction distribution than can be achieved using standard approaches (such as the mean direction difference). The concurrent data are used to obtain a joint frequency analysis of wind direction at the reference station and wind direction at the target site e.g. for 30° sectors the result is a 12x12 matrix of frequency counts. These counts are converted to percentage frequencies and then combined with the observed counts from the long period data at the reference station to produce estimates of the long-term wind direction distribution at the target site. Linear regression is used to relate the wind speeds at the two locations, with a separate equation for each direction sector.

The Met Office approach differs in that the matrix method is used for the wind speed as well as direction. 39 1m/s bins are used, plus with a 40th bin containing all winds over 40 m/s. This gives a total of 480 speed/direction bins, so that a year of hourly data gives an average of 18 samples per bin. In its current formulation, empty bins are assigned a unitary transformation, i.e. any data from the reference site outside the training period, falling into these bins, are carried through unchanged.

Note that this method only produces a prediction of the frequency distribution for each speed/direction sector at the target site – unlike regression based MCP techniques, it does not produce a time series of predicted speeds and directions.

Reference

Woods, J.C., Watson, S.J. (1997): A new matrix method of predicting long-term wind roses with MCP, *Journal of Wind Engineering and Industrial Aerodynamics*, **66** (2), 85-94

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