Comparison of corrections to site wind speeds in the offshore environment: value for short-term forecasting

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Abstract

This paper focuses on quantifying the impact of corrections to short-term forecasts of wind speed at wind turbine hub-height used to predict power output from large offshore wind farms. The effects considered are: wind speed gradients in the coastal zone, vertical wind speed profile extrapolation to hub-height and wake effects. It is shown that if wind farms are more than 10 km from the coast the spatial gradients across a wind farm 4-5 km wide are negligible – assuming that, typically, turbine hub-heights are above 50 m and conditions are near-neutral. Stability conditions have important implications for wind speed profiles, and possibly for wakes, although current lack of data means this cannot be confirmed.

Keywords: Offshore Modelling Wakes Forecasting

Introduction

As large offshore wind farms in the hundred's of megawatt class are developed, a number of special issues arise in terms of forecasting power output. On the positive side wind speeds offshore in the power producing classes appear to be more persistent, with lower probability and persistence of calms [1]. On the other hand, the development of wind farms in coastal areas (<50 km to the coast) where wind speed gradients and profiles increase the complexity of generating short-term forecasts. Short-term forecasts from a National Weather Service models are typically at coarse resolution in time and space which are then downscaled accounting for local influences on the wind speed (orography, roughness changes etc) using either statistical or dynamic approaches [2]. Large offshore wind farms cover areas ~20 km^2 and so a gradient of wind speeds may need to be applied across the wind farm in order to capture the spatial variability. Additionally, short-term variations in stability can lead to the wind speed profile deviating from logarithmic giving large errors in predicted wind speeds at turbine hub-heights. Finally wake effects are likely to be extremely important in dictating turbine-to-turbine variations in power output, averaging of the order 10 % power loss in an 80 turbine wind farm but exceeding this in specific situations. The analysis present considers three Danish sites – Horns Rev and Nysted have large (>70 turbine) wind farms and Omø Stålgrunde has also been considered as the site for an offshore wind farm (Figure 1). All three locations have extensive in situ meteorological measurements [3], [4].

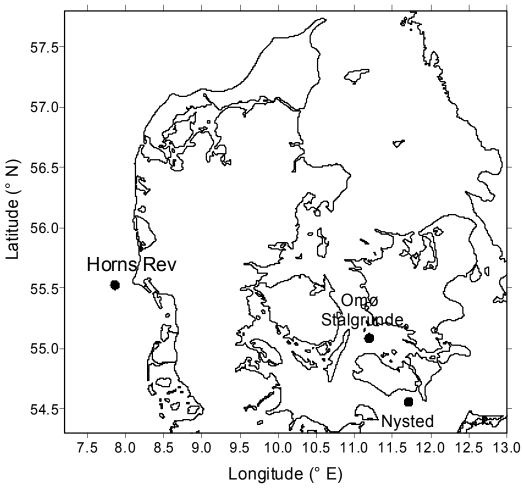

Figure 1. Locations of Horns Rev, Nysted and Omø Stålgrunde.

1. Quantifying the spatial variation of coastal wind speeds

Wind speeds in offshore coastal zones (<50 km from the coast) are generally not in equilibrium with the underlying surface [5]. Therefore, there can be substantial horizontal gradients in wind speed. Since short-term prediction methods typically use one wind speed for the prediction of power output from the wind farm [6] strong gradients might affect the predicted power output over very large wind farms. The largest offshore wind farms to date at Horns Rev and Nysted both cover more than 20 km^2. Here we focus on quantifying gradients at Horns Rev although these are likely to be smaller than gradients at Nysted because the fetch (distance to the nearest land) is very long at Horns Rev in the dominant westerly/south-westerly wind directions. At Nysted in most directions the fetch is less than 50 km so gradients might be expected to be larger.

1.1 Mesoscale model results

Here we utilise results from mesoscale model runs (KAMM [7]) made at Horns Rev shown in Table 1. The spatial resolution of these runs is 1 km by 1 km in a domain of 120 km by 120 km. Table 1 gives the geostrophic wind speed and direction from the 1000 mb pressure level. Stability is determined from the temperature gradient used as model input. Wind speeds at the hub-height of 62 m are linearly extrapolated from model results at 54.5 m and 85.8 m. These simulations have been discussed in [8].

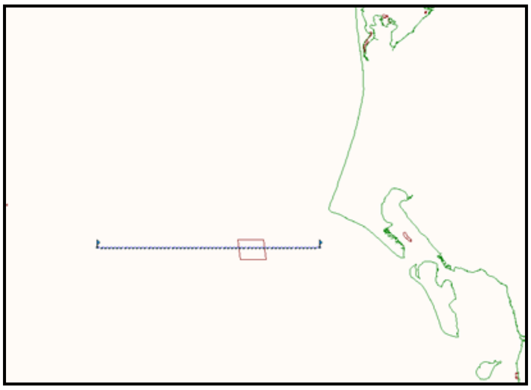

Figure 2. Map of western Denmark showing the Horns Rev wind farm and the 40 km transect (each point represents 1 km)

Transects (see Figure 2) for the 13 cases where the geostrophic wind speed was above 5 m/s are shown in Figure 3. Wind speed gradients away from the coast tend to be small and quite smooth. Wind speeds on the 40 km transect are within 2% of the average and in absolute terms the wind speed gradient across the wind farm is predicted to be less than 0.1 m/s in all but one case (7 Mar 2000). Clearly the situation would be different if the wind farm was closer to the coast but at this height, at this location, gradients in wind speed are determined by the mesoscale model as negligible.

Table 1. Mesoscale model cases

	ID (Time/date)	Geostrophic wind speed (1000 mb pressure level) (m/s)	Geostrophic wind direction (1000 mb pressure level) (°)	Stability
A	00Z21MAY1999	0.67	220	Very stable
B	12Z26MAR2000	1.96	131	"
C	00Z30JUL1999	3.54	270	"
D	12Z10AUG1999	5.07	165	"
E	12Z23NOV1999	5.76	72	"
F	00Z31AUG1999	6.56	116	Stable
G	12Z16MAY2000	7.76	15	"
H	18Z10JUL1999	8.87	270	"
I	00Z22JUN1999	9.26	124	"
J	00Z08OCT1999	11.72	86	"
K	12Z19OCT1999	11.97	279	Near-neutral
L	12Z03OCT1999	16.18	59	"
M	12Z16JAN2000	16.74	142	"
N	12Z01FEB2000	17.80	71	"
O	12Z07MAR2000	17.94	108	"
P	00Z17DEC1999	21.23	77	"

The question then arises whether these few mesoscale model runs can be determined to be representative. To calculate an approximate climatological weighting the simulations were compared with data from Horns Rev for the period 1999-2003. The data were divided into three wind speed classes (0-5, 5-10 and 10-15 m/s) and 8 wind direction sectors and then a weighting factor calculated for each simulation in order to reproduce the wind climate at Horns Rev. Figure 4 shows the weighting factors and the wind direction distribution from [4]. These weighting factors were applied to each of the mesoscale model runs to approximate an average gradient which is shown in Figure 5.

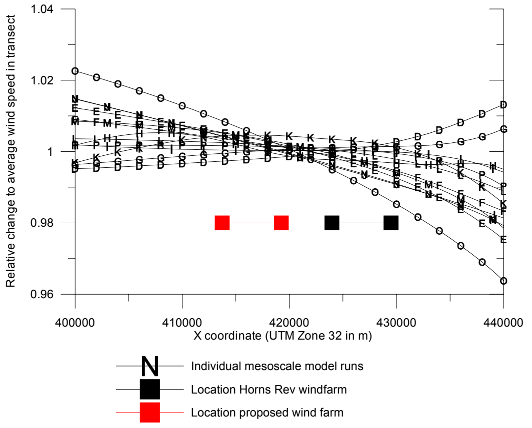

Figure 3. Transects of relative wind speed at 62 m height predicted by the mesoscale model for Horns Rev. Also shown are the locations of the current wind farm (black) and the proposed new wind farm (red). Note that the most easterly point shown is approximately 13 km from the coastline on the westerly transect.

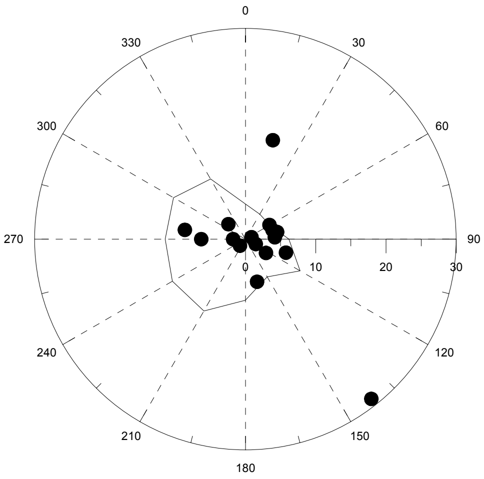

Figure 4. Frequency distribution of wind direction from Horns Rev [4] (line) and climatological weighting (dots) applied to KAMM runs which accounts for the wind speed and direction frequency.

1.2 WAsP Engineering results

Simulations were made with WAsP Engineering [9] for the same domain and the same geostrophic wind speed and direction as for the mesoscale model runs listed in Table 1. On average the maps tend to be smoother and with fewer features than predicted by the mesoscale model, presumably because mesoscale thermal effects are not modelled in WAsP Engineering. In order to make a simpler comparison the same transects were calculated as for the mesoscale model runs and subject to the same climatological weighting. The results are shown in Figure 5. This indicates a broadly similar wind speed gradient on average of less than 0.4 m/s over the transect. Note there is a significant difference in the absolute wind speeds with WAsP Engineering predicting higher wind speeds than KAMM. However, as shown, the wind speed gradient is consistent.

1.3 Comparison with satellite-derived wind speeds

To compare a gradient calculated from Synthetic Aperture Radar images of the Horns Rev area a slightly different approach was needed. The derivation of the mean wind map was described in [10]. Derived wind speeds are for 10 m so the wind speed gradient cannot be compared directly with the KAMM results but the gradient was recalculated from WAsP Engineering at 10 m. As shown in Figure 4 the gradient derived from the satellite images is about 0.8 m/s along the transect – about twice as large as is predicted by WAsP Engineering which predicts approximately the same gradient for both 10m and 62 m heights and is in good agreement with the KAMM average at 62 m. The reason that the satellite images predict a larger gradient might be that the satellite-derived wind speeds use the roughness of the sea surface to determine a wind speed at a nominal height of 10m [11].

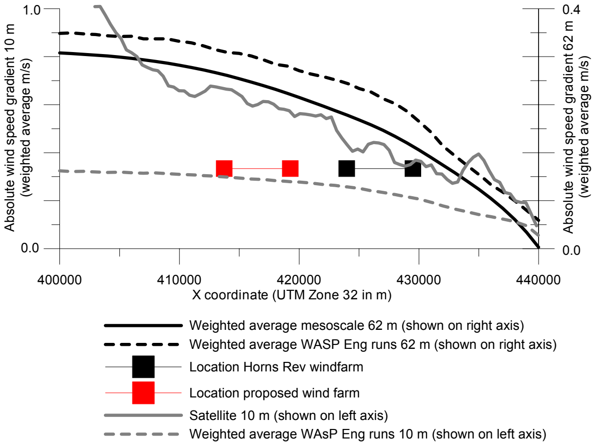

Figure 5. Wind speed gradients on a westerly transect through the Horns Rev wind farm. The most easterly point shown 440000 m E in UTM zone 32 is 13 km from the coastline in the transect direction).

1.5 Gradients at Nysted

For comparison the WAsP Engineering simulations shown in Table 1 were also run for the domain containing the Nysted wind farm shown in Figure 6. Wind speed gradients across the wind farm are strongly influenced by the wind direction due to the comparatively short fetch in the north and north-easterly directions. However as shown in Figure 7, gradients in wind speed across the wind farm are less than 0.4 m/s on average and therefore can be disregarded in the current context.

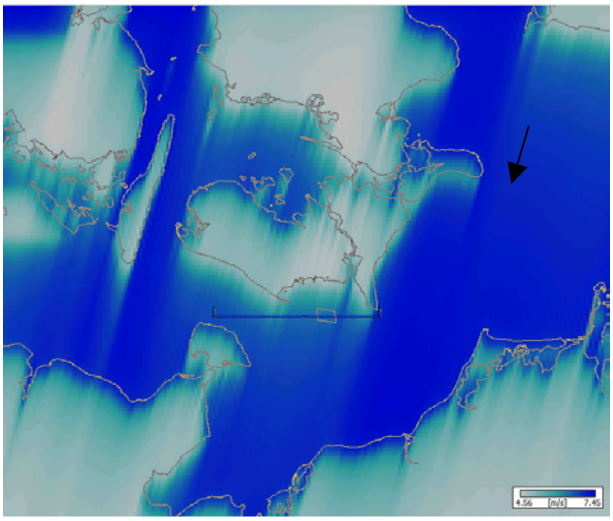

Figure 6. The domain for the Nysted simulations showing the westerly transect and the wind farm location. This WAsP Engineering simulation is for 16 May 2000 (shown as G in Table 1).

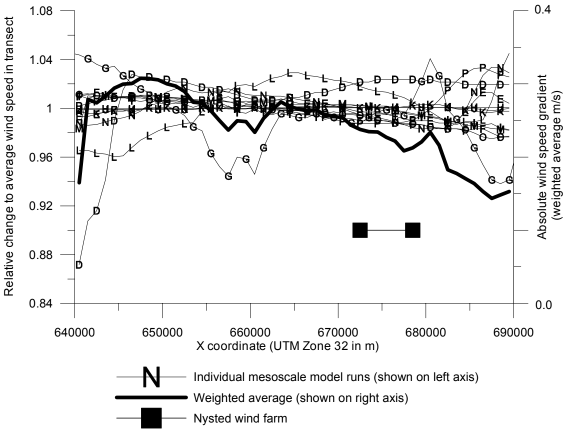

Figure 7. Gradients of wind speed on a westerly transect through the Nysted Windfarm.

2. Role of stability

Temperature gradients influence the wind resource more strongly offshore because ambient turbulence is lower than it is over most land surfaces [12]. The stability climate at a particular site seems to be strongly synoptic with a smaller influence of the fetch (defined here as the distance to the coastline) assuming the wind farm is placed beyond 10 km from the nearest coast [13]. As shown in Figure 8 (based on data from Nysted) the wind speed profile takes much longer time/distance to reach equilibrium in stable than near-neutral or unstable cases. Hence we can anticipate that both coastal gradients and vertical wind speed profiles are influenced by stability and these are discussed below. Much less clear is the role of stability on the rate of wake propagation downstream. Although it might be anticipated that wakes propagate further in stable conditions than unstable conditions, high turbulence generated by the wind farms may negate the impacts of stability within, and possibly downwind, of large wind farms.

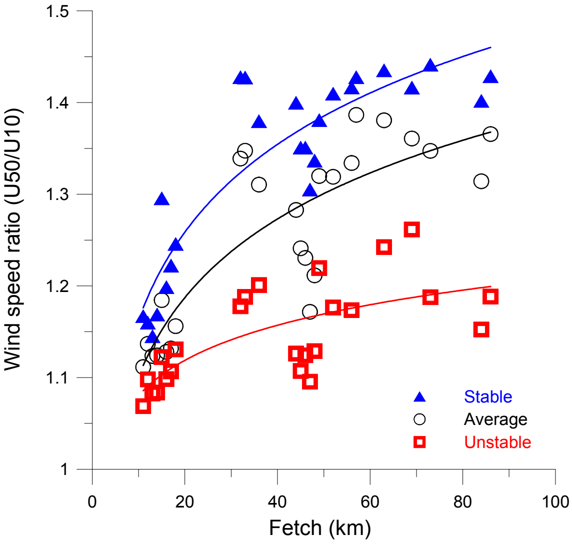

Figure 8. Ratio of wind speeds at 50 m to those at 10 m height for different fetches and stability conditions.

2.1 Calculation of stability

The correct way to calculate stability is to use the measured air temperature difference and not to take the difference between two temperature measurements [3]. Determination of the temperature gradient should be precise to two decimal places – and this is very difficult to achieve with two temperature sensors – even if they are calibrated correctly. Using the difference between the measured air temperature and the measured sea temperature compounds this problem – now there are two separate measurements but also the sea temperature measured is not typically the sea surface temperature which affects the wind speed gradient but a temperature measured at some depth (usually 2-4 m). Using the sea temperature rather than the air temperature gradient tends to force conditions away from near-neutral due to the likelihood of extreme temperature differences.

Stability conditions can be estimated based on measurements of air temperature, wind speed and temperature profile following the approach of [14]. In Figures 8 and 9 stability classes are defined based on the Monin-Obukhov length (L) where L is defined:

$$L = \frac{u_*^3}{\kappa \frac{g}{T} \overline{w'T'}} \tag{1}$$

where g is acceleration due to gravity, T is temperature and $\overline{w'T'}$ is the heat flux.

Once the Monin-Obukhov length has been defined for each observation the wind speed profile is corrected using:

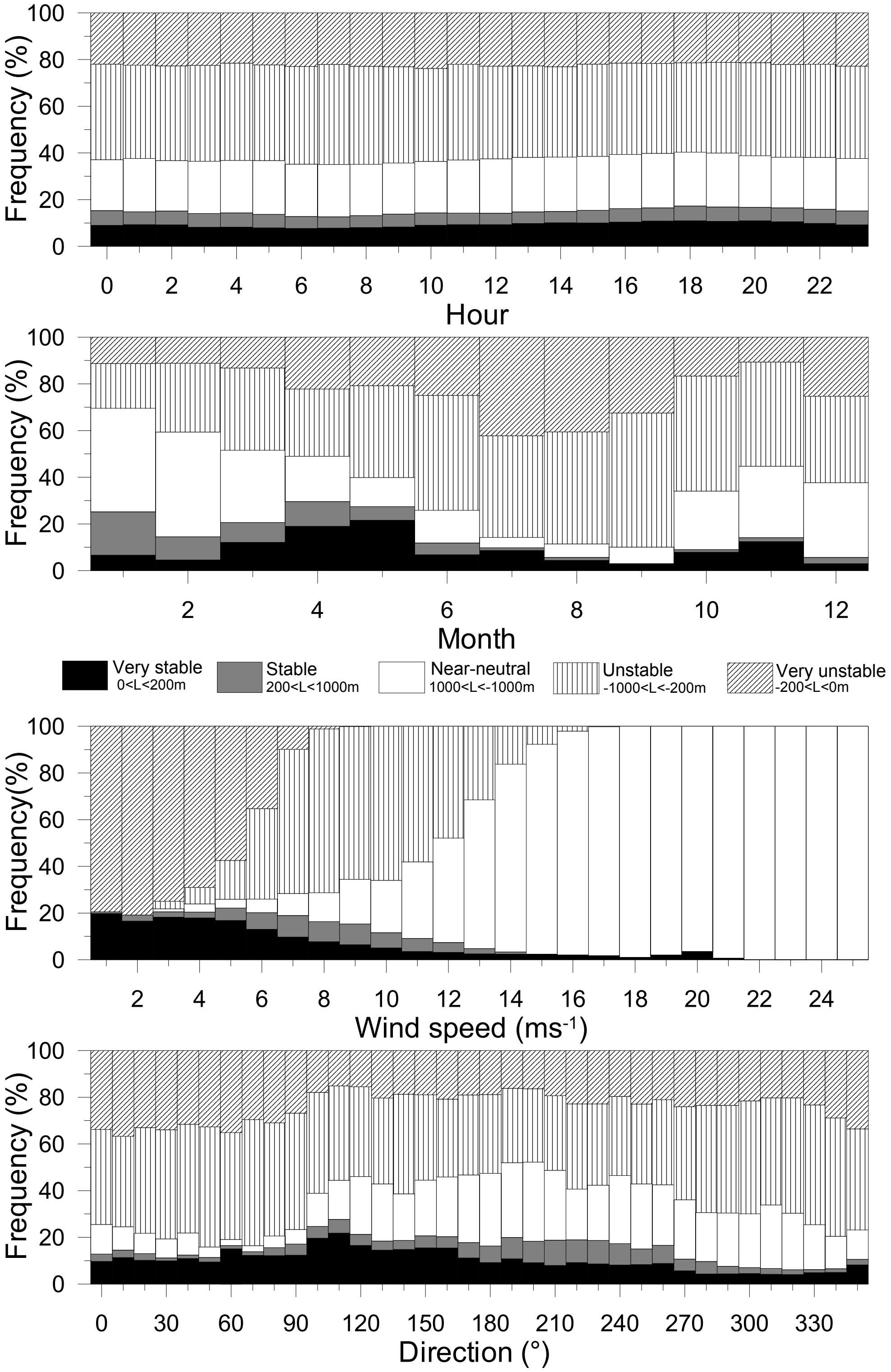

Figure 9. Stability climate at Horns Rev.

$$U = \frac{u_*}{\kappa} ln\left(\frac{z}{z_0}\right) - \psi(z/L) \qquad (2)$$

where the function $\psi(z/L)$ is defined according to the stability (see e.g. [15]). The wind speed profile can then be determined for each observation. The calculation of stability for Horns Rev is based on the measured wind speed at 15 m and the measured temperatures at 13 m and 55 m. For Horns Rev, the period from October 1999 to December 2003 was chosen for the stability analysis shown in Figure 9 – since data recovery was not equal in all months – otherwise calendar years should be selected because stability is seasonal offshore. This choice of data period gives observations distributed nearly equally between the climatological seasons with the fewest in winter 23.6% and the most in spring 26.2 %. As shown in Figure 9, there is relatively little diurnal variation in stability while the seasonal variation is more pronounced. In addition to the relationship between air and sea temperature that leads to an increase in the number of stable conditions in spring, stability is also influenced by the wind speed with the number of near-neutral conditions increasing with increasing wind speed. This contributes to a large number of near-neutral conditions in the winter months. Stability is also influenced by the direction – westerly/south-westerly winds have long fetch and higher wind speeds giving a larger proportion of near-neutral conditions.

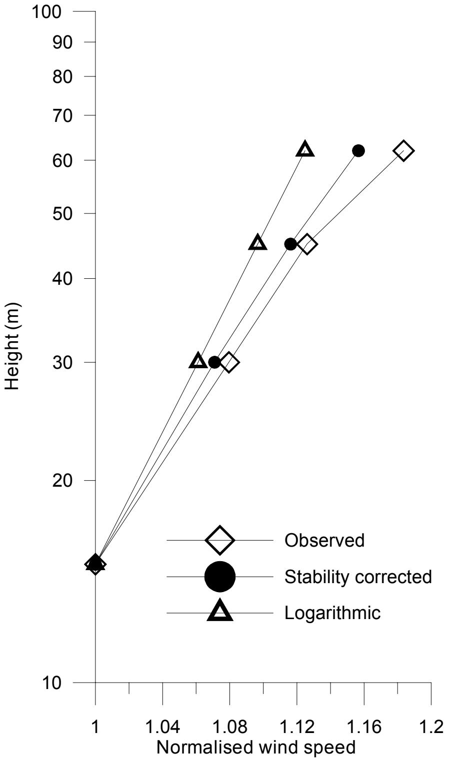

Figure 10. Comparison of normalised wind speed profiles at Horns Rev.

At Rødsand and Omø Stålgrunde, about 60% of the ten minute measurements fall in the near-neutral (|L| >1000 m) and slightly unstable (-200>L> -1000 m) categories [16] which is similar to the fraction at Horns Rev. The difference is that while employing the stability correction improves the prediction of the vertical wind speed profile to 50m at both Rødsand and Omø Stålgrunde (in terms of the mean wind speed, a reduced standard deviation and root mean square (r.m.s) error) only the mean wind speed prediction is improved at Horns Rev (in comparison with a logarithmic profile). The standard deviation and r.m.s. error are both increased at Horns Rev.

This suggests that the stability correction may not be the correct approach for the wind speed gradient at Horns Rev, despite the improved prediction of the wind speed profile (Figure 10). It is worth noting that [17] suggest that the wave boundary layer is shallower than 100 m offshore and that the wind speed profile should be modelled using the Ekman layer approach.

2.2 Impact of stability corrections on power output

In brief, using logarithmic or stability corrected wind speeds from 10 m height to extrapolate to 62 m and then calculate power output makes a significant difference to estimated power output. Assuming that the observations from Horns Rev give the correct power output 100%, using a stability corrected profile gives a power output of 98% of the observed while using a logarithmic profile gives an estimate of 88%. Further work remains to be done to evaluate the extrapolated profiles from Numerical Weather Prediction models in order to assess their accuracy.

3. Roughness variations offshore

Roughness of water varies with wind speed with the simplest relationship being given by Charnock [18]:

$$z_0 = a\frac{u_*^2}{g} \qquad (3)$$

There has been a lot of discussion regarding the value of the constant *a* which is likely not a constant but varies according to the distance to the coast line, water depth, wave heights e.g. [19], [20]. The role of varying roughness of the water surface has no significant impact on the calculation of wind resources offshore [21]. This is due to the low roughness in the logarithmic wind equation:

$$U = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \qquad (4)$$

Even quite large changes in a low roughness make a very small difference to the extrapolation of wind speeds from 10 m to turbine hub-heights as shown in Figure 11. Clearly using data from the measured or modelled height closest to hub-height is preferable and will result in the lowest errors. Wind speeds may also be extrapolated from a model layer e.g. at 100 m down to turbine hub-heights. In some circumstances (e.g. using buoy data from 2m height) the choice of roughness length will have a profound impact on the predicted wind speed.

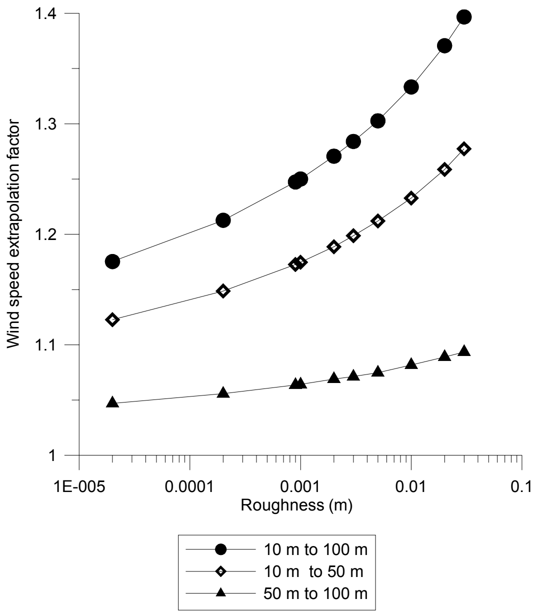

Figure 11. Wind speed extrapolation factor based on a logarithmic profile for different heights and roughnesses.

An extreme example is shown in Figure 12. Here we assume that the wind speed at 10 m height increases by 2 m/s per hour until it reaches 26 m/s. The choice of timescale here is irrelevant. Assuming a constant standard roughness of 0.0002 m for offshore, the wind speed at 100 m is predicted using the logarithmic wind profile equation (equation 4). Alternatively we can use equation 3 to determine the roughness length and then equation 4 to predict the wind speed at 100m. The largest absolute difference between the two predicted 100 m wind speeds is at the highest wind speed of 26 m/s at 10m where it is 1.36 m/s. However, in terms of power output only differences in predicted wind speeds between cut-in and rated affect the outcome. Assuming a cut-in wind speed of 4m/s and a rated wind speed of 16 m/s – here the largest difference between these two predictions is 0.4 m/s. Hence given the uncertainty in determining the roughness precisely, it is illustrated that using a constant roughness of 0.0002 m will not significantly impact the predicted wind speed at heights up to 100 m assuming that the height of the initial measured/modelled wind speed is not below 10m and that the logarithmic profile law is applicable.

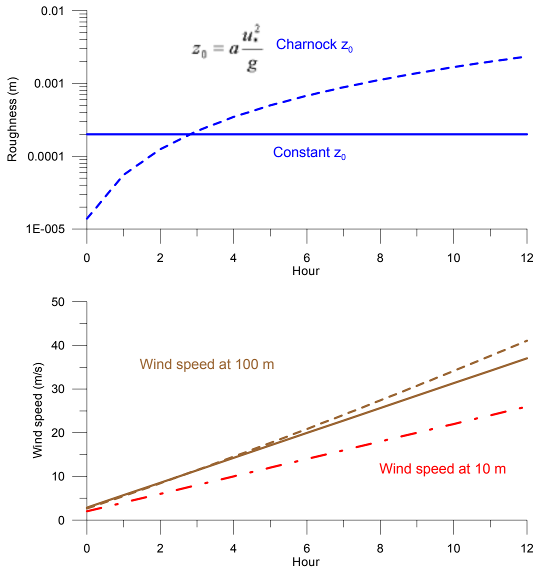

Figure 12. Example illustrating the impact of changing wind speed/roughness on extrapolated wind speed at 100 m height.

It is worth noting here that there is often confusion about the height of measured/modelled offshore wind speeds. While most models will assume the height given refers to the height above mean sea level, measured heights may be given with reference to height above the mast base (where the mast base may be several metres above mean sea level) or heights may be given with reference to a specific tide such as the highest astronomical tide and some maps give sea level with reference to lowest astronomical tide. Given mean tidal ranges of 3 m or so which are quite common in the North Sea [22] using different height references, particularly for the lowest height, can result in significant differences in the prediction. Tidal range is not though to have a significant impact on wind resources [23], [21] but tidal flats may have an effect on wind resource modelling. Assuming the surface is always water will give an over-estimate of wind power.

4. Wakes

Wakes within a large offshore wind farm are predicted to causes power losses of the order 10% [24]. This depends on many factors such as the turbine orientation and spacing, wind climate and turbine type. However, most wake models were developed for single wakes and there are even substantial differences between the wake losses predicted for single wakes by different models [25], [26] although the best results in terms of model agreement and model agreement with limited data sets is at moderate turbulence and moderate wind speeds. Prediction of multiple wakes likely requires feedback between wake and boundary-layer development [27]. Until data are collected and processed from large offshore wind farms, there is some uncertainty how well current state of the art models model wind farm wakes. In order to provide a first assessment a test case based on Horns Rev is shown below.

In terms of mean wake loss we assume here a test climate based on a general climate for Denmark. As shown in Figure 13, the percentage mean wake loss depends on the position of the wind turbine inside the wind farm with central turbines obviously experiencing larger losses. While wake losses from the more frequent and higher wind speed west and south west sectors are more important to the overall power loss from the wind farm, percentage losses by sector are higher from the north and east sectors, presumably because of higher wake losses at low wind speeds. For central turbines in the southern most row these sector wake losses are predicted to exceed 20-25% giving mean wakes losses of the order 13%. This indicates that in terms of correcting power output from large wind farms, accurate assessment of wakes is by far the most important of the factors considered.

5. Summary

Gradients of hub-height wind speed away from the near-coastal zone (greater than about 10 km) from the coast are shown to be typically quite smooth and of the order 0.1 m/s per 10 km. However, the effects of stability have not been explicitly considered and gradients at 10 m or below appear to be much larger. Short-term variations in roughness length have been shown to have little impact on wind resources and can be neglected except at high wind speeds or when extrapolating from below 10 m height. Wind turbine wakes in large wind farms are considered to be the largest correction which is needed beyond accurate wind speed at hub-height in large offshore wind farms. However, further work remains to be done evaluating the impact of gradients and stability in Numerical Weather Prediction forecasts. If forecast wind speeds are made for a grid with resolution of 5-20 km, then location of the grid with regard to the coast is important for correct assessment of wind speed gradients.

6. Acknowledgements

This work was funded in part by the Danish Public Service Obligation PSO (FU4103), STVF SAR-WAKE (26-02-0312), STVF SAT-WIND (2058-03-006) and the Anemos project (ENK5-CT-2002-00665) funded by the European Commission under the 5th (EC) RTD Framework Programme (1998 - 2002) within the thematic programme "Energy, Environment and Sustainable Development". We also acknowledge ESA EO-1356 for the SAR data.

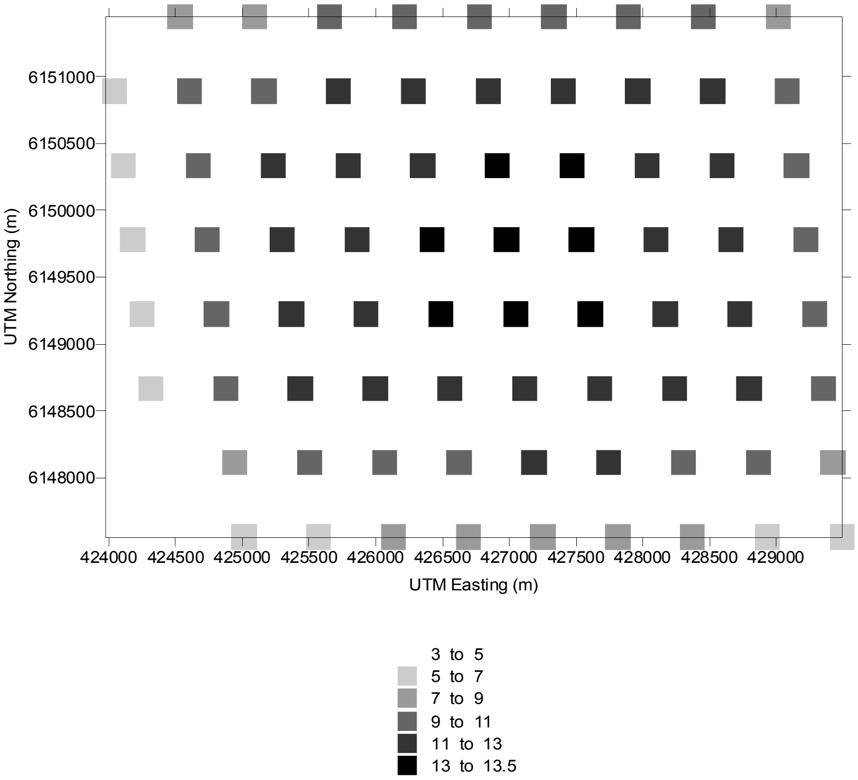

Figure 13. Mean wake losses (percentage of power output) predicted by WAsP for a general Danish wind climate at Horns Rev.

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