MODELLING THE VERTICAL WIND SPEED AND TURBULENCE INTENSITY PROFILES AT PROSPECTIVE OFFSHORE WIND FARM SITES

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ABSTRACT: Monin-Obukhov theory predicts the well-known log-linear form of the vertical wind speed profile. A turbulence intensity profile can be estimated from this by assuming that the standard deviation of the wind speed is proportional to the friction velocity. Two parameters, namely the aerodynamic surface roughness length and the Monin-Obukhov length, are than needed to predict the vertical wind speed and turbulence intensity profiles from a measurement at one height. Different models to estimate these parameters for conditions important for offshore wind energy utilisation are discussed and tested: Four models for the surface roughness and three methods to derive the Monin-Obukov-length from measurements are compared. They have been tested with data from the offshore field measurement Rødsand by extrapolating the measured 10 m wind speed to 50 m height and comparing it with the measured 50 m wind speed.
The mean wind speed at 50 m height is under-predicted by 2% to 5% when extrapolated from a 10 m measurement. For the sea surface roughness it has been found that the simplest approach, a constant roughness, gave the best result. From the models to derive the Monin-Obukhov length the bulk method performed best. It has been shown that this is due to shortcomings of the description of the stability influence in the stable regime. The measured turbulence intensities show a large spreading, which is not captured in the modelling by any of the sea surface roughness models.

1 INTRODUCTION

It is expected that an important part of the future expansion of wind energy utilisation at least in Europe will come from offshore sites. The first large offshore wind farms are currently being built in several countries in Europe. For the resource estimation the vertical wind speed profile is important since wind measurements are often made at low heights and the results have to be extrapolated the planned hub height of the turbines. For turbine design the wind shear and turbulence intensity of the marine surface layer are important design parameters, especially since the growing rotor diameter makes turbines more vulnerable for spatial and temporal wind speed variations.
For typical offshore sites with a distance to land of more than 10 km the atmospheric stability and the sea surface roughness are the most important parameters for the description of the vertical wind speed profile.
The wind profile in the atmospheric surface layer is commonly described by Monin-Obukhov theory, which predicts a log-linear form:

$$u(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right] \qquad (1)$$

It describes the wind speed u at height z by means of the friction velocity u_*, the roughness length z_0 and the Monin-Obukhov length L. κ denotes the von Karman constant, taken as 0.4, and Ψ_m is the stability function.
The turbulence intensity I, defined as standard deviation of wind speed divided by mean wind speed σ_u/u, can be estimated from the friction velocity using the empirical relation $\sigma_u = Au_*$, where A is an empirical constant. A value of 2.4 is commonly used.
To derive the friction velocity from eq. (1) or to extrapolate wind speeds from one height to another the surface roughness z_0 and the Monin-Obukhov length L are needed.
Different ways to derive these parameters from measurements are presented and compared. The models used to derive the sea surface roughness and Monin-Obukhov length are discussed in sections 3 and 4, respectively. Data from the field measurement Rødsand (see section 2) are used to test the models. The combinations of the different methods are used to predict the 50 m wind speed at Rødsand from the measurement at 10 m height as a test application in chapter 5.

2 THE RØDSAND MEASUREMENT

The Rødsand field measurement is located about 11 km south of the coast of Lolland (see Figure 1) and consists of a 50m high meteorological mast combined with underwater wave and current sensors. The meteorological measurement includes a sonic anemometer, cup anemometers at three heights, wind direction, temperature and temperature difference measurements. For a description of the measurement and the quality control of the data see (Lange et al., 2001). Wind speeds were corrected for flow distortion of the mast and booms with a method described in (Højstrup, 1999). Records with wind speed sensors in the shade of the mast were excluded as well as records with low wind speeds u_{50} < 5 m/s. The final data set consisted of about 4900 half-hourly records.

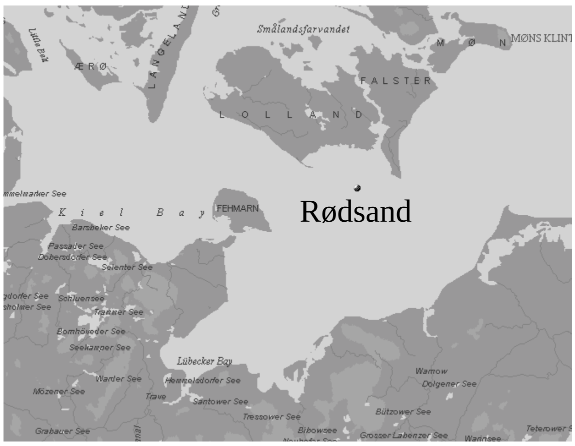

Figure 1: Rødsand measurement site

3 MODELS OF SEA SURFACE ROUGHNESS

3.1 Description of the models

Compared to land surfaces the surface roughness of water is very low. Additionally, it is not constant, but depends on the wave field, which in turn is caused by the wind speed, fetch (distance to coast), etc. Four models for sea surface roughness are compared:

1. Constant: The simplest approach of a constant sea surface roughness is often used in wind power applications, e.g. in the wind resource estimation program WAsP (Mortensen, 1993). A value of z_0=0.2 mm is assumed.
2. Charnock relation: The most common model taking into account the wave field by its dependence on wind speed is the Charnock relation (Charnock, 1955):

$$z_0 = z_{ch} \frac{u_*^2}{g} \qquad (2)$$

   Here z_{ch} is the Charnock parameter, which in this approach is a constant. A common value for the Charnock parameter is 0.0185 (Wu, 1980).
3. Wave age dependent model: The Charnock relation works well for the open ocean, but for coastal areas is was found that the Charnock parameter is site specific. This reflects the influence of other physical variables on the wave field. Several attempts have been made to extent the Charnock relation by including additional quantities which describe the wave field. Several approaches have been tested (Lange et al., 2001b) and a parameterisation of the Charnock parameter with wave age by (Johnson et al., 1998) has been chosen:

$$z_{ch} = A \left(\frac{c_p}{u_*} \right)^B \qquad (3),$$

   where c_p/u_* is the so-called wave age with velocity of the peak wave component c_p and friction velocity u*. A and B are empirical constants estimated to A=1.89 and B=-1.59.
4. Fetch dependent model: In practical applications wave quantities are often not available. An empirical relation has been used to estimate the wave age from upstream fetch. Combined with the wave age model this leads to (Lange et al, 2001b):

$$z_0 = \frac{u_*^2}{g} A C^B \left(\frac{g}{u_*^2} x_{eff} \right)^{BD} \qquad (4),$$

   where x_{eff} is the effective fetch, i.e. the distance to a straight perpendicular coastline which would lead to a similar wave field. The empirical constants have been estimated by (Kahma and Calkoen, 1992) to C=3.08 and D=-0.27.

The different models have been investigated in (Lange et al, 2001b). For the prediction of wind speed from measured quantities only small improvements compared to the Charnock equation could be obtained by the introduction of wave field dependent parameters in a power law relation.

3.2 Turbulence intensity

The capability of the sea surface roughness models to predict the turbulence intensity at 10 m height from the measured wind speed has been tested. No stability correction has been applied and three different models for the sea surface roughness have been used:

- The constant roughness assumption, which predicts a turbulence intensity independent of wind speed.
- The Charnock relation, which predicts an increase of turbulence intensity with wind speed.
- The wave age model, which additionally uses the measured wave age for the prediction.

The model results are shown in Figure 2 together with the measured turbulence intensities versus wind speed. The measurement data show a large spread of turbulence intensities for a certain wind speed especially at lower wind speeds. This spread is not captured by any of the models. However, the general trend of the measure data especially at higher wind speeds seems to be captured best by the Charnock approach.

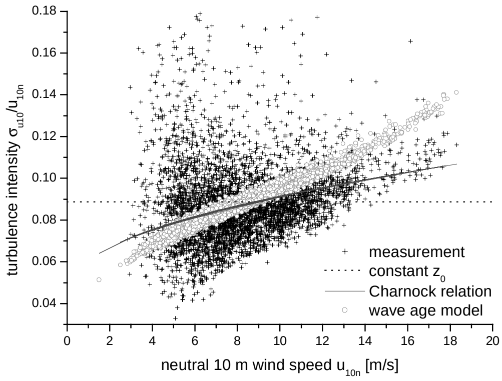

Figure 2: Measured and modelled turbulence intensities at 10 m height at Rødsand versus 10m wind speed

4 DERIVATION OF MONIN-OBUKHOV LENGTH

4.1 Description of the different methods

The atmospheric stability differs greatly between land and water areas. For wind energy applications the stability is more important offshore compared to land sites due to the low surface roughness of water, which means that also for higher wind speeds the stability can deviate substantially from neutral.

Stability is usually described with Monin-Obukov similarity theory using the Monin-Obukov-length L as stability parameter. Three different ways to derive this parameter are considered:

1. Sonic: L is determined directly from sonic anemometer measurements of friction velocity and heat flux by:

$$L = - \frac{u_*^3}{\kappa \frac{g}{\overline{T}} \overline{w'T'}} \qquad (5)$$

   Here $\overline{w'T'}$ is the covariance of temperature and vertical wind speed fluctuations.
2. Gradient: Temperature and wind speed difference measurements at 10 m and 50 m height are used to estimate the gradient Richardson number Ri_Δ:

$$Ri_\Delta(z') = \frac{\frac{g}{\overline{T}} \left(\frac{\Delta \overline{T}}{\Delta z} + \frac{g}{H_p} \right)}{\left(\frac{\Delta \overline{u}}{\Delta z} \right)^2} \qquad (6)$$

   Here $\Delta T/\Delta z$ is the temperature difference ΔT at a vertical height difference Δz. Equally Δu/Δz is the wind speed difference at the vertical height difference Δz. H_p is the specific heat of air at constant pressure. The height z' at which this Ri number is valid can be estimated as $z'=(z_1-z_2)/\ln(z_1/z_2)$. The gradient Richardson number can be converted to L by means of the following relations:

$$L = \begin{cases} \left(\dfrac{z'}{Ri}\right) & Ri < 0 \\ \dfrac{z'(1-5Ri)}{Ri} & 0 < Ri < 0.2 \end{cases} \qquad (7)$$

3. Bulk: Air and sea temperature measurements together with the wind speed at 10 m height are used. An approximation method proposed by (De Bruin et al., 2000) has been followed.

<u>4.2 Investigation of the different methods</u>

The measured ratio between the wind speeds at 50 m and 10 m height has been bin-averaged according to the stability parameter 10/L, where the Monin-Obukhov length L was determined with the three different methods described above. The dependencies of the ratio on stability are compared with the prediction of Monin-Obukhov theory in Figure 3. The Charnock relation has been used for the roughness description. For unstable conditions (negative 10/L) large differences of the ratio can be seen for the sonic method, while the other methods, especially the gradient method, closely follow the theoretical curve. In the stable regime all methods show deviations and the bulk method is closest to theory.

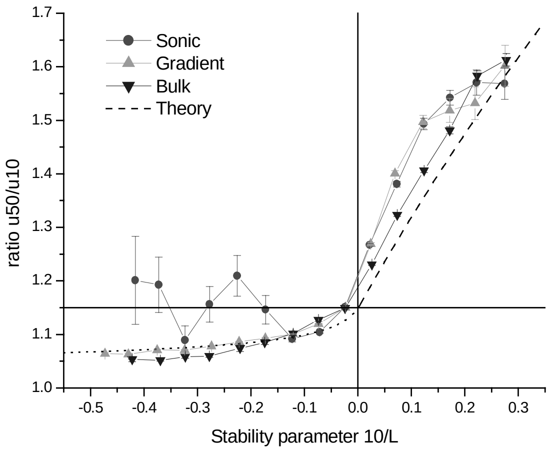

Figure 3: Bin-averaged measured wind speed u50/u10 versus stability parameter 10/L determined with three different methods

The different methods have been used to predict the wind speed at 50 m height from that measured at 10 m. The Charnock relation has been used to estimate the roughness. The ratio of measured and predicted wind speeds at 50 m has been built.

As an example a scatter plot of the ratio versus the stability parameter 10/L is shown in Figure 4 for the gradient method. It can be seen that the prediction works well in the unstable regime, while a large and systematic deviation is found for stable stratification. The deviation already exists for neutral conditions.

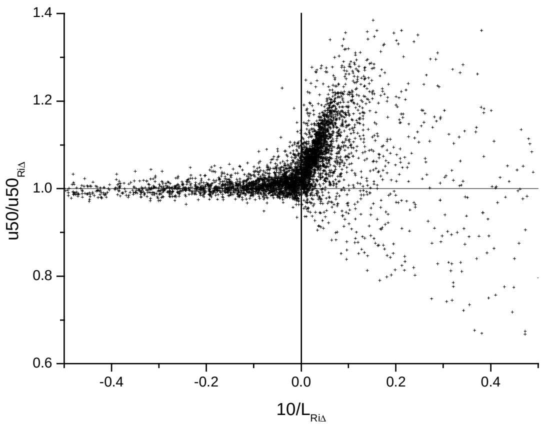

Figure 4: Ratio of measured and calculated wind speed at 50m height versus atmospheric stability; the wind speed has been calculated from the 10m wind speed using the Charnock roughness description and the stability determined via Ri number

The deviations of the different methods to determine the stability are compared in Figure 5. The deviations from theory found in Figure 3 are repeated here. At unstable conditions the sonic methods shows deviations of up to 15%, while for the other methods the deviations are only up to 2%. In the stable regime they all have a tendency to under-predict the 50 m wind speed. Errors of up to 15 % are found. This tendency increases first with increasingly stable stratification. At a certain point, which is very different for the different methods, the trend reverses and the ratio of measured and predicted wind speed decreases with increasing 10/L.

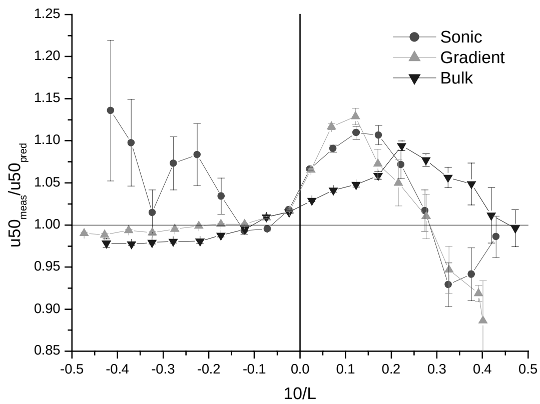

Figure 5: Comparison of different methods to determine the atmospheric stability; ratios of measured and calculated wind speeds at 50m height versus atmospheric stability are shown

It can be seen that the Monin-Obukhov theory with all three methods to determine the Monin-Obukhov length has shortcomings in the stable regime.

This indicates that other effects not described by this approach might play an important role: The height of the surface layer depends on stability and might for stable situations be below the measurement height of 50m. The length of the upstream sea fetch has an influence on the atmospheric stability due to the internal boundary layer developing at the coastline (see (Højstrup, 1999)). The roughness length might be different at different heights due to the variation of the wave field with distance to the coast. In stable stratification an uncoupling of surface layer wind from wind at higher heights might occur, causing low level jets (see e.g. (Smedman et al., 1996)). Further investigations are necessary to explain the unexpected behaviour found.

5 WIND SPEED PROFILE

The extrapolation of the wind speed from 10m to 50m has been tested with combinations of different models. Standard values have been used for all empirical constants. The ratio between measured and estimated 50 m wind speed has been built and its bias and rms-error calculated. It is given in the left two columns of Table 1.
From the models to derive L the bias and rms-error are lowest for the bulk method. For the sea surface roughness the constant value of WAsP, which is the simplest method, shows the best results both with respect to bias and rms-error.
The data were also divided into cases with stable and unstable atmospheric conditions (see Table 1). The Monin-Obukov-length L used for the selection was determined from sonic anemometer measurements with the eddy-correlation method. It can be seen that the bias is very different between both conditions. The rms-errors are about the same when L is determined with the sonic method, but different for the other two methods. The comparison shows clearly the shortcomings of the models in the stable regime.

Table 1: Comparison of different methods to predict the wind speed at 50 m height from the 10m wind; Bias and standard deviation of modelled time series compared to the measured one are shown for all data and separately for stable and unstable conditions

	all data		**stable data**		**unstable d.**	
(all in%)	bias	rms	bias	rms	bias	rms
L from Sonic method						
Constant	4.2	10.9	6.4	10.9	1.9	10.3
Charnock	4.9	11.2	7.7	11.1	1.9	10.6
Wave age	5.1	11.5	8.2	11.3	1.8	10.8
Fetch	5.2	11.5	8.2	11.3	1.9	10.7
L from Gradient method						
Constant	2.6	9.1	4.9	11.2	0.2	5.0
Charnock	3.4	9.1	6.2	11.0	0.3	5.0
Wave age	3.6	9.4	6.8	11.1	0.2	5.2
Fetch	3.7	9.3	6.8	11.1	0.3	5.1
L from Bulk method						
Constant	1.9	6.3	3.7	7.6	-0.1	3.5
Charnock	2.5	6.6	4.9	7.9	0.0	3.5
Wave age	2.8	7.0	5.4	8.2	-0.1	3.7
Fetch	2.8	6.9	5.5	8.1	0.1	3.7

7 CONCLUSION

The mean wind speed at 50 m height is under-predicted by 2% to 5% when extrapolated from a 10 m measurement for the offshore site Rødsand. The variation in the prediction of half-hourly records is in the order of 6-11% rms-error.
From the models to derive the M-O-length L the bias is lowest for the bulk method, which also shows the lowest rms-error. Results with the four sea surface roughness models show little difference. The constant value for the sea surface roughness, which is the simplest method, is slightly better than the other models both with respect to bias and rms-error.
Comparing the predictions for different atmospheric stratification shows large biases and rms-errors for the stable regime. It is shown that this is due to shortcomings of the methods to derive the M-O-length in the stable regime. Deviations of the measured wind speed ratio from the expectation of M-O-theory are found for all three methods.
A comparison of measured and modelled turbulence intensities showed that the large spreading present in the measurements is not captured by any of the models. The general trend of the turbulence intensity with wind speed seems to be modelled best with the Charnock model.

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