# EVALUATION OF MODELS FOR THE VERTICAL EXTRAPOLATION OF WIND SPEED MEASUREMENTS AT OFFSHORE SITES

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ABSTRACT: Monin-Obukhov theory predicts the well-known log-linear form of the vertical wind speed profile. Two parameters, namely the aerodynamic surface roughness length and the Monin-Obukhov-length, are needed to predict the vertical wind speed profile 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 measurements 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.

Satisfying results could be obtained for the mean value. The root-mean-square-error of the predicted time series of half-hourly values is large. For the sea surface roughness it has been found that the simplest approach, a constant roughness, gave the best result. For the stability influence the direct measurement of L yielded the lowest bias, but also the largest rms-error. Other methods lead to an increased bias in predicted wind speed. It has been shown that this is due to shortcomings of the models in the stable regime. There are indications that these deviations are dependent on the length of the upstream fetch.

Keywords: Off-shore, Coastal Sea Areas, Resources, Roughness, Atmospheric Stability, Wind Shear Effects, Rødsand

## 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 planning of offshore wind farms the vertical wind speed profile is needed for two main reasons: Wind measurements are often made at low heights and the results have to be extrapolated the planned hub height of the turbines. The profile produces a wind shear across the vertical extension of the (usually large) rotor, which is an important load factor.

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. $\kappa$ denotes the von Karman constant, taken as 0.4, and $\Psi_m$ is the stability function. 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 are used (see section 2). 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.

*Figure 1: Rødsand measurement site*

For a description of the measurement and the quality control of the data see (Lange et al., 2001). For this analysis data from 1998 to 2000 have been used. The Monin-Obukov-length L was determined by different methods and records were selected by requiring the different values of L to be consistent. Additionally, extreme situations (0>L>-20m and 0<L<50m) were excluded and a single peaked wave spectra (wave spectrum bandwidth<0.25) was requested. This excluded about 60% of the available data. 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. The final data set consisted of about 3500 half-hourly records.

## 3 MODELS OF SEA SURFACE ROUGHNESS

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 of the sea surface roughness are compared:

1. WAsP: The simplest approach is the one taken in the wind resource estimation program WAsP (Mortensen, 1993). A constant sea surface roughness 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). It was found that only small improvements compared to the Charnock equation could be obtained by the introduction of wave field dependent parameters in a power law relation. This is tested further together with the influence of atmospheric stability in section 5.

## 4 DERIVATION OF MONIN-OBUKHOV-LENGTH

### 4.1 Description of the different methods

The atmospheric stability differs greatly between land and water areas. Seasonal variations of the atmospheric stability are seen over the sea instead of the daily variations usually dominant over land. 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:

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

   Here $\overline{w'T'}$ is the vertical temperature flux measured with the eddy correlation method.

2. Gradient: Temperature and wind speed difference measurements at 10 m and 50 m height are used to estimate the gradient Richardson number $Ri_?$:

$$Ri_? (z') ? \frac{\frac{g}{T} ? \frac{?\overline{T}}{?z} ? \frac{g}{H_p} ?}{? \frac{?\overline{u}}{?z} ?^2} \qquad (6)$$

   Here ?T/?z is the temperature difference ?T at a vertical height difference ?z. Equally ?u/?z is the wind speed difference at the vertical height difference ?z. $H_p$ 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:

$$L ? \begin{cases} \frac{z}{Ri} & Ri ? 0 \\ \frac{z ? 1 ? 5Ri ?}{Ri} & 0 ? Ri ? 0.2 \end{cases} \qquad (7)$$

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.

4.2 Investigation of the different methods

The different methods described above have been used to predict the wind speed at 50 m height from the measured 10 m wind. The Charnock relation has been used to estimate the roughness. The ratio of the measured and predicted wind speed 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 2 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.

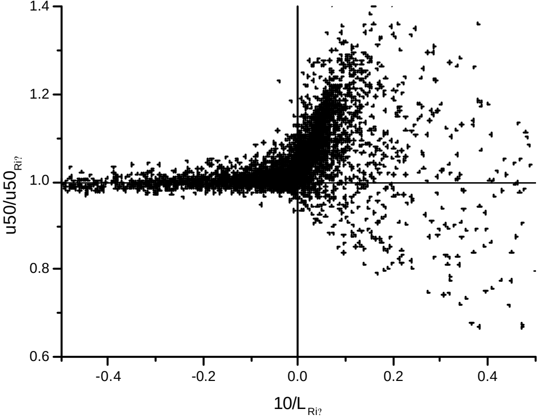

*Figure 2: Ratio of measured and calculated wind speed at 50m height versus atmospheric stability; the wind speed has been calculated from the 10m wind speed using the Charnock roughness description and the stability determined via Ri number*

The different methods to determine the stability are compared in Figure 3. All methods show a similar behaviour at unstable and neutral situations. In the stable regime they all have a tendency to underpredict the 50 m wind speed. 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.

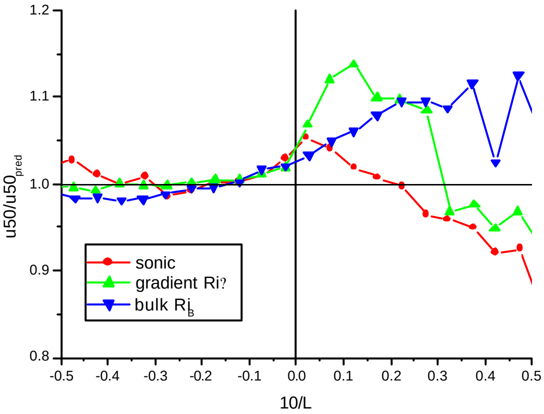

*Figure 3: Comparison of different methods to determine the atmospheric stability; ratios of measured and calculated wind speeds at 50m height versus atmospheric stability are shown*

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 TEST APPLICATION

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 and low wind speeds < 5 m/s have been excluded. The ratio between measured and estimated 50 m wind speed has been built and its bias and rms-error calculated. The result is shown in Table 1.

From the models to derive L the bias is lowest for the sonic method. However, this shows the highest rms-error, while the bulk method has the lowest. 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 wave age method leads to large errors.

*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*

| L from | $z_0$ from | bias [%] | rms-error [%] |
|---|---|---|---|
| Sonic | WAsP | 0 | 13 |
| | Charnock | 1 | 13 |
| | Wave age | 9 | 13 |
| | Fetch | 2 | 12 |
| Gradient | WAsP | 3 | 9 |
| | Charnock | 4 | 9 |
| | Wave age | 11 | 11 |
| | Fetch | 4 | 9 |
| Bulk | WAsP | 2 | 6 |
| | Charnock | 2 | 7 |
| | Wave age | 11 | 9 |
| | Fetch | 3 | 7 |

To investigate possible causes for the errors the ratio between measured and predicted 50m wind speed has been stratified with respect to the atmospheric stability and plotted as wind direction bin averages in Figure 4. The gradient method has been used to estimate L and the Charnock relation has been used to derive $z_0$. The deviations responsible for the bias occur for stable conditions. There is some indication that the deviations also depend on fetch.

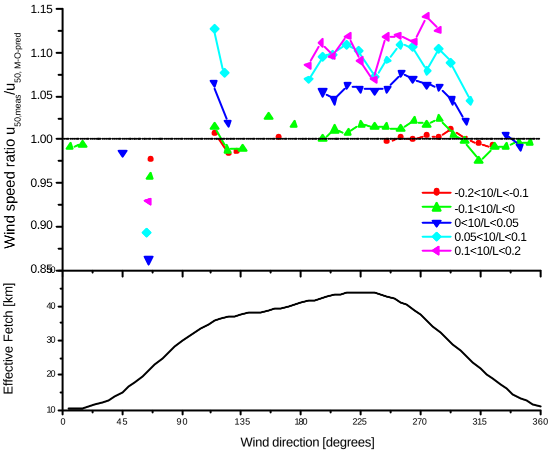

*Figure 4: Ratio between measured and predicted (from 10 m wind with Charnock roughness and gradient stability) 50m wind speed stratified with respect to the atmospheric stability and plotted versus wind direction*

## 6 CONCLUSION

Satisfying results have been found for the bias in the extrapolation of wind speed from 10 to 50 m for the offshore site Rødsand. However, the rms-error in the predicted time series is large. For the sea surface roughness it has been found that the simplest approach, a constant roughness, gave the best result. For the stability influence the direct measurement of L yielded the lowest bias, but also the largest rms-error. Other methods lead to an increased bias in predicted wind speed. It has been shown that this is due to shortcomings of the models in the stable regime. There are indications that these deviations are dependent on the length of the upstream fetch.

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