

## THE WIND SPEED PROFILE AT OFFSHORE WIND FARM SITES

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**ABSTRACT:** Using Monin-Obukhov theory the vertical wind speed profile can be predicted from the wind speed at one height, when the two parameters Monin-Obukhov length and sea surface roughness are known. The applicability of this theory for wind power prediction at offshore sites is investigated using data from the measurement program Rødsand in the Danish Baltic Sea. Different methods to estimate the two parameters are discussed and compared. Significant deviations to the theory are found for near-neutral and stable conditions, where the measured wind shear is larger than predicted. A simple correction method to account for this effect has been developed and tested.

As a test application, the wind speed measured at 10 m height is extrapolated to 50 m height and converted to wind turbine power output. The models for the estimation of the sea surface roughness were found to lead only to small differences, while for the different methods to derive the Monin-Obukhov length  $L$  have an important impact on the power output estimations. The simple wind profile correction method, which has been developed, leads to a clear improvement of the wind speed and power output predictions. For the extrapolation with Monin-Obukhov theory with different  $L$  and  $z_0$  estimations the prediction error is 5-9%. When the correction is applied, the error reduces to 2-5%. This can be compared with the result of the WAsP method, which is about 4%.

### 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. A reliable prediction of the wind resource is therefore crucial. This requires the modelling of the vertical structure of the surface layer flow, especially the vertical wind speed profile.

The wind speed profile in the atmospheric surface layer is commonly described by Monin-Obukhov theory (see e.g. Garratt, 1994). In homogenous and stationary flow conditions, it predicts a log-linear relation:

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

The wind speed  $u$  at height  $z$  is determined by friction velocity  $u_*$ , aerodynamic roughness length  $z_0$  and Monin-Obukhov length  $L$ .  $\kappa$  denotes the von Karman constant (taken as 0.4) and  $\Psi_m$  is a universal stability function.

Thus, if the wind speed is known at one height, the vertical wind speed profile is determined by the two parameters  $z_0$  and  $L$ .

### 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 50 m 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 detailed description of the measurement see Lange et al. (2001).

The air temperature over land in the upwind direction from Rødsand has been estimated from measurements at synoptic stations of the German Weather Service (DWD) and the measurement station Tystofte in Denmark (operated by the Risø National Laboratory) (see figure 1). For a more detailed description see Lange et al., 2002.

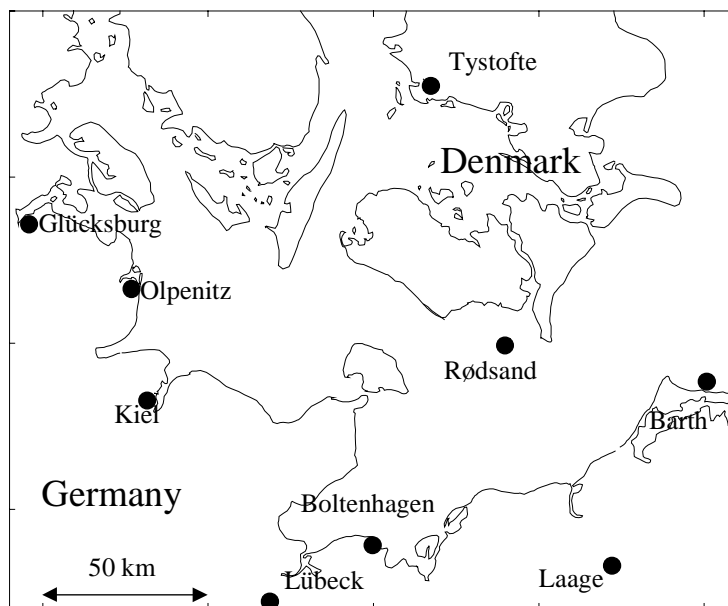


Figure 1: Map of the measurement stations

### 3 METHODS OF EXTRAPOLATION

#### 3.1 Derivation of Monin-Obukhov length

Atmospheric stability is described in Monin-Obukhov theory with the Monin-Obukhov length scale  $L$  as stability parameter. Three different ways to derive this parameter are considered using different input data (see e.g. Garratt, 1994):

- The calculation of  $L$  with the eddy-correlation method requires fast response measurements, e.g. by an ultrasonic anemometer.
- Wind speed and temperature gradient measurements at different heights can be used to derive  $L$  via the Richardson number.
- The method with least experimental effort employs a wind speed measurement at one height, water and air temperatures to calculate the bulk Richardson number, which is then related to  $L$ .

### 3.2 Sea surface roughness

Compared to land surfaces the surface roughness of water is very low. Additionally, it is not constant with wind speed like for land surfaces, but depends on the wave field, which in turn is determined by the wind speed, fetch (distance to coast), etc. It is investigated how different models to describe the sea surface roughness influence the prediction of the wind profile. Four models for sea surface roughness  $z_0$  are considered:

- The simplest 'model' is the assumption of a constant roughness, which is e.g. used in the WAsP program ( $z_0=0.2$  mm) (Mortensen et al., 1993).
- Most commonly used is the Charnock model (Charnock, 1955), which only depends on friction velocity.
- Numerous attempts have been made to improve this description by including more information about the wave field, e.g. by including wave age (Johnson et al. 1998) as additional parameters.
- These additional parameters require wave measurements, which are often not available for wind power applications. A fetch dependent model has therefore been developed, where the wave age has been replaced by utilising an empirical relation between wave age and fetch (Lange et al., 2001a).

### 3.3 Comparison with Rødsand measurements

From Monin-Obukhov theory (see eq.(1)) the wind speed at 50 m height is calculated from the measured 10 m wind. A deviation  $\Delta$  is defined as the ratio between this predicted and the measured wind speed. This deviation  $\Delta$  has been computed for the Rødsand data for all combinations of the three models to derive the Monin-Obukhov length  $L$  and the four models for the sea surface roughness.

Systematic deviations are always found for stable stratification. As example, the deviation  $\Delta$  for the gradient method to derive  $L$  is shown in figure 2 with the Charnock relation used to model  $z_0$ . A good agreement is found in the unstable region ( $10/L < -0.05$ ). For stable conditions the wind speed at 50 m height is systematically underpredicted. The deviation increases with increasing stability parameter  $10/L$ .

For comparison of the different methods, bin-averaged

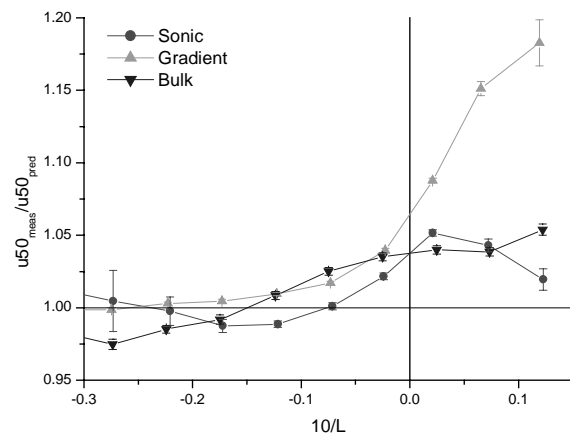


Figure 3: Bin-averaged ratio of measured and predicted 50 m wind speed versus stability parameter  $10/L$  with  $L$  determined by the sonic, gradient and bulk methods and  $z_0$  with Charnock model

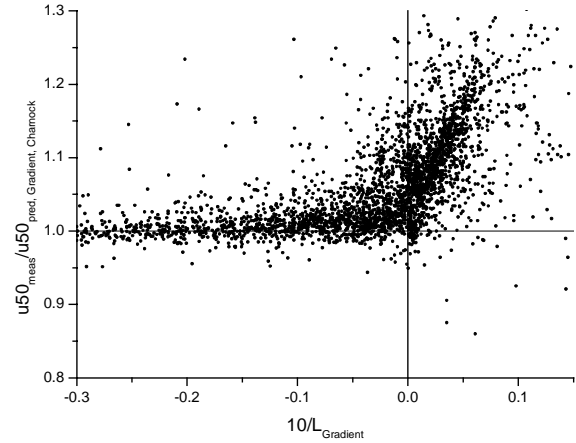


Figure 2: Deviation between measured and predicted 50 m wind speeds versus  $10/L$ ;  $L$  derived with the gradient method and  $z_0$  with the Charnock model

deviations  $\Delta$  for the three different methods to derive  $L$  are shown in figure 3 together with their standard errors. It can be seen that for all methods the agreement is good for unstable stratification. For near-neutral and stable stratification the wind speed at 50 m height is underpredicted with all methods. The difference in the magnitude of the deviations is due to the different calculation methods for  $L$ .

To investigate if the deviations  $\Delta$  can be caused by inappropriate modelling of the sea surface roughness, the four different roughness models are compared in figure 4. The bin-averaged deviations  $\Delta$  are plotted versus the stability parameter  $10/L$ . The bulk method has been used to derive  $L$ . It can be seen that the choice of model for the sea surface roughness does not have a large impact on the dependence of the deviations on the stability parameter  $z/L$ .

## 4 COASTAL INFLUENCE

### 4.1 Description of the flow regime

The measurement station Rødsand is surrounded by land in distances between 10 and 100 km and thus the air in the boundary layer will always be advected from land. Due to the large differences in heat capacity and

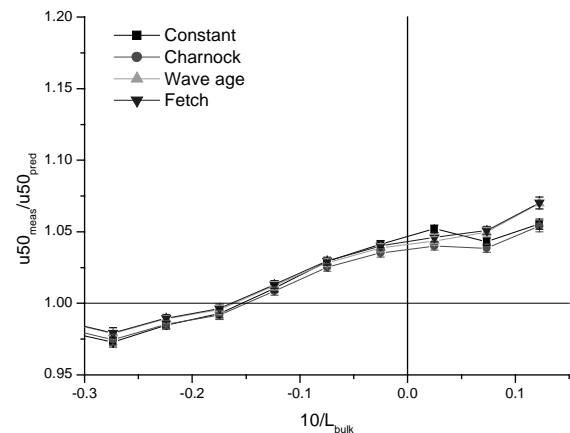


Figure 4: Bin-averaged ratio of measured and predicted 50 m wind speed versus stability parameter  $10/L$  with  $L$  determined by the bulk method and  $z_0$  modelled with four different models (see text)

conduction between land and water the air over land will often be warmer than the sea surface temperature. The flow regime that develops in this situation has been described by several authors. We follow the explanation given by Csanady (1974):

When warm air is blown over the cold sea, immediately a stable stratification develops as the air adjacent to the sea surface will be cooled. Simultaneously an internal boundary layer develops at the shoreline due to the roughness and heat flux change. In the case of warm air advection over cold sea this is a stable internal boundary layer (SIBL), characterised by low turbulence and therefore small fluxes and slow growth. The warm air is cooled from below while the sea surface temperature will remain almost constant in this process due to the large heat capacity of water. Eventually, the air close to the sea surface will have the same temperature as the water and atmospheric stability will be close to neutral at low heights. Above the internal boundary layer the air still has the temperature of the air over land and near the top of the SIBL an inversion lid has developed with strongly stable stratification separating these two regions. Thus, while the stability in the mixed layer is close to neutral, the elevated stable layer influences the wind speed profile and leads to a larger wind speed gradient than expected for an ordinary near neutral condition.

Due to the small fluxes through the inversion lid this flow regime is a quasi-equilibrium state and can survive for large distances before eventually the heat flow through the inversion evens out the difference in potential temperatures. Eventually the neutral boundary layer is recovered, which is known from open ocean observations (Edson and Fairall, 1998).

#### 4.2 Prediction of the inversion height

Csanady (1974) proposes the following expression for the depth of the mixed layer  $h$  in equilibrium conditions:

$$h = A \frac{1}{g} \frac{\rho}{\Delta\rho} u_*^2 \quad (2)$$

He estimates the empirical parameter  $A$  to 500. Here  $g$  is the gravitational acceleration,  $\rho$  the air density,  $\Delta\rho$  the air density difference between surface and geostrophic level

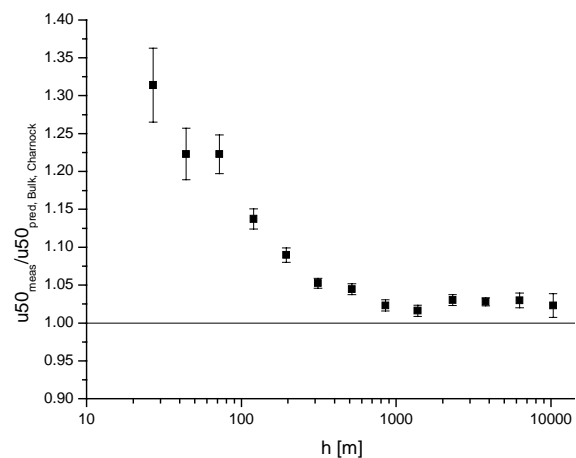


Figure 5: Deviation  $\Delta$  bin averaged for the estimated height of inversion layer  $h$  (from eq. (2))

at constant pressure and  $u_*$  the friction velocity. For the Rødsand measurement the air density at geostrophic level has been estimated from the measured data at the Rødsand mast and at the surrounding land stations (see Lange et al., 2002).

The bin averaged deviation  $\Delta$  for situations with long fetch ( $>30$  km) is shown versus the inversion height  $h$  in Figure 5. The bulk method has been used to determine  $L$  and the Charnock equation for the estimation of  $z_0$ . Large deviations occur for low inversion heights of below 100 m, decreasing rapidly with increasing inversion height and reaching a constant level at an inversion height of about 1000 m. This is in accord with the picture that an inversion height in the order of the boundary layer height will not lead to changes in the profile.

#### 4.3 Development of a simple correction method

A micrometeorological model to take into account these effects is not available. Therefore a simple ad hoc correction method is developed here to investigate the importance of this effect for wind resource estimations. In Figure 6 it is shown that the deviation decreases with increasing height of the inversion layer. It is assumed that the deviation increases linearly with height. The simplest correction method is therefore to add a linear correction term to the wind speed profile of Monin-Obukhov theory (see eq. 1), which is proportional to the measurement height  $z$  and inversely proportional to the estimated inversion height  $h$ :

$$u(z) = \frac{u_*}{\kappa} \left[ \ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right) + c \frac{z}{h} \right] \quad (3)$$

From the Rødsand measurements the correction factor  $c$  is estimated to be about 4.

The effect of this correction on the deviation  $\Delta$  is shown in Figure 6, where  $\Delta$  is bin averaged with respect to the stability parameter  $10/L$  for different methods to derive  $L$ . This can be compared to figure 3, where the same is shown without correction. It can be seen that the deviations on the stable side are reduced considerably for all three methods.

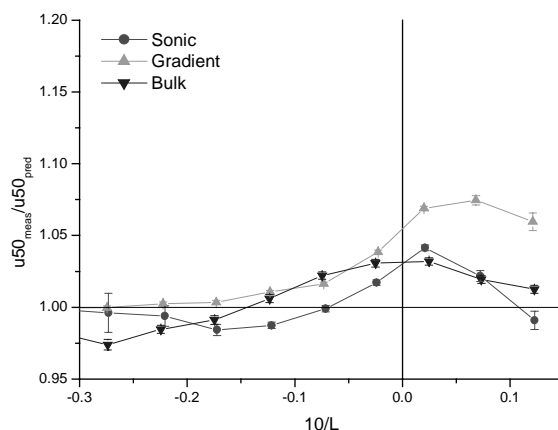


Figure 6: Bin-averaged ratio of measured and predicted 50 m wind speed versus stability parameter  $10/L$  with  $L$  determined by the sonic, gradient and bulk methods and  $z_0$  with Charnock model; the proposed correction method for thermal influences is used

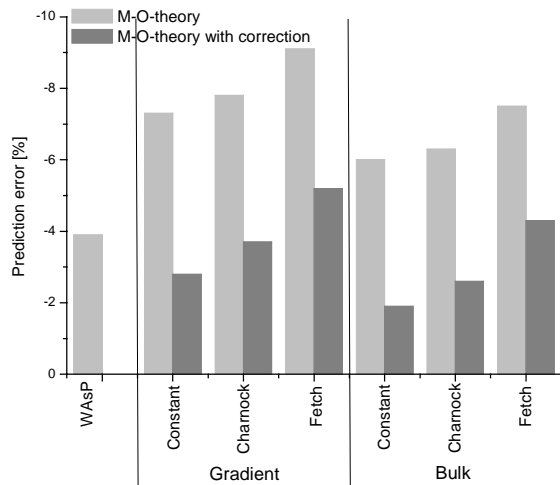


Figure 7: Error in power output prediction ( $P_{\text{pred}} - P_{\text{meas}} / P_{\text{meas}}$ ) of an example turbine for the 2 year long Rødsand data set; different methods to extrapolate the wind speed measurement at 10 m height to 50 m are used (see text); the result with the WASP method is also shown

## 5 PREDICTIONS OF POWER PRODUCTION

In the context of wind energy utilisation it is important to know, which impact these different approaches have for the prediction of the power output of an offshore wind turbine. This is investigated in an example application: The power production of an example wind turbine with hub height 50 m and 1 MW rated power output is estimated from the wind speed measurement at 10 m height using the different methods and models described in the previous sections. The estimated production is then compared with that obtained by using the measured wind speed at 50 m height. For this test a 2 year long time series from Rødsand has been used, where only part of the measurements are available. Therefore the sonic method to derive  $L$  and the wave age model for  $z_0$  could not be compared.

In Figure 7 the power output prediction error, defined as  $(P_{\text{pred}} - P_{\text{meas}}) / P_{\text{meas}}$ , is shown for all extrapolation methods. The estimated production with wind speed extrapolation is lower than that using the measured wind speed at hub height in all cases with errors ranging from 2% to 9%. For the gradient method to derive  $L$ , prediction errors of 7-9% are found. For the bulk method these are about 6-7%. For the different sea surface roughness methods it can be seen that the constant roughness assumption and the Charnock relation lead to almost equal results. The fetch model shows a slightly (about 1%) larger error. Using the correction method for the profile, the errors are reduced by about 4%. The results are also compared with the error of the WASP method, which is about 4%.

## 6 CONCLUSION

Wind resource estimation at offshore sites is more complex than often believed. Not only the variable sea surface roughness, the determination of the atmospheric stability and the growth of the internal boundary layer complicate the situation, but also the land-sea discontinuity can lead to a special flow situation far offshore. In this flow regime the wind speed increases more rapidly with height than predicted by Monin-

Obukhov theory. It should be noted that these deviations, although caused by the coastal discontinuity, were found far offshore for fetches of 30 to 100 km.

Currently these conclusions can be drawn for the site Rødsand only and need to be validated with other measurements. But from this example it can be seen that the flow modification in conditions of warm air advection from land plays an important role in the flow regime at offshore sites. At Rødsand this is the dominating uncertainty in the description of the wind conditions. We expect that a better understanding of this effect is a prerequisite for future improvements in the description of the wind regime over the coastal zone.

To improve the wind resource estimation for offshore sites, a model for the flow regime in conditions of warm air advection from land over sea is needed. The simple correction method introduced in this paper is intended to show the importance of the effect, but can not be used as a general model of the flow regime. Further development with data from additional sites is needed. Until such a model is available, measurements at or close to hub height are necessary for an accurate estimation of the wind resource of an offshore location.

## ACKNOWLEDGEMENT

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