

# Importance of thermal effects and sea surface roughness for wind resource and wind shear at offshore sites

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## Abstract

The economic feasibility of offshore wind power utilisation depends on the favourable wind conditions offshore as compared to sites on land. However, not only the mean wind speed is different, but the whole flow regime, as can e.g. be seen in the wind shear of the vertical wind speed profile. Monin-Obukhov theory is often used for this flow. Its applicability for wind power prediction at offshore sites is investigated using data from the measurement program Rødsand, located in the Danish Baltic Sea.

From a given wind speed at one height, the profile is predicted using two parameters, Obukhov length and sea surface roughness. Different methods to estimate these parameters are discussed and compared. Significant deviations to Monin-Obukhov theory are found for near-neutral and stable conditions when warmer air is advected from land with a fetch of more than 30-km. The measured wind shear is larger than predicted.

As a test application, the wind speed measured at 10-m height is extrapolated to 50-m height and the power production of a wind turbine at this height is predicted with the different models. To be able to quantify the importance of the deviations from Monin-Obukhov theory, a simple correction method has been developed. The models for the estimation of the sea surface roughness were found to lead only to small differences, the different methods used to derive the Obukhov length  $L$  were found to differ significantly. The proposed wind profile correction method leads to a clear improvement. The power output estimation has also been compared with the method of the resource estimation program WAsP.

For the measured wind shear, a strong dependency on atmospheric stability has been found. This is not usually accounted for in turbine design guidelines, which therefore underestimate the wind shear in stable conditions.

**Keywords:** Off-Shore, Meteorology, Boundary-Layer, Production Estimation, Wind Resource Assessment

## 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 economic viability of such projects depends on the favourable wind conditions of offshore sites, since the higher energy yield has to compensate for the additional installation and maintenance costs. 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. This is needed, e.g., to be able to extrapolate wind speed measurements performed at lower heights to the planned hub height of a turbine. Also, for turbine design the wind shear is an important design parameter, especially for the large rotor diameters planned for offshore sites.

The wind speed profile in the atmospheric surface layer is commonly described by Monin-Obukhov theory. In homogenous and stationary flow conditions, it predicts a log-linear profile:

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

The wind speed  $u$  at height  $z$  is determined by friction velocity  $u_*$ , aerodynamic roughness length  $z_0$  and Obukhov length  $L$ .  $\kappa$  denotes the von Karman constant (taken as 0.4) and  $\Psi_m$  is an universal stability function. Thus, if the wind speed is known at one height, the friction velocity can be derived from eq. (1) and the vertical wind speed profile is determined by two parameters: the surface roughness  $z_0$  and the Obukhov length  $L$ . This relation for the surface layer flow has originally been developed from the Kansas experiment with measurement height of up to 32-m [1]. It can not in general be expected to be valid for the hub heights of today's large wind turbines of 80-m to 100-m or even for the wind shear across the rotor with tip heights of up to 150-m. For such heights it has to be investigated if instead of the surface layer equations an outer layer scaling, i.e. the geostrophic drag law, has

to be used. However, the data used in this study are for heights of up to 50-m only, where the surface layer equations can be assumed to be appropriate.

The surface roughness of the sea is low compared to land surfaces. This is the main reason for the high wind speeds offshore. However, the roughness is not constant with wind speed as it is for land surfaces. Instead, it depends on the wave field present, which in turn depends on wind speed, upstream fetch (distance to coast), water depth, etc. Different models have been proposed to describe these dependencies. Most commonly used is the Charnock model [2], 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 [3] or wave steepness [4] 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 [5].

The Obukhov length  $L$  has to be derived from measurements at the site. Different methods are available using different kinds of input data: 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 [6]. The method with the 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  $L$  [7].

Monin-Obukhov theory, although developed from measurements over land, has been found to be generally applicable over the open sea [8]. This has been questioned for sites where the flow is influenced by the proximity of land. [9] and [10] showed that the land-sea discontinuity influences the flow for distances of up to 100-200 kilometres. Offshore wind power plants will therefore always be subject to such influences.

In coastal waters, when wind is blowing from land over the sea, the coastline constitutes a pronounced change in roughness and heat transfer. These changes pose a strong inhomogeneity to the flow, which may limit the applicability of Monin-Obukhov theory. Stimulated by measurements of large wind stress over Lake Ontario, Csanady described the processes governing the flow regime under the condition of warm air advection over colder water [11]. He developed an equilibrium theory of a well-mixed layer with a capping inversion for this condition (see sections 4.1 and 4.2).

Monin-Obukhov theory is a key part of the European Wind Atlas method [12] and the wind resource estimation program WASP [13], which is most

commonly used for offshore wind potential studies (see e.g. [14]) and wind resource estimations from measurements (see e.g. [15]). Also other approaches, like the methodology used in the POWER project [16] are based on this theory.

Also mesoscale flow modelling is used for wind power studies. A comparison of the mesoscale model MIUU [17] and the WASP program shows differences of up to 15% in mean wind speed [18]. However, such models are too computationally demanding to be used in wind power applications and a simpler model is needed to be able to estimate these effects.

A validation study with three offshore masts in Denmark revealed differences between measurements and WASP model results, which correlated with fetch [19]. A combination of the simplified assumptions used in WASP was believed to be responsible for the deviations.

In this study the impact of different methods and models for the extrapolation of wind speed measurements on the prediction of the wind turbine power production is re-investigated with data from the Rødsand measurement program in the Danish Baltic Sea, about 10-km off the coast (see section 2). In section 3, Monin-Obukhov theory is used to predict the wind speed profile with different methods for the derivation of  $L$  and models for estimating  $z_0$ . A simple ad hoc correction to the Monin-Obukhov wind speed profile is developed in section 4 with the aim to investigate the importance of deviations from the Monin-Obukhov profile on wind resource estimations. The deviations occur when warm air is flowing from land over a colder sea, creating an inhomogeneous wind flow.

In section 5, measured wind speeds at 10-m height are extrapolated to 50-m height with Monin-Obukhov theory with different methods to derive  $L$  and different models for the sea surface roughness. This has been repeated including the simple wind profile correction for inhomogeneous wind flow. By converting the wind speeds to power output of an example turbine, the impact of the deviations in wind speed on the estimation of the power production is investigated. Their impact on the prediction of the wind shear is shown in section 6. Then conclusions are drawn in the final section.

## 2 The Rødsand field measurement program

The field measurement program Rødsand has been established in 1996 as part of a Danish study of wind conditions for proposed offshore wind farms. A detailed description of the measurement, instrumentation, and data can be found in [20] and [21].

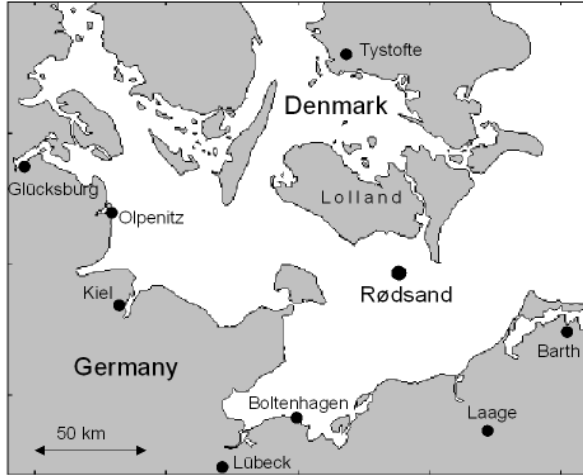


Figure 1: Map of measurement stations

The 50-m high meteorological mast is situated about 11-km south of the island Lolland in Denmark (11.74596°E, 54.54075°N) (see Figure 1). It is located in 7.7-m mean water depth with an upstream fetch (distance to coast) of 30-km to more than 100-km with wind directions from SE to WNW (120°N to 290°N). In the NW to N sector (300°N to 350°N) the fetch is 10-km to 20-km.

All wind speed data are corrected for flow distortion errors due to the mast and the booms with a method developed by Højstrup [22]. Records from situations of direct mast shade have been omitted. Friction velocity is calculated from the data of the ultrasonic anemometer with the eddy-correlation method. Simple correction procedures have been applied to account for the small decrease of the fluxes with height [21].

Not all instruments are available for long term measurements at Rødsand. Therefore, two data sets are used:

- For the analysis in section 4, a data set with shorter measurement period, in which ultrasonic and wave measurements are available. This data set consists of about 4200 half-hourly records.
- In the application for power production and wind shear calculations (sections 5 and 6), a long-term data set of two years measurement time (5/99 to 5/01), but without sonic and wave measurements, is used. This data set consists of 64000 records of 10-minute averages (61% availability).

The data have only been selected for the availability of

all measurements. For applications in wind power utilisation, all available data have to be used. Therefore the data have not been selected for stationarity, although Monin-Obukhov theory is only valid for stationary flow conditions. An analysis with data selected for the applicability of the theory can be found in [21].

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, located in Denmark (operated by the Risø National Laboratory) (see Figure 1). A more detailed description can be found in [21] and [23].

## 3 Extrapolation with Monin-Obukhov theory

### 3.1 Derivation of Obukhov length

Atmospheric stability is described in Monin-Obukhov theory with the Obukhov length scale  $L$  as stability parameter. Three different ways to derive this parameter are considered:

#### Sonic method

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

$$L_{sonic} = -\frac{u_{*s}^3}{\kappa \frac{g}{T} \overline{w'T'_s}} \quad (2)$$

Here  $\overline{w'T'_s}$  is the covariance of temperature and vertical wind speed fluctuation at the surface,  $u_{*s}$  the surface friction velocity,  $T$  the reference temperature,  $g$  the gravitational acceleration and  $\kappa$  the von Karman constant (taken as  $\kappa=0.4$ ). Humidity effects have been accounted for with a method described by Schotanus [24]. An average humidity profile has been assumed following Geernaert and Larsen [25], since humidity measurements are available (for details see [21]).

#### Gradient method

Temperature and wind speed difference measurements at 10-m and 50-m height are used to estimate the gradient Richardson number  $Ri_{\Delta}$ :

$$Ri_{\Delta}(z') = \frac{\frac{g}{T} \left( \frac{\Delta T_v}{\Delta z} + \frac{g}{C_p} \right)}{\left( \frac{\Delta u}{\Delta z} \right)^2} \quad (3)$$

Here  $\Delta T_v/\Delta z$  is the virtual temperature difference  $\Delta T_v$  at a vertical height difference  $\Delta z$ . Equally,  $\Delta u/\Delta z$  is the wind speed difference  $\Delta u$  at the vertical height difference  $\Delta z$ .  $C_p$  is the specific heat of air at constant

pressure. Humidity at the two heights has been estimated as described above. The height  $z'$  at which this  $Ri$  number is valid can be estimated as  $z'=(z_1-z_2)/\ln(z_1/z_2)$  [26]. The gradient Richardson number is converted to  $L$  by means of the following relation based on the Kansas results [1], [27]:

$$L_{Gradient} = \begin{cases} \left( \frac{z'}{Ri} \right) & Ri < 0 \\ \frac{z'(1-5Ri)}{Ri} & 0 < Ri < 0.2 \end{cases} \quad (4)$$

#### Bulk method

Air and sea temperature measurements are used together with the wind speed at 10-m height. An approximation method proposed by Grachev and Fairall [7] has been used. Humidity has been accounted for as stated above.

### 3.2 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 determined by the wind speed, distance to coast (fetch), etc. It is investigated how different models to describe the sea surface roughness influence the prediction of the wind profile (eq. (1)). Four models for sea surface roughness  $z_0$  are considered:

#### Constant roughness

The assumption of a constant sea surface roughness is often used in applications because of its simplicity, e.g. in the wind resource estimation program WAsP [13]. A value of  $z_0=0.2$  mm is assumed.

#### Charnock relation

The most common model taking into account the wave field by its dependence on friction velocity  $u_*$  is the Charnock relation [2]:

$$z_0 = z_{ch} \frac{u_*^2}{g} \quad (5)$$

Here  $g$  is the gravitational acceleration and  $z_{ch}$  the empirical Charnock parameter. The standard value of  $z_{ch}=0.0185$  has been used [28].

#### Wave age model

The Charnock relation works well for the open ocean, but for coastal areas it was found that the Charnock parameter is site specific, due to the influence of other physical variables like fetch on the wave field. To account for this, an extension of the Charnock relation by a parameterisation of the Charnock parameter with wave age as additional parameter by Johnson et al. [3] is used:

$$z_{ch} = A \left( \frac{c_p}{u_*} \right)^B \quad (6)$$

Here  $c_p / u_*$  is the wave age, the ratio of the velocity of the peak wave component  $c_p$  and the friction velocity  $u_*$ . The values for the empirical constants  $A$  and  $B$  are taken as  $A=1.89$  and  $B=-1.59$  [3].

#### Fetch model

Kahma and Calkoen [29] found the following empirical relation between the dimensionless peak frequency and the dimensionless fetch:

$$\frac{u_*}{g} \omega_p = C \left( \frac{g}{u_*^2} x \right)^D \quad (7)$$

Here  $\omega_p$  is the peak wave frequency and  $x$  the fetch in metres. Values of  $C=3.08$  and  $D=-0.27$  have been used for the coefficients [29].

The influence of fetch on wave parameters has been determined by field experiments with winds blowing approximately perpendicular to a straight coastline. To use these relations for any coastline, an effective fetch for a given direction  $\phi$  has been defined as the integral over all directions from  $\phi = -90^\circ$  to  $\phi = +90^\circ$ , weighted by a cosine squared term, normalised, and divided by the fetch which would result from a straight coastline:

$$x_{eff}(\phi) = \frac{2 \int_{-\pi/2}^{\pi/2} x(\phi - \varphi) \cos^2(\phi - \varphi) d\varphi}{4/\pi} \quad (8)$$

With the assumption of deep water conditions the left hand side of eq. (7) can be identified as the inverse wave age  $u_*/c_p$  using the dispersion relation. This relation can then be used to eliminate the wave age from eq. (6):

$$z_{ch} = AC^B \left( \frac{g}{u_*^2} x_{eff} \right)^{BD} \quad (9)$$

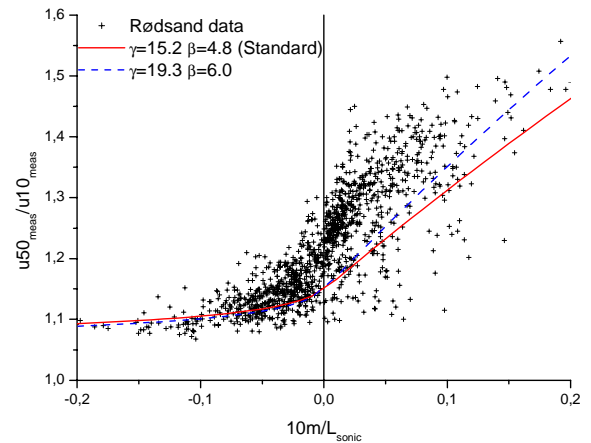


Figure 2: Ratios of wind speed at 50-m and 10-m height at Rødsand versus the stability parameter  $10m/L$  with  $L$  derived from the sonic anemometer measurements; also shown is the prediction of Monin-Obukhov theory with different sets of empirical constants

### 3.3 Comparison of predicted and measured wind speed profiles

An example for the measured wind speed increase with height is given in Figure 2. The ratio of measured 10-m and 50-m wind speeds is shown versus the stability parameter  $10m/L$ , where the sonic method has been used to derive  $L$ . The comparison with the prediction of Monin-Obukhov theory reveals a systematically larger wind speed ratio for near-neutral and stable conditions in the measurements. To investigate if this deviation can be caused by the choice of the values for the empirical constants used in the stability functions, the theoretical predictions are shown for different sets of these constants. It can be seen that the deviations between measurements and theory are much larger than the difference caused by the choice of the empirical constants.

The wind speed ratio between 10-m and 50-m height is predicted using Monin-Obukhov theory using the measured 10-m wind speed with equation (1). The ratio  $R = u_{50_{meas}}/u_{50_{pred}}$  between this predicted and the measured wind speed has been computed for the Rødsand data for all combinations of the models to derive the Obukhov length  $L$  and the sea surface roughness.

Systematic deviations are found in all cases for data with stable stratification. As example, the deviations  $R$  for the gradient method to derive  $L$  are shown in Figure 3, using the Charnock relation to model the sea surface roughness. A good agreement is found in the unstable region ( $10m/L < -0.05$ ). For stable conditions the wind speed at 50-m height is systematically higher than predicted by Monin-Obukhov theory. The deviation increases with increasing stability parameter  $10m/L$ .

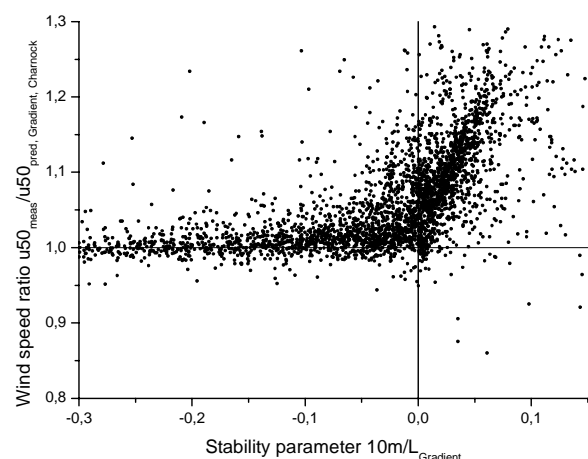


Figure 3: Deviation  $R$  between measured and predicted 50-m wind speeds versus  $10m/L$ ;  $L$  derived with the gradient method and  $z_0$  with the Charnock model

The large scatter, which is visible in Figure 3, is due to the fact that the data have not been selected for stationary flow conditions. From [21] it can be seen that the scatter is considerably reduced if this is done.

The bin-averaged deviations  $R$  for the three different methods to derive  $L$  are shown in Figure 4 together with their standard errors. Only bins with more than 20 records have been used. It can be seen that for all methods the agreement is good for unstable stratification. For near-neutral and stable stratification the wind speed prediction at 50-m height is too low. The deviations increase with increasing stability parameter  $10m/L$  for all methods, with the exception of the sonic method for stable conditions.

The different roughness models are compared in Figure 5. The bin-averaged deviations  $R$  are plotted versus the stability parameter  $10m/L$ . 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  $z/L$ .

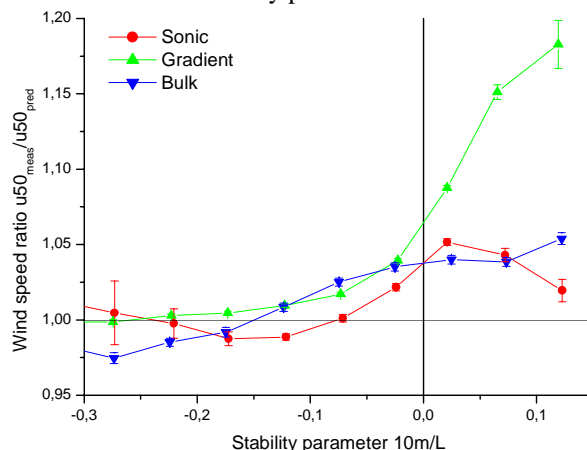


Figure 4: Bin-averaged ratio  $R$  of measured and predicted 50-m wind speed versus stability parameter  $10m/L$  with  $L$  determined by the sonic, gradient and bulk methods and  $z_0$  with Charnock model

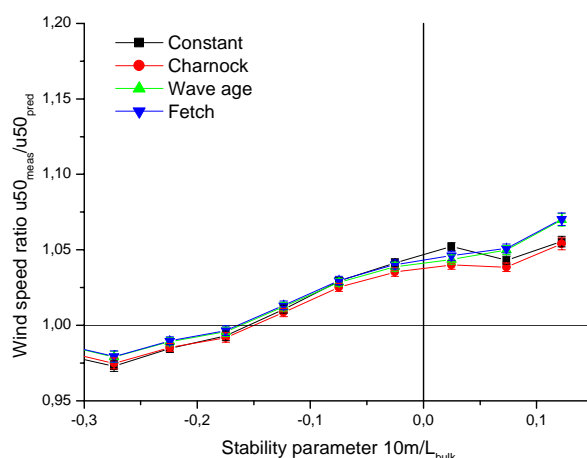


Figure 5: As Figure 4, but with different models for  $z_0$  (see text) and  $L$  determined by the bulk method

## 4 Correction of the Monin-Obukhov wind speed profile for coastal influence

### 4.1 Description of the flow regime

The measurement station Rødsand is surrounded by land in distances between 10-km 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 conduction between land and water the air over land will often be warmer than the sea surface temperature. Warm air is advected over the colder sea to the measurement station especially at daytime, when the land is heated by the sun, and in early spring, when the water temperature is still low from winter. Large temperature differences between the advected air and the sea surface can occur. At Rødsand, temperature differences of up to 9°C were measured.

The flow regime that develops in this situation has been described by several authors. We follow the explanation given by Csanady [11] and Smedman et al. [30]: When warm air is blown over the cold sea, a stable stratification develops immediately 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 changes. In the case when warm air advects over a cold sea, a stable internal boundary layer (SIBL) emerges, characterised by low turbulence and therefore small fluxes and slow growth (see Figure 6 (a)). 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 the 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. The wind speed above the inversion increases since the downward momentum flux through the inversion lid is reduced (see Figure 6 (b)). 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.

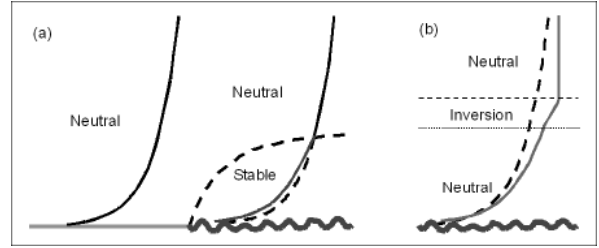


Figure 6: Conceptual sketch of the flow regime with warm air advection over colder sea. The wind profile is shown compared with a neutral profile.

Due to the small fluxes through the inversion lid, this flow regime is in a quasi-equilibrium state and can survive for large distances before the heat flow through the inversion eventually evens out the difference in potential temperatures. It can be expected that eventually the neutral boundary layer is recovered, which is known from open ocean observations [8].

### 4.2 Prediction of the inversion height

A theory for a mixed layer flow with capping inversion has been developed by Csanady [11]. Csanady proposes the following expression for the depth of the mixed layer  $h$  in equilibrium conditions [11]:

$$h = A \frac{1}{g} \frac{\rho}{\Delta\rho} u_*^2 \quad (10)$$

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 at constant pressure and  $u_*$  the friction velocity. The inversion height estimated from airborne measurements over the Baltic Sea has been found to agree reasonably well with eq. (10) [31]. For the Rødsand measurement, the geostrophic wind speed and the air density at geostrophic level have been estimated from the measured data at the Rødsand mast and at the surrounding land stations (see [21]).

The bin averaged ratio  $R$  for situations with long fetch (>30-km) is shown versus the inversion height  $h$  in Figure 7 (in logarithmic scale). A correlation can be seen with large ratios 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.

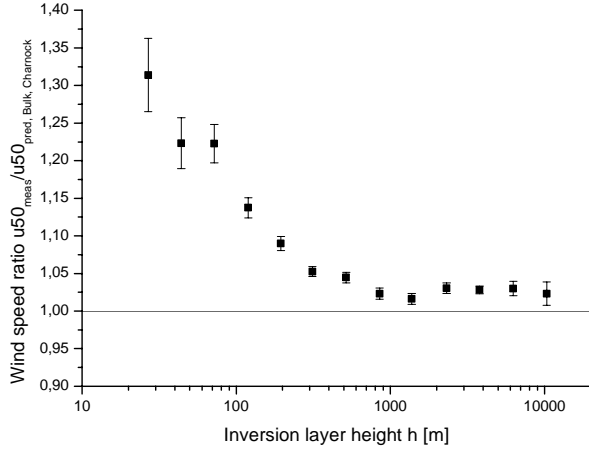


Figure 7: Deviation  $R$  bin averaged for the estimated height of inversion layer  $h$  (from eq. (10)); When estimating  $u_{50pred}$ , the bulk method has been used to determine  $L$  and the Charnock equation for the estimation of  $z_0$

It has to be kept in mind that the estimated inversion height  $h$  is for equilibrium conditions only, i.e. when the mixed layer and capping inversion already are developed. Therefore the theory can not be used for small fetches. The correlation between  $h$  and  $R$  has been found to hold for fetches larger than 30-km [21].

### 4.3 Development of a simple correction method

A micrometeorological model to take into account these effects is not available. Therefore a simple correction method for the wind profile below the inversion layer is developed here to investigate the importance of this effect for wind resource estimations. In Figure 7 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 the Monin-Obukhov theory (see eq. 1), which is proportional to the measurement height  $z$  and inversely proportional to the estimated inversion height  $h$ :

$$u(z) = \frac{u_*}{\kappa} \left[ \ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right) + c \frac{z}{h} \right] \quad (11)$$

From the Rødsand measurements the correction factor  $c$  is estimated to be about 4. The value for  $c$  has been estimated such that the ratio  $R$  becomes approximately independent of stability in the stable regime.

The effect of this correction on the ratio  $R$  is shown in Figure 8. The ratio  $R$  is bin averaged with respect to the stability parameter  $10m/L$  for different methods to derive  $L$ . This can be compared to Figure 4, 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. Especially for the

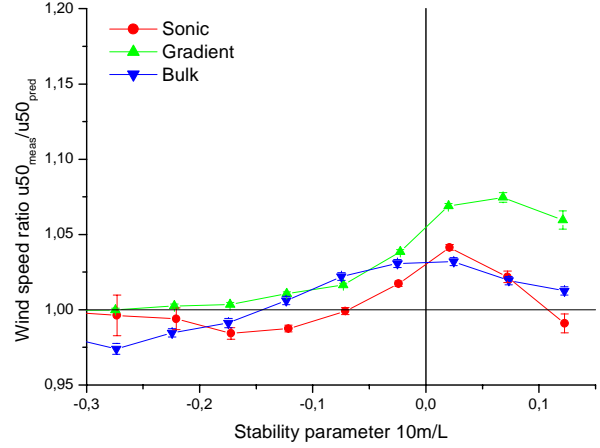


Figure 8: Bin-averaged ratio of measured and predicted 50-m wind speed versus stability parameter  $10m/L$  with  $L$  determined by the sonic, gradient and bulk methods and  $z_0$  with Charnock model; the proposed correction method for thermal influences is used

gradient method the deviation is greatly reduced since with this method the proposed wind speed profile with correction for thermal influences is used twice: in the calculation of  $L$  and in the prediction of the 50-m wind speed. For the sonic method also the deviation in the unstable regime decreases. This is due to the fact that some records with large deviations are erroneously regarded as unstable by the sonic method, probably due to the large measurement uncertainty and sampling variability of the friction velocity.

## 5 Predictions of power production

So far, different methods to derive the stability parameter  $L$ , different models for the sea surface roughness and a simple wind profile correction for the influence of a thermally modified flow regime have been discussed. 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. Because of the very non-linear characteristic of a wind turbine power curve, it is not only important how large an effect like e.g. the fetch dependence of the sea surface roughness is, but also how frequent it occurs and at which wind speed.

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. The background for this example is that often wind speed measurements are made at meteorological masts, which are lower than the hub height of the proposed turbines. These need to be extrapolated to hub height for the prediction of the power production.

For this test application the longer time series of measured data has been used (see section 2) to improve the representativity of the result. For this long time series, sonic anemometer and wave measurements are not available and hence the sonic method to derive  $L$  and the wave age model for  $z_0$  could not be used. In this time series, 36% of the observations show unstable stratification ( $10m/L < -0.05$ ), 22% stable stratification ( $10m/L > 0.05$ ) and 42% near-neutral stability.

In Figure 9 the power output prediction error, defined as  $(P_{pred}-P_{meas})/P_{meas}$ , is shown for all extrapolation methods.

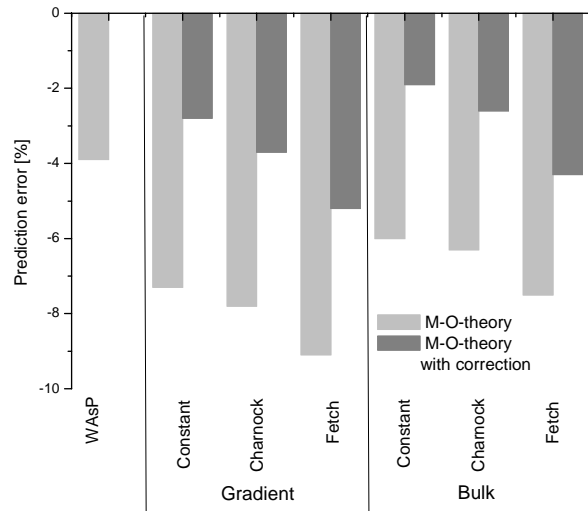


Figure 9: Relative error in power output prediction  $(P_{meas}-P_{pred})/P_{meas}$  of an example turbine for the 2 year long Rødsand data set; different methods to extrapolate the wind speed measurement at 10-m height to 50-m are used (see text); the result with the WASP method is also shown

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%. When no correction is applied for wind profile correction, the extrapolation methods described above show a higher prediction error than WASP, even though the atmospheric stability and sea surface roughness are estimated for each record, while the WASP method assumes a constant sea surface roughness and a slightly stable mean atmospheric stability. This means

that the mean stability used in WASP for the site Rødsand leads on average to better results than the actually measured atmospheric stability.

## 6 Prediction of the wind shear

Wind shear is the change of wind speed with height in the vertical wind speed profile. The blades of a wind turbine experience an alternating wind force for each rotation depending on their position in the wind profile. The wind shear is therefore an important parameter for design calculations. Often a power law profile as a simplified form of the wind profile is used to describe the wind speed variation with height:

$$u(z) = u(z_{hub}) \left( \frac{z}{z_{hub}} \right)^a \quad (12)$$

Thus, the wind speed  $u$  at height  $z$  is only determined by the wind speed at hub height  $u(z_{hub})$  and the power law exponent  $a$ . A value of  $a=0.2$  is recommended in the current version of the IEC certification guidelines [32].

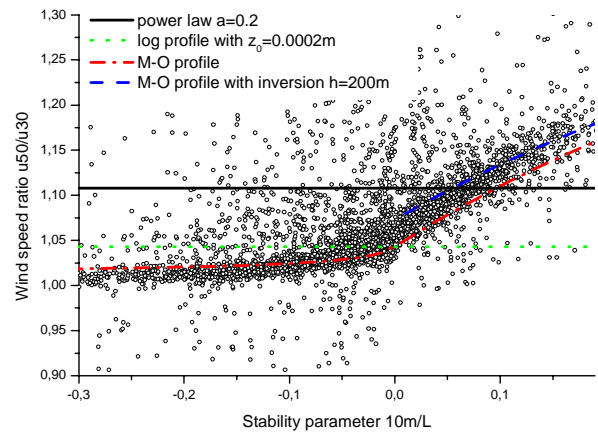


Figure 10: Wind speed ratio between 50-m and 30-m height measured at Rødsand versus atmospheric stability; also shown are calculations with different wind speed profiles

To compare the wind shear of the different profiles with the Rødsand measurements, the wind speed ratio between 50-m and 30-m height is used. Figure 10 shows how this ratio clearly depends on the atmospheric stability. Power law and logarithmic profiles lead to constant values for this ratio, as they do not take this stability into account. The wind shear predicted by the logarithmic profile with  $z_0=0.0002$  m is approximately that measured for neutral stability conditions. The power law profile with  $a=0.2$  leads to a higher wind shear estimate. But even for this the measured wind shear at stable conditions is systematically higher. The Monin-Obukhov profile does in general follow the measured dependence of the wind shear on stability, but predicts too small values for stable stratification. This is due to the effect of the



warm air advection with inversion layer discussed in section 4. An example of the result of the ad hoc correction term (eq.(11)) for an inversion layer height of 200-m is also shown in Figure 10. It can be seen that this effect can qualitatively explain the increased wind shear.

For load calculations it is also important at which wind speeds the cases of high wind shear occur. This can be seen in Figure 11 where the bin averaged wind speed ratio is shown versus wind speed at 10-m height along with their standard errors and standard deviations. The data have been segregated according to atmospheric stability in unstable ( $10m/L < -0.05$ ), near-neutral ( $-0.05 < 10m/L < 0.05$ ) and stable ( $10m/L > 0.05$ ) classes. For wind speeds of up to 13-ms-1 wind speed ratios with stable stratification exceed the estimation of the power law profile. Compared to land surfaces, in offshore conditions stably stratified flow can occur at higher wind speeds because of the low surface roughness.

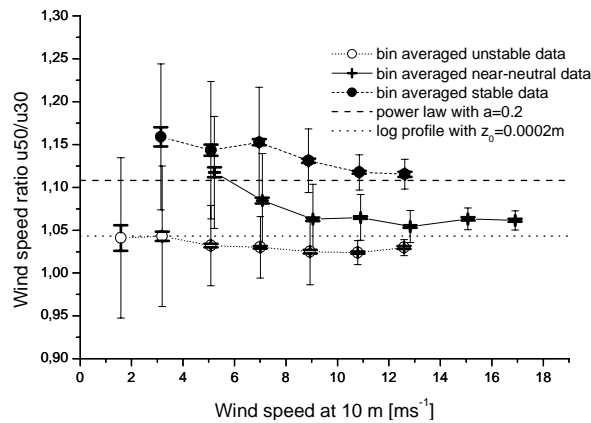


Figure 11: Bin averaged wind speed ratio between 50-m and 30-m height measured at Rødsand versus wind speed at 10-m height for different stability classes ( $10m/L < -0.05$  unstable,  $-0.05 < 10m/L < 0.05$  near-neutral,  $10m/L > 0.05$  stable stratification); also shown are calculations with different wind speed profiles

A strong dependency of the wind shear on atmospheric stability can be seen in Figure 11: While for unstable conditions the wind shear is even smaller than predicted by the logarithmic wind profile with  $z_0=0.0002$  m, for stable classification it exceeds the power law profile with  $a=0.2$ , which corresponds to  $z_0=0.34$  m at 50-m height. For the Rødsand data set the dependency of the wind shear on atmospheric stability seems more important than on wind speed. For the wind speed range available in the data set no clear effect of the sea surface roughness can be found, which would result in an increase of roughness with increasing wind speed. Data at higher wind speeds are necessary to investigate the importance of this effect for extreme wind conditions.

## 7 Summary and conclusion

Models to describe the flow regime in the coastal zone have been compared with data from the Rødsand measurement program in the Danish Baltic Sea. Focus of the investigation has been the description of the vertical wind speed profile for resource assessment and wind shear modelling in offshore wind power utilisation.

The vertical wind profile has been described by Monin-Obukhov theory and different models have been applied for the estimation of the two parameters used in this description: the Obukhov length and the sea surface roughness. For near-neutral and stable stratification large deviations from the measurements have been found in all cases. These are believed to be due to the inhomogeneous flow situation near the land-sea discontinuity. To investigate the importance of this effect for wind resource assessment, a simple correction method has been developed for the vertical wind speed profile.

To test the different models, the wind speed at 50-m height has been extrapolated from the measurement at 10-m height. The extrapolated wind speeds have been converted to power production estimates. The following options have been used for extrapolation:

- Three different methods to derive the Obukhov length have been used, which utilise different measured quantities.
- Four sea surface roughness models of different complexity have been tested.
- A simple correction term has been applied in the equation of the vertical wind speed profile to account for the modification of the wind speed profile in a flow regime of a mixed layer capped by an inversion.

The three different methods to derive  $L$  from the measurements were found to disagree for stable atmospheric conditions. This is believed to be a consequence of the flow regime with mixed layer capped by an inversion. Monin-Obukhov theory is not applicable here. The largest differences were found for the method deriving  $L$  via the Richardson number from measured profiles of temperature and wind speed. This is explained by the large difference in these profiles in the modified flow from usual Monin-Obukhov theory. Consequently, the simple correction method for the flow regime improved these results most. The derivation of  $L$  from sonic measurements ( $u^*$  and  $w'T'$ ) or from bulk measurements ( $T_{sea}$ ,  $T_{air}$ ,  $U$ ) showed less strong deviations.

The difference between the different models for the sea surface roughness is small compared to differences of other model choices. The simplest assumption of a constant roughness was found to be sufficient for the purpose of wind resource assessment. The reason is that errors of this method first become important at

high wind speeds, where the power curve of the turbine is flat. Therefore the wind speed prediction errors do not lead to errors in production estimation. Compared to the assumption of constant roughness, the Charnock relation does not lead to improvements in power output prediction. The more complex sea surface roughness models based on wave age dependency were found to actually increase the prediction error. The reason might be that the wave age dependency of the Charnock parameter suffers from self-correlation problems [33].

When the usual Monin-Obukhov profile is used, the wind shear in the surface layer is under-estimated at the Rødsand site by all models for  $L$  and  $z_0$ , when the atmospheric stratification is near-neutral or stable and the fetch is long ( $>30$ -km). This effect is believed to be due to the flow regime, which develops when warmer air is blown from land over a colder sea. At some distance behind the coastline a flow regime develops, which consists of a mixed layer at the surface, capped by an inversion layer. In such a flow regime Monin-Obukhov theory is no longer applicable.

A simple correction term has been applied in the equation of the vertical wind speed profile (see eq. (1)):

$$u(z) = \frac{u_*}{\kappa} \left[ \ln \left( \frac{z}{z_0} \right) - \Psi_m \left( \frac{z}{L} \right) + c \frac{z}{h} \right] \quad (13)$$

Here  $h$  is the height of the inversion and  $c$  is an empirical constant, estimated to  $c=4$  by a fit to the Rødsand data.

The power output estimation made by extrapolation of the wind speed measurements from 10-m to 50-m height with the different methods was compared with the standard WASP method. The WASP extrapolation yielded a 4% too low mean power output. This was slightly less than for the best methods using Monin-Obukhov theory. It shows that the assumption of a mean atmospheric stability performed even better than Monin-Obukhov theory, which uses the actually measured time series of stability conditions. The flow modification at the coastline leading to a mixed layer flow with capping inversion is believed to be the main cause of the prediction error. The error was reduced to only 2% when the proposed simple correction was applied.

From these findings it is concluded that the wind resource estimation at offshore sites is more complex than usually 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-km to 100-km.

The wind shear resulting from different forms of the vertical wind speed profile has been investigated by a comparison of the estimated and measured wind speed ratio between 50-m and 30-m height. For turbine design often a power law profile is used. This does not account for stability effects, which is shown to be a drawback, as these strongly influence the wind shear. From the measurements at Rødsand it can be seen that the power law profile proposed in the current IEC certification guidelines [32] underestimates the wind shear for stable stratification, especially in conditions with an elevated inversion layer, which lead to an increased wind shear compared to Monin-Obukhov theory. For load calculations it is also important to note that in offshore conditions flow with stable stratification occurs also at comparably high wind speeds. However, the influence of the wind speed itself on the wind shear is found to be less important for the wind speed range present in the data set.

Data measured at Rødsand are not sufficient to study the effect of the sea surface roughness on wind shear in extreme wind cases. For high wind speeds the surface roughness will increase according to the Charnock relation and possibly additionally due to the fetch limited wave field.

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. Other sources of uncertainties, like the derivation of  $L$ , can not be understood without taking this into account. 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.

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