The wind speed profile at offshore wind farm sites

Bernhard Lange[(1)], Søren E. Larsen[(2)], Jørgen Højstrup[(2)], Rebecca Barthelmie[(2)]

[(1)]University of Oldenburg, Faculty of Physics, Department of Energy and Semiconductor Research, D-26111 Oldenburg, Germany, Phone: +49-441-798 3927, Fax: +49-441-798 3326, e-mail: Bernhard.Lange@uni-oldenburg.de
[(2)]Risø National Laboratory, Roskilde, Denmark

Abstract

The economic feasibility of offshore wind power utilisation depends on the favourable wind conditions offshore compared to sites on land, which have to compensate the additional cost. But not only the mean wind speed is different, also the whole flow regime, as can e.g. be seen in the vertical wind speed profile. The commonly used models to describe this profile have been developed mainly for land sites. Their applicability for wind power prediction at offshore sites is investigated using data from the measurement program Rødsand in the Danish Baltic Sea.

Monin-Obukhov theory is often used for the description of the wind speed profile. From a given wind speed at one height, the profile is predicted using the two parameters Monin-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. The predicted wind speed is compared to the measured one and the predicted power output to the one using the measured wind speed. To be able to quantify the importance of the deviations from Monin-Obukhov theory, a simple correction method to account for this effect has been developed and is tested in the same way.

The models for the estimation of the sea surface roughness were found to lead only to little differences. For the purpose of wind resource assessment even the assumption of a constant roughness was found to be sufficient. The different methods to derive the Monin-Obukhov length L were found to differ significantly, when atmospheric stratification is near-neural or stable. For situations with near-neutral and stable atmospheric stratification and long (>30 km) fetch, the wind speed increase with height is larger than what is predicted from Monin-Obukhov theory for all methods to estimate L and z_0.

The power output estimation has also been compared with the method of the resource estimation program WAsP. For the Rødsand data set the prediction error of WAsP is about 4%. For the extrapolation with Monin-Obukhov theory with different L and z_0 estimations it is 5-9%. The simple wind profile correction method, which has been developed, leads to a clear improvement of the wind speed and power output predictions. When the correction is applied, the error reduces to 2-5%.

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. The economic viability of such projects depends on the favourable wind conditions of offshore sites, since the higher energy yield has to compensate the additional installation and maintenance cost. 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:

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

The wind speed u at height z is determined by friction velocity u_*, aerodynamic roughness length z_0 and Monin-Obukhov length L. κ denotes the von Karman constant (taken as 0.4) and Ψ_m is a universal stability function. Thus, if the wind speed is known at one height, the vertical wind speed profile is determined by two parameters: the surface roughness z_0 and the Monin-Obukhov length L.

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 like for land surfaces, but 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 [1], 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 [2] or wave steepness [3] 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 [4].

The Monin-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 [5]. 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 [5].

Monin-Obukhov theory, although developed from measurements over land, has been found to be generally applicable over the open sea [6]. This has been questioned for sites where the flow is influenced by the vicinity of land. [7] and [8] 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 [9]. He developed an equilibrium theory of a well-mixed layer with a capping inversion for this condition.

Monin-Obukhov theory is a key part of the European Wind Atlas method [10] and the wind resource estimation program WAsP [11], which is most commonly used for offshore wind potential studies (see e.g. [12]) and wind resource estimations from measurements (see e.g. [13]). Also other approaches, like the methodology used in the POWER project [14] is based on this theory.

Also mesoscale flow modelling is used for wind power studies. A comparison of the mesoscale model MIUU [15] and the WAsP program showed differences of up to 15% in mean wind speed [16]. 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 [17]. 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. A simple ad hoc correction to the Monin-Obukhov wind speed profile is developed with the aim to investigate the importance deviations from the Monin-Obukhov profile of on wind resource estimations. The deviations occur when warmer air is flowing from land over a colder sea, creating an inhomogeneous wind flow.

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. The results are compared with the measured wind speed at 50 m height. 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.

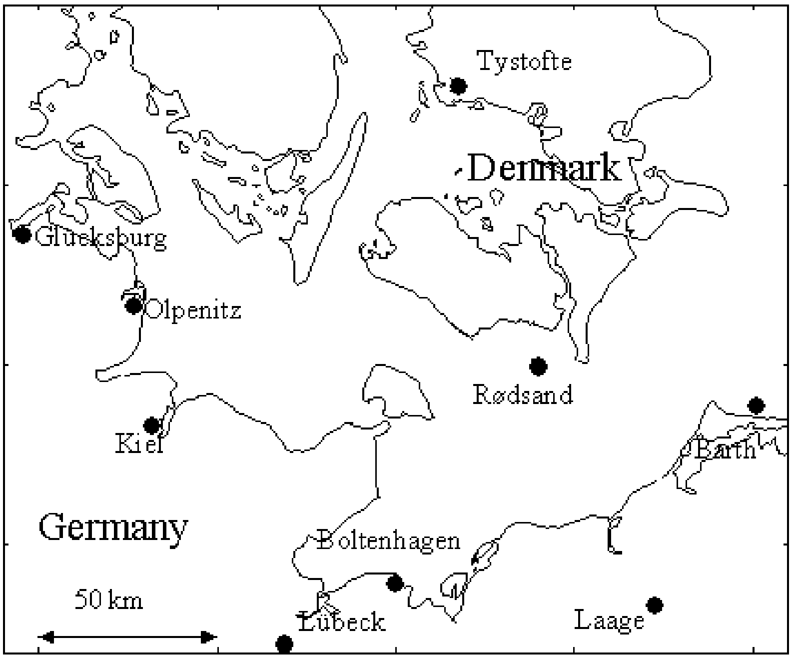

Figure 1: Map of the measurement stations

The Rødsand measurement program is briefly introduced in the following section. 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. The simple correction of the Monin-Obukhov profile for inhomogeneous wind flow in the coastal zone is developed in section 4. In section 5 the impact of the different methods, models and correction on the estimation of the power production of a wind turbine is investigated, before 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 [18] and [19]. 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 instrumented with cup anemometers at three heights, a ultrasonic anemometer, wind vane, temperature sensors, wave and current measurements. The mast is located in 7.7 m mean water depth with an upstream fetch of 30 to more than 100 km for 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 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 [20]. 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 (see [19]).
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). A more detailed description can be found in Lange et al. [19].

3 Extrapolation with Monin-Obukhov theory

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:
<u>Sonic method</u>
L is determined directly from sonic anemometer measurements of friction velocity and heat flux by:

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

Here $\overline{w'T'}_s$ is the covariance of temperature and vertical wind speed fluctuations at the surface and u_{*s} the surface friction velocity, T the reference temperature, g the gravitational acceleration and κ the von Karman constant (taken as κ=0.4).
The sonic anemometer measures sound virtual temperatures, which differ from virtual temperatures by $0.1\overline{T}\,\overline{w'q'}$ [21]:

$$\overline{w'T'_{sonic}} = \overline{w'T'} + 0.51\overline{T}\,\overline{w'q'} = \overline{w'\Theta'_v} - 0.1\overline{T}\,\overline{w'q'} = \overline{w'\Theta'_v} - 0.1\overline{T}u_*q_* \qquad (3)$$

Here q is the absolute humidity and Θ_v the virtual potential temperature. No humidity measurement is available at Rødsand. Therefore only an average humidity flux could be accounted for in the calculation of the stability parameters. Following Geernaert and Larsen [22], a relative humidity of 100% and 70% has been assumed at the surface and at 10 m height, respectively. The measured water temperature has been used to transform these to absolute humidity. The humidity scale q_* and the vertical humidity profile have been calculated with a diabatic profile with standard humidity stability functions and a humidity roughness length of $z_{0q}=2.1\cdot10^{-4}$ m [22].

<u>Gradient method</u>

Temperature and wind speed difference measurements at 10 m and 50 m height are used to estimate the gradient Richardson number Ri_Δ:

$$Ri_\Delta(z') = \frac{\frac{g}{\overline{T}}\left(\frac{\Delta\overline{T}_v}{\Delta z}+\frac{g}{C_p}\right)}{\left(\frac{\Delta\overline{u}}{\Delta z}\right)^2} \tag{4}$$

Here $\Delta T_v/\Delta z$ is the virtual temperature difference ΔT_v at a vertical height difference Δz. Equally, $\Delta u/\Delta z$ is the wind speed difference Δu at the vertical height difference Δz. 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 $z'=(z_1-z_2)/\ln(z_1/z_2)$ [23]. The gradient Richardson number is converted to L by means of the following relation based on the Kansas results [24], [25]:

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

<u>Bulk method</u>

Air and sea temperature measurements together with the wind speed at 10 m height are used. An approximation method proposed by Grachev and Fairall [26] has been used. In the calculation of the virtual temperatures, humidity has been accounted for with the assumptions stated above.

For the bulk method the sea surface temperature is required. This is not measured at Rødsand and therefore had to be replaced by the water temperature measured at a depth of about 2 m. This leads to a small but systematic over-prediction of the temperature difference between the surface and 10 m height and consequently to an over-prediction of the stability parameter |10/L|, i.e. the calculated values of 10/L are slightly higher for stable and lower for unstable conditions.

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:

<u>Constant roughness</u>

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 [11]. A value of z_0=0.2 mm is assumed.

<u>Charnock relation</u>

The most common model taking into account the wave field by its dependence on friction velocity u_* is the Charnock relation [1]:

$$z_0 = z_{ch} \frac{u_*^2}{g} \tag{6}$$

Here g is the gravitational acceleration and z_{ch} the empirical Charnock parameter. The standard value of z_{ch}=0.0185 has been used [27].

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. Numerous attempts have been made to find an empirical relation for the sea surface roughness with an improved description of the wave field. No consensus on the most suitable scaling groups has emerged yet. Different relations have been tested with the Rødsand data [4] and an extension of the Charnock relation by a parameterisation of the Charnock parameter with wave age as additional parameter by Johnson et al. [2] is used:

$$z_{ch} = A\left(\frac{c_p}{u_*}\right)^B \tag{7}$$

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 from [2]: A=1.89; B= -1.59.

Fetch model

The wave age model requires measurements of the peak wave velocity, which is 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.

Kahma and Calkoen [28] found the following empirical relation between the dimensionless peak frequency and the dimensionless fetch:

$$\frac{u_*}{g}\omega_p = C\left(\frac{g}{u_*^{\,2}}x\right)^D \tag{8}$$

Here ω_p is the peak wave frequency and x the fetch in metres. The coefficients were found to be C=3.08 and D= -0.27.

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 an effective fetch for a given direction, α has been defined as the integral over all direction from α= -90° to α= +90°, weighted by a cosine squared term, normalised and divided by the fetch which would result from a straight coastline.

$$x_{eff}(\phi) = \frac{2\int_{-\pi/2}^{\pi/2} x(\phi-\varphi)\cos^2(\phi-\varphi)\,d\varphi}{4/\pi} \tag{9}$$

With the assumption of deep water conditions the left hand side of eq. (8) 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. (7):

$$z_{ch} = AC^B\left(\frac{g}{u_*^{\,2}}x_{eff}\right)^{BD} \tag{10}$$

3.3 Comparison of predicted and measured wind speed profiles

The wind speed ratio between 10 m and 50 m height is predicted using Monin-Obukhov theory. From the diabatic wind profile (see eq. 1) the wind speed at 50 m height is calculated from the measured 10 m wind. The ratio $u50_{meas}/u50_{pred}$ between this predicted and the measured wind speed 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 found in all cases for data with stable stratification. As example, the ratio $u50_{meas}/u50_{pred}$ for the gradient method to derive L is shown in Figure 2 with the Charnock relation used to model the sea surface roughness. 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 higher than predicted by Monin-Obukhov theory. The deviation increases with increasing stability parameter 10/L.

The large scatter, which is visible in Figure 2 is due to the fact, that the data have not been selected for stationary flow conditions. Data from periods with large changes in the atmospheric flow lead to large scatter. From [19] it can be seen that the scatter is considerably reduced if records with large gradients in wind speed, wind direction, temperatures etc. are excluded from the analysis.

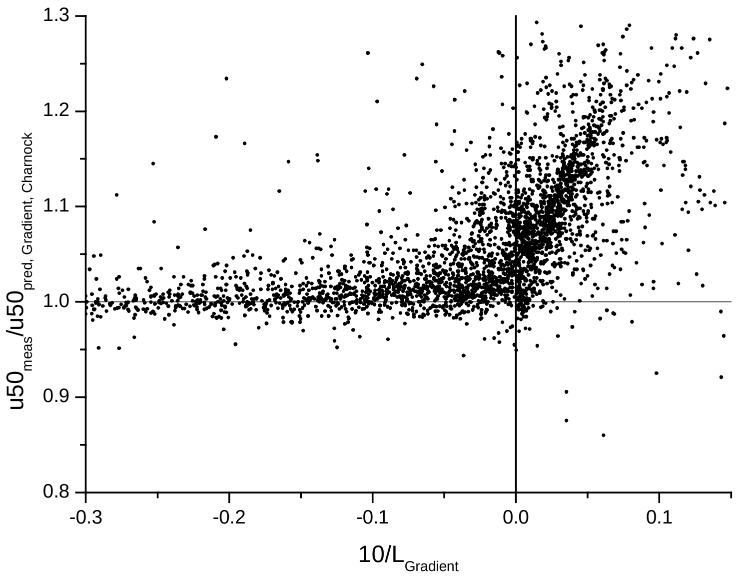

Figure 2: Ratio $u50_{meas}/u50_{pred}$ between measured and predicted 50 m wind speeds versus 10/L; L derived with the gradient method and z_0 with the Charnock model

For comparison of the different methods, the bin-averaged ratios $u50_{meas}/u50_{pred}$ for the three different methods to derive L are shown in Figure 3 (left) 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 at 50 m height is predicted too low with all methods. The deviations increase with increasing stability parameter 10/L for all methods, with the exception of the sonic method for stable conditions. Deviations are between -3% and 3% for unstable conditions and between 3% and 18% for stable conditions.

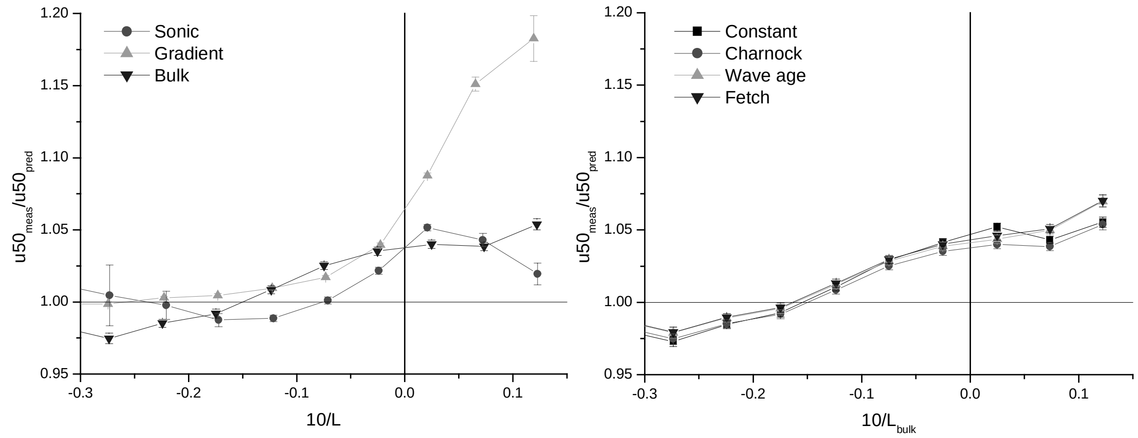

Figure 3: Bin-averaged ratio of measured and predicted 50 m wind speed versus stability parameter 10/L with: (1) L determined by the sonic, gradient and bulk methods and z_0 with Charnock model (left) and (2) L determined by the bulk method and z_0 modelled with four different models (right)

To investigate if the deviations can be caused by inappropriate modelling of the sea surface roughness, the four different roughness models are compared in Figure 3 (right). The bin-averaged ratios $u50_{meas}/u50_{pred}$ 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. Thus they can not be responsible for the deviations found.

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 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. Especially at daytime, when the land is heated by the sun, and in early spring, when the water temperature is still low from winter, warm air is advected over the colder sea to the measurement station. Large temperature differences between the advected air and the sea surface can occur. At Rødsand temperature differences of up to 9ºC were measured.

The flow regime that develops in this situation has been described by several authors. We follow the explanation given by Csanady [9] and Smedman et al. [29]: 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 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. 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 [6].

4.2 Prediction of the inversion height

A theory for a mixed layer flow with capping inversion has been developed by Csanady [9]. Csanady proposes the following expression for the depth of the mixed layer h in equilibrium conditions [9]:

$$h = A\frac{1}{g}\frac{\rho}{\Delta\rho}{u_*}^2 \qquad (11)$$

He estimates the empirical parameter A to 500. Here g is the gravitational acceleration, ρ the air density, Δρ the air density difference between surface and geostrophic level 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 [19]). The inversion height estimated from airborne measurements over the Baltic Sea has been found to agree reasonably well with eq. (11) [30].
The bin averaged ratio u_{meas}/u_{pred} for situations with long fetch (>30 km) is shown versus the inversion height h in Figure 4. The bulk method has been used to determine L and the Charnock equation for the estimation of z0. 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.
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 the ratio $u50_{meas}/u50_{pred}$ has been found to hold for fetches larger than 30 km in [19].

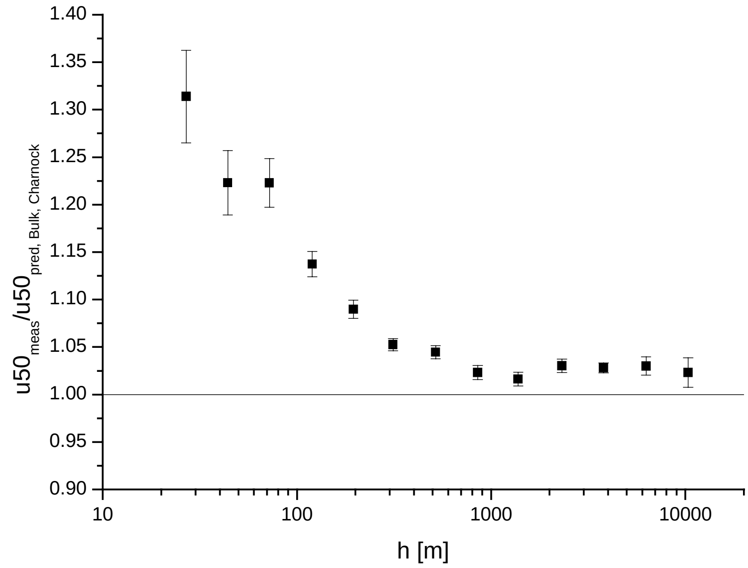

Figure 4: Ratio $u50_{meas}/u50_{pred}$ bin averaged for the estimated height of inversion layer h (from eq. (11))

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 4 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:

$$u(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right) + c\frac{z}{h}\right] \qquad (12)$$

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

The effect of this correction on the ratio $u50_{meas}/u50_{pred}$ is shown in Figure 5. The ratio $u50_{meas}/u50_{pred}$ 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. Especially for the 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.

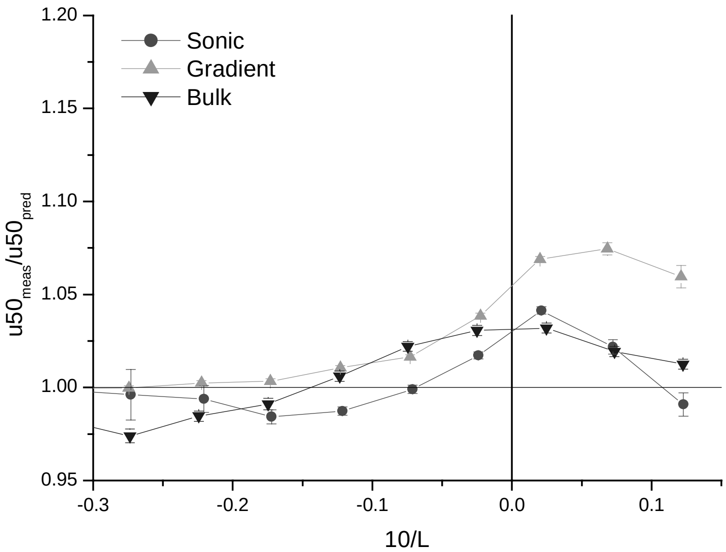

Figure 5: Bin-averaged ratio of measured and predicted 50 m wind speed versus stability parameter 10/L with L determined by the sonic, gradient and bulk methods and z_0 with Charnock model; the proposed correction method for thermal influences is used

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 than 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 z0 could not be compared.

In Figure 6 the power output prediction error, defined as (Ppred –Pmeas)/Pmeas, 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%.

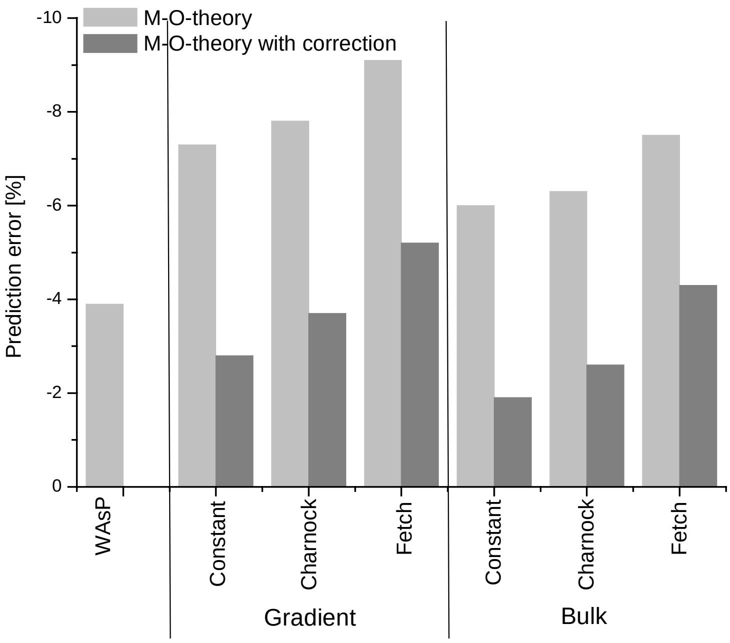

Figure 6: Error in power output prediction (P_{meas}-P_{pred})/P_{meas} of an example turbine for the 2 year long Rødsand data set; different methods to extrapolate the wind speed measurement at 10 m height to 50 m are used (see text); the result with the WAsP method is also shown

The results are also compared with the mean power production calculated with the wind resource assessment program WAsP in Figure 6. For the WAsP calculations, the same data as for the extrapolation with the different methods have been used, i.e. the wind speed measurements at 10 m height. The estimated mean production with WAsP is about 4% lower than that derived from the wind speed measurements at hub height.

When no correction is applied for wind profile correction, the extrapolation methods described above show a higher prediction error then WAsP, even though the atmospheric stability and sea surface roughness are estimated for each record, while the WAsP method uses a mean profile.

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 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 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 Monin-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. To investigate the importance of the differences for wind power output estimations, the extrapolated wind speeds have also been converted to power production estimates. The following options have been used for extrapolation:

- Three different methods to derive the Monin-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.

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). In contrast, all models showed reasonable results for unstable stratification. Also for wind directions with short fetch (<20 km) the deviations for near-neutral and stable conditions are at least smaller.

This effect is believed to be due to a certain flow regime, developing 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):

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

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 mean 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. This shows that the very simple assumption of a constant roughness made in WAsP does not lead to important errors. The assumption of a mean atmospheric stability performed even better than the use of the actually measured time series of stability conditions. However, the flow modification at the coastline leading to a mixed layer flow with capping inversion is 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, where 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. 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.

Acknowledgements

The original instrumentation and maintenance of the Rødsand measurement station were funded by the EU-JOULE program and the Danish Energy Ministry’s UVE program ’Offshore Wind Resources’. Subsequent instrumentation, operation and maintenance were funded by SEAS Distribution A.m.b.A. The technical support team at Risø, particularly Ole Frost Hansen, are acknowledged for their contribution to the data collection. Mr Kobbernagel of Sydfalster-El performed the maintenance and data collection at Rødsand.

References

[1] Charnock H. Wind stress over a water surface. Quart. J. Roy. Meteor. Soc., Vol. 81(1955) p. 639-640.

[2] Johnson HK, Højstrup J, Vested HJ, Larsen SE. On the Dependence of Sea Surface Roughness on Wind Waves. J. Phys. Oceanogr., Vol. 28 (1998) p. 1702-1716.

[3] Taylor PK, Yelland MJ. The dependence of sea surface roughness on the height and steepness of the waves. J. Phys. Oceanogr., Vol. 31 (2001) p. 572-590.

[4] Lange B, Højstrup J, Larsen SE, Barthelmie RJ. A fetch dependent model of sea surface roughness for offshore wind power utilisation. Proceeding of the European Wind Energy Conference 2001, Copenhagen, Denmark (2001) p. 830-833.

[5] Garratt JR. The atmospheric boundary layer. Cambridge, Cambridge University Press. (1994).

[6] Edson JB. Fairall CW. Similarity relationships in the marine atmospheric surface layer for terms in the TKE and scalar variance budgets. J. Atmos. Sci. Vol. 55 (1998) p. 2311-2328.

[7] Källstrand, B., H. Bergström, J. Højstrup and A.-S. Smedman: Mesoscale wind field modifications over the Baltic Sea. Boundary-Layer Meteorology Vol. 95 (2000) p. 161-188.

[8] Frank, H. P., S. E. Larsen and J. Højstrup: Simulated wind power off-shore using different parameterisations for the sea surface roughness. Wind Energy Vol. 3 Issue 2 (2000) p. 67-79.

[9] Csanady GT. Equilibrium theory of the planetary boundary layer with an inversion lid. Boundary-Layer Meteorol. Vol. 6 (1974) p. 63-79.

[10] Troen, I. and E. L. Petersen: European Wind Atlas. Roskilde, Risø National Laboratory, Denmark (1989).

[11] Mortensen, N. G., Landberg L., Troen, I., and Petersen, E. L.: Wind Analysis and Application Program (WASP) - User's Guide, Report Risø-I-666(EN) (v.2), Risø National Laboratory, 4000 Roskilde, DK, (1993) 133 pp.

[12] Matthies, H.G., A.D. Garrad: Study of Offshore Wind Energy in the EC. Executive Summary. Report: Joule 1 (JOUR 0072), Part 1 of 5 Volumes. (1993) p. 1-13

[13] Lavagnini, A., S. Martorelli and L. Cavaleri: The wind climatology of the Adriatic Sea deduced from coastal stations. Il Nuovo Cimento Vol. 19(C1) (1996) p. 37-50.

[14] Halliday, J. A., G. M. Watson, J. P. Palutikof, T. Holt, R. J. Barthelmie, J. P. Coelingh, L. Folkerts, E. J. v. Zuylen and J. W. Cleijne: POWER - A methodology for predicting offshore wind energy resources. European Wind Energy Conference 2001, Copenhagen, Denmark (2001).

[15] Enger, L.: Simulation of dispersion in a moderately complex terrain. Part A. The fluid dynamic model. Atmos. Environ. Vol. 24A (1990) p. 2431-2446.

[16] Bergström, H. and R. Barthelmie: Offshore boundary-layer modelling. Global Windpower Conference 2002, Paris, France (2002).

[17] Lange, B. and J. Højstrup: Evaluation of the wind-resource estimation program WAsP for offshore applications. Journal of Wind Engineering and Industrial Aerodynamics Vol. 89 (2002) p. 271-291.

[18] Lange B, Barthelmie RJ, Højstrup J. Description of the Rødsand field measurement. Report Risø-R-1268, Risø National Laboratory, 4000 Roskilde, DK, (2001) 60 pp.

[19] Lange B, Larsen S, Højstrup J, Barthelmie R.: The influence of thermal effects on the wind speed profile of the coastal marine boundary layer. submitted to Boundary-Layer Meteorol.

[20] Højstrup J.: Vertical Extrapolation of Offshore Windprofiles. Wind energy for the next millennium. Proceedings. 1999 European wind energy conference (EWEC '99), Nice (FR). Petersen, E.L.; Hjuler Jensen, P.; Rave, K.; Helm, P.; Ehmann, H., Eds., (1999) p. 1220-1223.

[21] Schotanus, P.: Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes Boundary-Layer Meteorol. Vol. 26 (1983) p. 81-93.

[22] Geernaert G, Larsen S: On the role of humidity in estimating marine surface layer stratification and scaterometer cross section J. Geophys. Res. Vol. 98(C1) (1993) p. 927-932.

[23] Larsen, SE: Observing and modelling the planetary boundary layer. Raschke E, Jacob D (eds.). Energy and water cycles in the climate system. NATO ASI series I, volume 5, Springer-Verlag, Berlin, Heidelberg, (1993) p. 365-418.

[24] Businger JA, Wyngaard JC, Izumi Y, Bradley EF. Flux-profile relationships in the atmospheric surface layer. J. Atmos. Sci. Vol. 28 (1971) p. 181-189.

[25] Högström, U: Nondimensional wind and temperature profiles. Boundary-Layer Meteorol. (1988) Vol. 42 p. 55-78.

[26] Grachev AA, Fairall CW: Dependence of the Monin-Obukhov stability parameter on the bulk Richardson number over the Ocean. J. Appl. Meteor. Vol. 36 (1997) p. 406-414.

[27] Wu J: Wind-stress Coefficients over Sea Surface near Neutral Conditions – A Revisit. J. Phys. Oceanogr. Vol. 10 (1980) p. 727-740.

[28] Kahma KK, Calkoen CJ: Reconciling discrepancies in the observed growth of wind-generated waves. J. Phys. Oceanogr. Vol. 22 (1992) p. 1389-1405.

[29] Smedman AS, Bergström H, Grisogono B: Evolution of stable internal boundary layers over a cold sea. J. Geophys. Res. Vol. 102(C1) (1997) p. 1091-1099.

[30] Tjernström M, Smedman AS: The vertical turbulence structure of the coastal marine atmospheric boundary layer. J. Geophys. Res. Vol. 98(C3) (1993) p. 4809-4826.