COMPARISON OF WIND CONDITIONS OF OFFSHORE WIND FARM SITES IN THE BALTIC AND NORTH SEA

Bernhard Lange
ForWind - Center for Wind Energy Research, University of Oldenburg, 26111 Oldenburg, Germany

Summary
Field measurement data from the Rødsand measurement program in the Baltic Sea and from the FINO I platform in the North Sea are used to characterize and compare the different wind conditions for the Baltic and North Sea. Rødsand is surrounded by land in 10 km to 100 km distance, while the FINO I platform is located in the open North Sea with a minimum distance to the coast (fetch) of 45 km.
Cup anemometer measurements at different heights are used to derive the wind speed profiles at both locations. The data are corrected for the influence of the mast flow distortion. The atmospheric stability is determined with the eddy-correlation method from ultrasonic anemometer measurements. Mean profiles as well as profiles for different stability conditions are compared. The measured profiles are compared with standard Monin-Obukhov theory.
A difference in the steepness of the mean profiles is found, with larger wind shear present at Rødsand. For conditions with neutral stratification both profiles show deviations from a logarithmic form. The mean profiles are also compared with the profile calculated with the wind resource estimation program WAsP, which was found to agree well with the FINO I data, but not with the Rødsand measurement. At the Rødsand site it is known that thermal effects are responsible for a systematic deviation of the vertical wind profile from standard Monin-Obukhov theory for near neutral and stable conditions. This was not found at the FINO I site.

1 Introduction

For the planning and design of offshore wind farms and turbines, detailed knowledge of the offshore wind conditions is of crucial importance. Compared to sites on land, where both the meteorological knowledge and the experience of the wind industry are large, relatively little is known about the conditions faced by turbines in the marine environment.
Offshore, the influence of the sea surface leads to important changes in the near surface wind conditions, while the forcing of the wind due to pressure gradients does not change abruptly between land and water. The most obvious effects in the marine boundary layer are due to the sea surface roughness and thermal properties of water.
At the Rødsand site it has been found that for wind resource calculations the dependence of sea surface roughness on wind and waves is less important compared to thermal effects [1]. Also, thermal effects are responsible for a systematic deviation of the vertical wind speed profile from standard Monin-Obukhov theory, which is found for near neutral and stable conditions. This is believed to be caused by the inhomogeneity of the flow due to the coastline. It has been shown that the effect has important implications for wind resource assessment and turbine design [2].
Data from the newly installed measurement site FINO I in the North Sea are used in this study to investigate if this effect is also found there. In the next section the measurements are briefly characterised and in section 3 the data processing is described. Standard Monin-Obukhov theory is briefly recalled in section 4 before the mean vertical wind speed profiles of both sites are compared with each other and with theoretical expectations in section 5. The dependence of the wind speed gradients at the two sites on atmospheric stability is discussed in section 6 and compared with Monin-Obukhov theory. Conclusions are drawn in the final section.

2 Measurements

2.1 FINO 1

The FINO measurement platform [3], [4] is located 45km north of the island Borkum in the North Sea (see Figure 1). The height of the measurement mast is 100m. Seven cup anemometers are installed at heights of 30m to 100m on booms mounted in south-east direction of the mast. One cup anemometer is mounted at the top of the mast in 100m height. Three ultrasonic anemometers are present at heights of 40m, 60m, and 80m on north-westerly oriented booms. Additional meteorological measurements consist of wind direction, air temperature, moisture, air pressure and solar irradiation. The oceanographic measurements include waves, wave height, water current and physical properties of the sea water.
Data from November 2003 to May 2004 have been

Figure 1: Locations of the measurement sites

used in this study. The data set contains about 14.000 records of 10-minute mean values.

2.2 Rødsand

The field measurement program Rødsand [5] has been established in 1996 as part of a Danish study of wind conditions for proposed offshore wind farms. The 50 m high meteorological mast is situated about 11 km south of the island Lolland in Denmark (see Figure 1). It is instrumented with cup anemometers at three heights, an ultrasonic anemometer, wind vane, temperature sensors, wave and current measurements.
The data set used here consists of about 3.400 records of 30-minute mean values, collected in the time period from March 1998 to January 2000.

3 Data correction and derived quantities

3.1 Correction of mast flow distortion

For wind profile analysis, cup anemometer measurements are used. These are corrected for flow distortion effects of mast and booms with a method developed by Højstrup [6]. Records from situations with direct mast shade are omitted. For Rødsand, the parameters of the correction method have been derived from measurements at a similar mast at the Vindeby site [7]. At FINO I, a comparison of top and boom mounted cup anemometers as well as a comparison of cup and sonic anemometers at different sites of the mast are used [8]. Figure 2 shows the layout of the FINO I mast with the two booms. The measured ratios of cup and sonic anemometers at 40m height at the FINO I mast are compared with the correction function in Figure 3. The correction method uses a linear correction as first approximation. An offset between correction function and data can be seen, which stems from an offset between cup and sonic anemometer measurements.

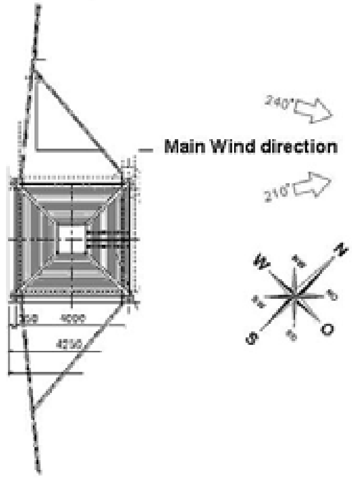

Figure 2: Layout of the measurement mast at FINO I (from www.fino-offshore.de)

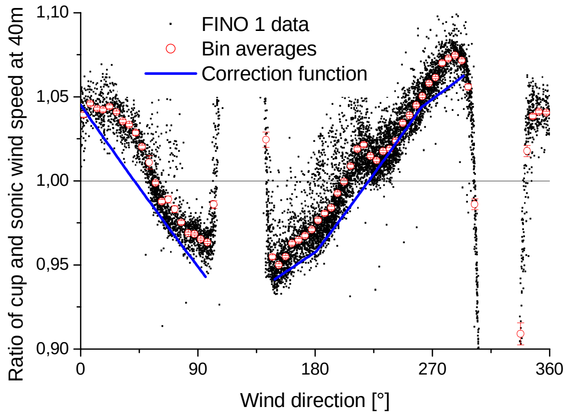

Figure 3: Measured ratios of cup and sonic anemometer wind speeds at 40m height at the FINO I mast; also shown is the correction function

3.2 Flux measurements

Ultrasonic anemometer measurements are utilized to derive fluxes and determine the atmospheric stability. At FINO I, a 3-dimensional calibration is applied to reduce the measurement error of the ultrasonic anemometers [9]. The planar fit method [10] is used for tilt correction and linear regression for trend removal before momentum and heat fluxes are calculated with the eddy-correlation method. The Obukhov length L is derived from these fluxes [11].

4 Monin-Obukhov Theory

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:

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

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. The Businger-Dyer formulation [12] of the stability function with parameters of the reanalysis by Högström [13] are used.
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 Obukhov length L. In the following, a constant roughness of z_0=0.0002m and the Obukhov-length calculated from the ultrasonic anemometer at 40m height are used.

5 Vertical wind speed profiles

5.1 Measured mean profiles

The cup anemometer wind speeds are averaged for the whole data period. They are plotted versus height in Figure 4. The wind speeds have been normalized with the wind speed measured at 50m height, to allow comparison between the FINO I and Rødsand data sets despite their different mean wind speeds. Also shown is the wind speed profile calculated with the wind resource estimation program WAsP for an offshore site. In WAsP, the values for roughness and stability are constant and hence the vertical wind speed profile does not depend on the site if it is far enough from land. Already for the Rødsand site the difference in the profile is negligible.

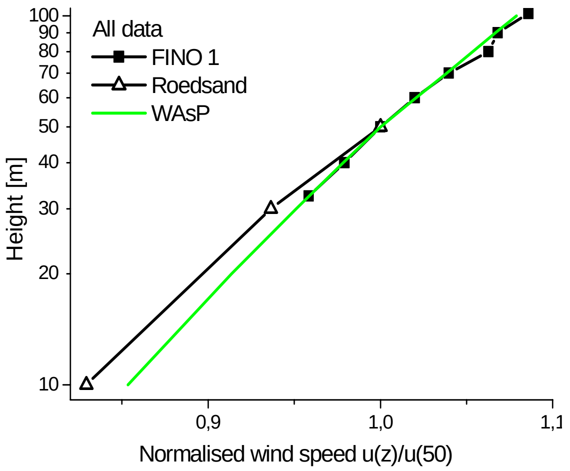

Figure 4: Mean vertical wind speed profiles measured with the cup anemometers at the FINO I and Rødsand sites, normalized with the wind speed measured at 50m height; also shown is the prediction of the WAsP model

The wind speed increase with height (wind shear) is larger at the Rødsand site compared to the FINO I measurement. At Rødsand, wind speed measurements from heights above 70m show larger wind shear than expected, especially the 80m and 100m measurements. It has to be investigated if this is due to a change in the profile at higher heights or due to calibration or correction inaccuracies. The WAsP model agrees astonishingly well with the measured profile at FINO I, but underestimates the wind shear at Rodsand. However, the data sets averaged here are not representative of a long term wind climate at the sites, and the comparison with a climatological model like WAsP has to be treated with care.

5.2 Stability dependent profiles

To investigate the wind speed profiles more closely, the data are segregated into unstable ($-2 < 10m/L < -0.02$), near neutral ($-0.02 < 10m/L < 0.02$) and stable ($0.02 < 10m/L < 0.05$) situations. The result is shown in Figure 5. As expected, the stable data show a larger and the unstable data a smaller wind shear compared to near neutral conditions. At both sites, the form of the profile at near neutral conditions deviates from a logarithmic profile. Instead, the profiles show a slight curvature to the right, which would usually be expected for slightly stable conditions. The difference in wind shear between the two sites found in the mean profiles (see Figure 4) can be seen in all three stability classes.

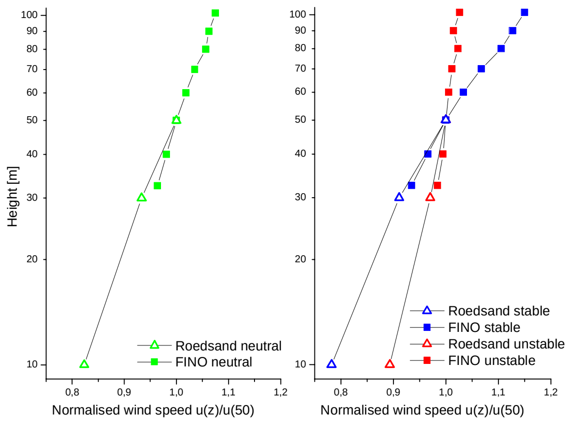

Figure 5: As Figure 4, but data segregated into different stability classes

6 Wind speed gradients

A more detailed comparison of the measured wind shear with the predictions of Monin-Obukhov theory is made by plotting the measured wind speed ratio at two heights versus stability parameter 10m/L. The heights of 50m and 30m are chosen, since they are available both at FINO I and Rødsand. Only records with wind speeds above 5 ms^{-1} have been used to avoid increased scatter.

Figure 6 shows the measured data of the FINO I station, their bin averages and the prediction of Monin-Obukhov theory. A large scatter can be seen in the measurement data. This is caused by two effects:

- Instationary flow situations, where a relation between wind shear and stability can not be expected.
- Large sampling variability of covariance measurements at a relatively high height and with an averaging period of only 10 minutes.

It can be seen that the measurements show systematically lower wind shear than the theory for unstable conditions, while for stable stratification the agreement is better.

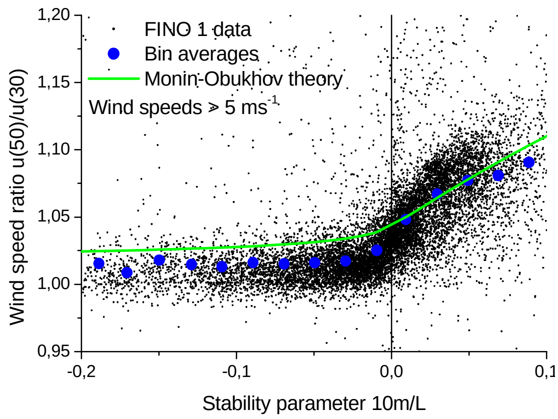

Figure 6: Measured wind speed ratio (wind shear) between the wind speeds at 50m and 30m height versus stability parameter 10m/L for the FINO I site

In Figure 7 the stability dependent wind speed ratios of both stations are compared. Only bin averages and the theoretical prediction are shown. At very unstable conditions both measurements agree with each other in showing smaller wind shear values than theoretically expected. At slightly unstable and stable conditions a marked difference between the two sites is visible. The Rødsand data show a clearly and almost constantly higher wind shear for near neutral and stable conditions compared to the FINO I measurement and compared to Monin-Obukhov theory.

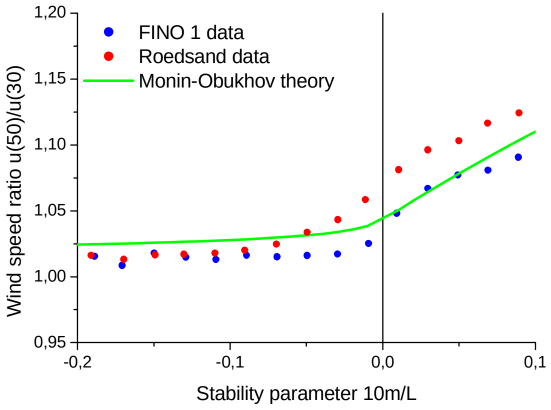

Figure 7: As Figure 6, but bin averaged measurements from both FINO I and Rødsand

7 Conclusion

First measurement data from the station FINO 1 in the North Sea have been analyzed and compared to results from the station Rødsand in the Baltic Sea.
The comparison reveals differences in the wind conditions between both sites. At Rødsand, deviations from Monin-Obukhov theory for non-neutral and stable atmospheric stratification are known. They have been attributed to effects of the land-sea discontinuity, which changes the flow at the Rødsand site, where distances to land (fetch) are between 10km and 100km. This is probably also the cause for the large mean wind shear found at Rødsand compared to FINO 1 and to WAsP.
At the FINO 1 site, where the fetch is generally much larger, similar effects were not found in the present data set. This supports the explanation, that the deviations found at Rødsand are caused by the land-sea discontinuity. However, further investigations with a larger data set are needed to confirm this finding.

Acknowledgement

This work has partly been funded by the DBU (Deutsche Bundesstiftung Umwelt) within the BAGO project (Az. 21223). FINO 1 is funded by the BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) and is managed by Germanischer Lloyd WindEnergie GmbH. The meteorological measurements at FINO 1 are conducted by the German Wind Energy Institute (DEWI). The measurements at Rødsand have been made by Risø National Laboratory, Denmark, and fnuded by the EU-JOULE program, the Danish Energy Ministry's UVE program and SEAS (now Energi E2). The cooperation with Thomas Neumann (DEWI) and Rebecca Barthelmie (Risø) is especially acknowledged.

References

[1] B. Lange, S. Larsen, J. Højstrup, R. Barthelmie, The influence of thermal effects on the wind speed profile of the coastal marine boundary layer. *Boundary-Layer Meteorology* **112** (2004) 587-617

[2] B. Lange, S. Larsen, J. Højstrup, R. Barthelmie, Importance of thermal effects and sea surface roughness for offshore wind resource assessment. *Journal of Wind Engineering and Industrial Aerodynamics* **92 11** (2004) 959-998

[3] P. Rakebrandt-Gräßner, T. Neumann, The German Research Platform in the North Sea. *OWEMES 2003*, Naples, Italy, 2003, published on CD

[4] T. Neumann, K. Nolopp, K. Herklotz, Erste Betriebserfahrungen mit der FINO1-Forschungsplattform in der Nordsee. *DEWI Magazin* **24** (2004) 27-34

[5] B. Lange, R.J. Barthelmie, J. Højstrup, *Description of the Rødsand field measurement*. Risø-R-1268, Risø National Laboratory, DK-4000 Roskilde, Denmark, 2001

[6] J. Højstrup, Vertical extrapolation of offshore wind profiles. *1999 European Wind Energy Conference*, Nice, France, 1999, 1220-1223

[7] B. Lange, H.K. Johnson, S. Larsen, J. Højstrup, H. Kofoed-Hansen, M.J. Yelland, On detection of a wave age dependency for the sea surface roughness. *J. Phys. Oceanogr.* **34** (2004) 1441-1458

[8] B. Lange, S. Tautz, *Bestimmung von Wärme- und Impulsfluß in der marinen atmosphärischen Grenzschicht für die Offshore-Windenergienutzung (BAGO) - DRAFT*. ForWind Bericht 2004-02, University of Oldenburg, Oldenburg, 2004

[9] S. Tautz, *Thermal Effects in the Atmospheric Boundary Layer above the North Sea*. Diplomarbeit (MSc thesis), University of Oldenburg, Oldenburg, 2004

[10] J.M. Wilczak, S.P. Oncley, S.A. Stage, Sonic anemometer tilt correction algorithms. *Boundary-Layer Meteorology* **99** (2001) 127-150

[11] S. Tautz, B. Lange, D. Heinemann, Correction of the heat and momentum flux measurements with the ultrasonic anemometers at the FINO I offshore meteorological mast for flow distortion and mounting effects. *German Wind Energy Conference DEWEK 2004*, Wilhelmshaven, Germany, 2004, published on CD

[12] J.A. Businger, J.C. Wyngaard, Y. Izumi, E.F. Bradley, Flux-profile relationships in the atmospheric surface layer. *Journal of the Atmospheric Sciences* **28** (1971) 181-189

[13] U. Högström, Non-Dimensional Wind And Temperature Profiles In The Atmospheric Surface Layer: A Re-Evaluation. *Boundary-Layer Meteorology* **42** (1988) 55-78