Summary

The paper summarizes the results of four years of observations at FINO1 within the project OWID. The data offer an unprecedented view on the vertical structure of wind and turbulence in the marine boundary layer. They are relevant for the design of offshore wind energy converters (WEC). Results on the connection between wave height and wind speed, the vertical structure of the marine boundary layer and the frequency distribution of the power law exponent, the frequency of inversions, and on different numbers characterising turbulence and extreme wind conditions are presented. A major part deals with a check of the meteorological assumptions made in the load cases described in the IEC 61400-1 and IEC 61400-3. This check shows that not all assumptions are conservative. This is especially true for power law exponent and the 90th percentile of the turbulence intensity. The paper concludes with a few analytical estimations on offshore wind parks.

1. Introduction

Four years of 10 min-mean and 10 Hz meteorological data from the 100 m mast on the FINO1 platform, 45 km off the coast in the German Bight, have been analysed. The data have relevance for a comprehensive description of the atmospheric marine boundary layer (MBL) and for a check for the assumptions made in the standard IEC 61400-3 (design requirements for offshore wind turbines).

2. Vertical structure of the marine boundary layer

Main characteristic of the sea surface is its varying roughness increasing with increasing wind speed. Additionally, the roughness elements (waves) are moving. Therefore the ratio between their speed and the wind speed (the so-called wave age) is an influencing factor, too. The wave height has a considerable influence on the vertical structure of the marine boundary layer (Fig. 1).

3. Mean profiles

The analysis of the mean data e.g. delivered wind speed profiles, Hellmann exponents (Fig. 2) and estimations for 50-year extreme wind speeds.

Fig. 2. Hellmann exponent as function of wind speed.

The power law exponents (Hellmann exponents) are clearly dependent on wind speed and the thermal stratification of the MBL. For small wind speeds and unstable stratification the exponent is small (below 0.1) but for large wind speeds around 25 to 30 m/s we find mean exponents of 0.13. For stable stratification mean values of 0.19 are observed, which is considerably beyond the value of 0.14 assumed in the IEC 61400-3.

4. Turbulence

Large efforts have been made to analyse the turbulence in the MBL. Not only has the mean turbulence intensity (\(\sigma_u/u\)) been analysed but also the size of turbulence elements and their inclination was investigated. Further, in addition to these mean parameters characterizing the turbulence, it was looked at the strength of temporal variations of...
isolated turbulence elements (such as "Mexican hats").

Fig. 3. Observed variation of turbulence intensity with 10 min mean wind speed at 90 m at FINO1 in the period September 2003 to August 2007.

Fig. 3 shows the variation of the turbulence intensity with the mean wind speed. For low wind speeds (below 10 to 12 m/s) considerable parts of the turbulence are due to thermally induced turbulence (convection in cold air over a warm sea surface). Above 12 m/s turbulence intensity is increasing again with wind speed due to the increasing roughness of the sea surface (higher waves). For values of the estimated extreme wind with a 50-year return period (this is about 40 to 42 m/s from the present data) we expect from extrapolation of the data in Fig. 3 a turbulence intensity of about 0.10.

Fig. 4. Measured 90th percentiles of the turbulence intensity for four heights (30, 50, 70, and 90 m, red lines) compared to the parameterization used in the IEC 61400-3 (dotted black lines).

Fig. 4 shows the measured 90th percentiles of the turbulence intensity in four different heights at FINO1. It turns out that there are three wind speed ranges within which the parameterization used in the IEC 61400-3 is not satisfying. One range is below 7 m/s where the parameterized values are far below the observed values. Another range is above about 20 m/s where the parameterized values are slightly below the observed values. Here, obviously the increase of turbulence due to higher waves is somewhat underestimated. A third range is around the most frequent wind speeds around 12 m/s. Here, the parameterization, which is based on Prandtl-layer theory, delivers too high values because the measurement heights (30 to 90 m above sea level) are already within the Ekman layer (the layer above the Prandtl layer) which usually exhibits lower turbulence than the Prandtl layer.

A first suggestion to change this parameterization has been made in [1]. Based on this, we propose

$$\sigma_{u,r} = a \frac{V_{\text{hub}}}{\ln(z_{\text{hub}} / z_0)} + \frac{2V_{\text{hub}}}{V_{\text{hub}}} (1,44 m/s) I_{15} + bV_{\text{hub}}$$

This leads to a better approximation in the whole range of possible hub height wind speeds. The first term copies Prandtl-layer theory, the second term deals with the increase towards low wind speeds, and the third term raises the curve for high wind speeds.

Fig. 5. Measured 90th percentiles of the turbulence intensity for 90 m height (full line) compared to the modified parameterization proposed above (dotted line) with $a=.63$, $b=.0012$, $I_{15}=4.9\%$, $V_{\text{hub}}=12 m/s$.

Scanning the 10 Hz data has yielded examples (Fig. 6) and statistics (Fig. 7) for "Mexican hat"-shaped turbulence structures (gusts) in the wind speed time series.

Fig. 6. Example of a "Mexican hat"-shaped gust at 80 m above sea level (upper curve). This gust is not present at 40 and 60 m height (lower two curves).

Fig. 6 shows an example of such a gust which – in this case – is only observable at 80 m height. There are other cases where such gusts appear in all three heights. A statistical evaluation shows that "Mexican hats" with smaller duration (e.g. 8 s) are 1.6 times more frequent than "Mexican hats" with 10.5 s duration (the assumption which is made in the IEC 61400). Such gusts with even longer duration (e.g. 14 s) are even less frequent (63% compared to the 10.5 s gusts).
Fig. 7 shows that “Mexican hats” do not need to be “upright”. Actually, the statistics reveal that about 57% of all “hats” are negative hats (i.e. they looked like hats turned upside down).

![Figure 7](image7.png)

**Figure 7.** Amplitude statistics for “Mexican hat”-like turbulence gusts with 10.5 s duration at 80 m height (440 cases in the year 2005).

Fig. 8. Frequency distribution of the turbulent length scale in three different heights (40, 60, and 80 m).

The turbulence length scale is slightly increasing with height at FINO1. Mean values of 249 m (40 m), 280 m (60 m), and 302 m (80 m) have been found (Fig. 8). Theinclination of the large majority of the turbulence elements (Fig. 9) is forward.

![Figure 8](image8.png)

**Figure 8.** Frequency distribution of the turbulent length scale in three different heights (40, 60, and 80 m).

Fig. 9. Frequency distribution of the inclination of the turbulence elements between 40 and 60 m height at FINO1.

Positive values mean forward inclination (i.e. the upper edge arrives first), negative values indicate a backward inclination. (The gap at zero degree inclination (perfectly upright elements) is due to the limited temporal resolution (10 Hz) of the available turbulence data.)

![Figure 9](image9.png)

**Figure 9.** Frequency distribution of the inclination of the turbulence elements between 40 and 60 m height at FINO1.

Fig. 10 shows the frequency distribution of the maximum wind direction change with time intervals of 6, 10, and 14 s from 10 Hz data at FINO1. The mean value for 6 s is 10.7 degrees, for 10 s it is 11.3 degrees and for 14 s it is 11.7 degrees. This behaviour is well described by the EDC model of the IEC 61400.

![Figure 10](image10.png)

**Figure 10.** Frequency distribution of the maximum wind direction change for three different time intervals (6, 10, and 14 s).

Fig. 11 displays the correlation between the maximum wind speed change and the simultaneous wind direction change as described in the ECD model of the IEC 61400.

![Figure 11](image11.png)

**Figure 11.** Correlation between maximum wind speed change (x axis) and the simultaneous wind direction change (y axis).

5. Implications of low offshore turbulence on wind parks

Generally, the turbulence intensity offshore is lower than onshore. This has implications not only on the loads and power gains from single wind turbines but also on the density of turbines within larger wind parks and finally also on the distance between different wind parks offshore. In order to assess such effects on wind parks a simple analytical model formulated by Emeis and Frandsen in 1993 [2] has been enhanced.

The enhanced model predicts the mean wind speed reduction at hub height in an indefinitely large wind park based on a balance between momentum extraction by the wind turbines and a replenishment of momentum by turbulent fluxes from above. These turbulent fluxes are not only determined by the
momentum extraction of the turbines but also by the roughness of the underlying surface. And this latter aspect makes the difference for offshore wind parks. Offshore the underlying surface is much smoother than onshore and therefore the downward turbulent momentum fluxes are somewhat smaller than onshore. This results in larger wind speed reductions at hub height within an offshore wind park than in an onshore wind park (given the same wind speed above). The enhanced model now analyses this roughness effect together with the influence of the thermal stratification of the MBL (this latter aspect was not considered in the original version in [2]).

Fig. 12. Reduction of wind speed at hub height in an indefinitely large wind park as function of the thermal stratification of the MBL (denoted on the x axis) and as function of the roughness of the underlying surfaces (different curves, full lines: offshore conditions, dotted lines: onshore conditions).

Fig. 13. Vertical wind profiles in an indefinitely large wind park with (full lines) and without (dotted lines) a wind park for offshore conditions (left) and onshore conditions (right). The hub height is marked by the horizontal line.

Fig. 12 indicates that over smooth offshore surfaces the wind speed reduction at hub height within a large wind park is considerably larger than over a rough onshore surface. The difference between the offshore and the onshore conditions is the larger the more unstable the thermal stratification of the MBL is (to the left in Fig. 12). Generally, the wind speed reduction within a wind park increases with increasing thermal stability of the MBL (to the right in Fig. 12). The stronger reduction of the wind speed at hub height can be reduced if the spacing between single wind turbines within the wind park is increased. Following this simple analytical model the wind turbine density in an offshore wind park has to be reduced by about 35% in order to get the same wind speed reduction as in an onshore wind park.

Likewise it is probable that the distance between wind parks has also to be increased offshore. An enhancement of the simple analytical model in order to compute the necessary distances between different wind parks is still under way.

Fig. 13 shows sample vertical wind profiles from this simple analytical model. Although the wind speed reduction is larger offshore (left frame of Fig. 13) the mean wind speed at hub height within a wind park offshore is about the same as onshore (given the same undisturbed geostrophic wind speed above). This indicates that the positive effects of the smoother surfaces offshore (higher mean wind speeds upstream of a wind park) and the negative effects (larger wind speed reduction within the wind park) are cancelling out to a large extent.

6. Conclusions

The FINO1 data offered an unprecedented insight into the wind and turbulence characteristics of the MBL. From the vertical structure of the MBL it becomes obvious that large offshore wind turbines with hub heights around 90 m will mainly operate within the Ekman layer. Only if the wind speed is above 20 to 25 m/s they will operate within the Prandtl layer (as they usually do at onshore sites).

Most of the offshore characteristics are covered by the IEC 61400 standard. Problems still seem to exist with the power law exponent and the 90th percentiles of the turbulence intensity.

The implications of the generally rather low turbulence intensities offshore have been demonstrated with a simple analytical model predicting the wind speed reduction at hub height within a wind park.

7. Acknowledgements

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8. References:
