The role of atmospheric stability/turbulence on wakes at the Egmond aan Zee offshore wind farm

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Abstract. The aim of the paper is to present results from the NREL SOWFA project that compares simulations from models of different fidelity to meteorological and turbine data from the Egmond aan Zee wind farm. Initial results illustrate that wake behavior and impacts are strongly impacted by turbulence intensity \cite{1}. This includes both power losses from wakes and loading illustrated by the out of plane bending moment. Here we focus on understanding the relationship between turbulence and atmospheric stability and whether power losses due to wakes can effectively be characterized by measures of turbulence alone or whether atmospheric stability as a whole plays a fundamental role in wake behavior. The study defines atmospheric stability using the Monin-Obukhov length estimated based on the temperature difference between 116 and 70 m. The data subset selected using this method for the calculation of the Monin-Obukhov length indicate little diurnal or directional dependence of the stability classes but a dominance of stable classes in the spring/unstable classes in fall and of near-neutral classes at high wind speeds (Figure 2). The analysis is complicated by the need to define turbulence intensity. We can select the ratio of the standard deviation of wind speed to mean wind speed in each observation period using data from the meteorological mast, in which case a substantial amount of data must be excluded due to the presence of the wind farm. An alternative is to use data from the wind turbines which could provide a larger data set for analysis. These approaches are examined and compared to illustrate their robustness. Finally, power losses from wakes are categorized according to stability and/or turbulence in order to understand their relative importance in determining the behavior of wind turbine wakes.

1. Introduction

Previous research has indicated that wind turbine wakes are responsible for significant power losses and increased wind turbine fatigue loading in both onshore and offshore wind farms (where the ‘deep array’ effect is particularly marked) \cite{2}. The goals of this research are thus to: (1) Optimize techniques associated with characterizing the atmospheric parameters responsible for varying wake behavior. (2) Improve physical understanding of wake development and wake merging under different wind speed, turbulence and atmospheric stability conditions, and thus reduce uncertainty in wind farm power prediction by better quantification, modeling and description of wakes.
In prior research [2], we analyzed data from two offshore wind farms in Denmark – Horns Rev and Nysted and showed that total wind farm efficiency appeared to exhibit a clearer variation (and greater absolute magnitude of variability) with stability (as measured using the Monin-Obukhov length) than with turbulence intensity (as described using the standard deviation of wind speed to the mean). Herein we investigate whether the degree to which one can differentiate the effects of ambient turbulence versus stability metrics on wake recovery and behavior is a function of the precise metrics used and which of these properties provides a clearer forensic diagnostic of wake behavior using data from the Egmond aan Zee (OWEZ) wind farm in the Netherlands.

There are different indices that can be used to describe the atmospheric stability (e.g. the gradient (or bulk) Richardson number, and the Monin-Obukhov length) and depending on which metric is used and the approach applied to compute the index, they can generate quite different stability climates [3], [4]. Here we employ the Monin-Obukhov length \( L \) in part because it has a strong theoretical foundation that can be used quantitatively to correct wind speed profiles in the surface layer [5]:

\[
L = -\frac{\theta' u'^2}{kg \left\langle w' \theta' \right\rangle}
\]  

where \( \theta \) is the virtual potential temperature, \( u' \) is the friction velocity, \( \left\langle w' \theta' \right\rangle \) is the mean virtual heat flux, \( k \) is the von Karman constant (0.4) and \( g \) is acceleration due to gravity.

Where measurements of the virtual heat flux are not available, a range of techniques (see section 3) can be applied to derive estimates of \( L \), though the method used to determine each value of \( L \) does to some extent determine the result and thus the resulting stability climate. For example, if \( L \) is calculated from the Richardson number (see Section 3) then it is strongly impacted by wind shear - and is sensitive to measurement error therein and the depth of the layer over which it is computed. Using \( L \) determined from an estimate of heat flux as in equation (1) [6] tends to produce a large number of observations in the stable or unstable classes, likely because it is more sensitive to any measurement errors in the high-frequency temperature observations. \( L \) is function of the cube of the friction velocity and therefore tends towards high values (neutral conditions) at high wind speeds (and \( |L| \rightarrow \infty \)). In unstable conditions then buoyant production of turbulent mixing increases, although shear production may be declining (and \( L \) is negative and \( \rightarrow 0 \)). In a stable atmosphere turbulent motions are acting against gravity hence turbulence is suppressed by buoyancy while turbulence is generated mechanically by wind shear (\( L \) is positive and \( \rightarrow 0 \)) [5]. Because \( L \) is unbounded, it is often (as here) presented normalized by measurement height \( z \) (i.e. as \( z/L \)). \( z/L \) is a surface layer scaling parameter.

While stable conditions tend to be predominately associated with low turbulence, and higher turbulence tends to occur in unstable conditions [2], the occurrence of low turbulence conditions does not necessarily determine that conditions are stable. Equally higher turbulence conditions can occur in stable conditions [7]. Thus far it is unclear whether stability or turbulence intensity is most important to wake propagation and recovery or even whether the two quantities act in different ways. For example, it is possible that turbulence intensity at large length scales determines the degree of wake meander (i.e. lateral movement of the wake centreline) that acts to apparently widen wakes in unstable conditions while stability controls the extent of downward mixing of momentum (and thus wake dispersion) which is an important control of wake recovery in large wind farms. Here we use observations from the OWEZ wind farm to determine the interplay between stability and turbulence and wake properties, and thus address one of the key objectives of the Simulator for Wind Farm Applications (SOWFA) project.
2. The OWEZ wind farm

The OWEZ wind farm is located between 10 and 18 km off the Dutch North Sea coast, at 52°36’N, 4°23’E (Figure 1). It comprises 36 Vestas V90 3.0 MW turbines in 4 rows oriented from the NW to the SE. The rotor diameter is 90 m and the hub-height 70 m. The turbine spacing is 7.1 D (rotor diameters) within the row and 11.5 D between rows. Meteorological data are available from a 116 m meteorological mast located southwest of the wind farm (Figure 1). Meteorological data are available for 2005-2010 and turbine data from 2007-2010. Note that water temperature is missing for 2009 and 2010. Data availability for each turbine, after applying quality control and related data screening criteria (see Section 3) are shown in Figure 1. Consistent with analyses of data from other offshore wind farms, prior analyses of OWEZ data indicated; (i) a strong dependence of wake losses on wind direction and wind speeds, and a dominance of nearest wakes [8] and (ii) evidence of amplification of wake losses under stable stratification [1].

Figure 1. Wind farm location (red square in bottom left inset map of the Netherlands) and layout of the turbines at the Offshore Wind Farm Egmond aan Zee (OWEZ). The spacing shown on each axis is 1 km. The groups of turbines shown are used in the freestream calculation. The scale indicates the percentage of observations available after the quality control described in Section 3 is applied and is normalized to the wind turbine with the most observations leading to a value greater than 100% for the meteorological mast data

3. Turbulence intensity and stability

3.1 Determining stability from meteorological data

Prior analysis of stability conditions at OWEZ in [4] suggested:
- avoiding the wind farm sector (135-315°) and using the freestream sector 225-315°
- using wind speeds > 4 ms⁻¹
- using the bulk Richardson number method to characterize stability
- subtracting 0.82 K from the measured water temperature when used to compute stability.

As is the case for most offshore wind farms, direct measurements of the sensible and latent heat fluxes are not available from OWEZ. Thus, a number of approaches for determining the Monin-Obukhov length were tested here including:
- Using combinations of the sea surface temperature, the air temperature difference between measurements at different heights 116-70 m, 116-18 m and 70-18 m. Note that temperature differences were not measured directly and so can be impacted by sensor calibration errors.
Using different methods for the calculation including:

1. the AMOK tool [9] which uses the Richardson number based approach
2. the Beljaars [6] routines (here denoted as BJx-y, where xy are the heights of the temperature measurements used) that estimate surface fluxes based on the temperature and wind speed profiles and find an iterative solution for L
3. calculation of a bulk Richardson number which can then be used to estimate an Obukhov Length based on [10] (Here denoted as GRx-y where x and y are the heights of the wind speed and temperature).

Using AMOK most of the observations fall into the neutral class with very few in either stable or unstable classes. This is an indication that there is a temperature offset (likely a calibration issue) between the air and water temperature. Applying the temperature correction suggested in [4] did not improve results from AMOK significantly but improved the results from BJ in terms of the distribution of stability classes by wind speed, direction, time of day and month (Figure 2). A prior analysis based on the gradient Richardson number indicated a dominance of the near-neutral and unstable classes with very few stable observations except at low wind speeds. Since no unbiased estimate of L was available, the ‘best’ method was determined by using each of the L estimates to predict wind speeds at 116 m and the functions given in [6]. Using BJ116-70 minimized the root mean square error (RMSE) in the prediction of the wind speed relative to observations and thus in the following we use the BJ116-70 method for classifying stability. This approach was used previously in e.g.[11]. It is worth noting that calculating L using data from these heights is also subject to errors since Monin-Obukhov similarity theory applies only in the surface layer (see discussion in [4]).

Figure 2. Distribution of observations by stability class where L is calculated using the Beljaars [6] routines with data from 116-70m (i.e. BJ116-70) conditionally sampled by hour of the day, month, wind direction and wind speed.
Table 1. Percentage of observations in different stability classes based on OWEZ data for 2007-2010 and the different approximation approaches listed above.

| % of observation in each stability class | Very stable | Stable | Slightly stable | Near-neutral | Slightly unstable | Unstable | Very Unstable |
|----------------------------------------|-------------|--------|-----------------|--------------|------------------|----------|--------------|
| $L$ in m                                |             |        |                 |              |                  |          |              |
| $10 \leq L \leq 50$                      | 1           | 9      | 11              | 23           | 15               | 23       | 18           |
| $50 \leq L \leq 200$                     | 2           | 8      | 17              | 67           | 1                | 1        | 1            |
| $200 \leq L \leq 500$                    | 14          | 19     | 25              | 10           | 1                | 1        | 3            |
| $|L| > 500$                              | 3           | 5      | 12              | 60           | 4                | 6        | 4            |
| $200 \leq L \leq 1000$                   | 35          | 27     | 26              | 8            | 5                |          |              |
| $|L| > 1000$                              | 15          | 15     | 44              | 19           | 6                |          |              |

Figure 3. Relationship between $TI$, $z/L$ and $U$ with $TI$ and $U$ using OWEZ data from 116 m height. The black solid lines depict the mean value, the vertical bars show ± one standard deviation (±1sd), and the grey dots show the individual data points. The $TI$ rose (top right) is also from 116 m height and is for all wind speeds. The black line shows the mean by 1° direction bin and the gray lines ±1sd.

3.2 Estimating turbulence intensity from meteorological data

An estimate of ambient turbulence intensity $TI$ can be derived using the ratio of the standard deviation of wind speed in each 10 minute observation period, $\sigma$, divided by the mean of the wind speed $U$ in the period, presuming that the meteorological data are available that are representative of the freestream conditions. The relationships between $TI$ and $z/L$ and $U$ derived using data from the 116 m height follows patterns that have been observed in other offshore environments [2] (Figure 3). $TI$ is high at low wind speeds, decreases with wind speed and then increases slightly as wind speeds continue to increase and there is an increase in mechanical generation of turbulence due to the increasingly rough sea-surface. Consistent with the definitions of stability indices higher mean turbulence intensity is observed in unstable conditions, and lower $TI$ occurs in stable conditions. However, as shown by the
error bars, lower turbulence intensity can occur in unstable conditions and vice versa. In the freestream direction $TI$ is less than 6%. Higher $TI$ to the north and east of the mast is driven by flow through the wind farm, and hence is a motivation behind sections 3.3 and 3.4 wherein we determine whether robust estimates can be derived from the turbine power output.

3.3 Estimating the freestream wind and power

As indicated above, the meteorological mast at OWEZ is very close to WT06 and WT07 and frequently in the ‘wind farm wake’ and thus data from the mast cannot be used to determine the freestream wind speed or ambient turbulence intensity for use in wake analyses or to estimate whole wind farm efficiency (see Figure 4, right). In the absence of these data we thus determined the degree to which data from the wind turbine nacelle-mounted anemometers and the variability of wind turbine power output can be used as proxies of freestream wind speed and turbulence intensity respectively using the approach described in [12]. Data from groups of turbines are used to determine the freestream wind speed by direction (Figure 1) and the arithmetic mean of the data from nacelle-mounted anemometers is used to approximate the freestream wind speed. The results (Figure 4) show this approach gives a reasonable estimate of the freestream power curve as a function of freestream wind speed derived as the average of the nacelle-mounted anemometers.

![Figure 4. Left: The freestream power curve plotted against the freestream wind speed as derived from the nacelle-mounted anemometers. Right: Ratio of wind speeds at 70 m from the meteorological mast ($U_{met}$) to those selected as the freestream from the nacelle anemometer ($U_{turb}$).](image)

3.4 Estimating turbulence intensity from power data

To estimate turbulence intensity at each turbine two measures were tested. One in which $TI$ is derived as above but using data from the nacelle anemometer and the second in which the power output and its standard deviation are used as in [13]:

$$\sigma_p = B\sigma_u \left( \frac{\partial P}{\partial U} \right)$$  \hspace{1cm} (2)

where $\sigma_p$ is the standard deviation of power output, $\sigma_u$ is the standard deviation of wind speed, $B$ is a constant which is in the range of 0.8–0.9, depending on mean wind speed [13], $P$ is power output and $U$ is the wind speed.

The former approach may be deficient because of turbulence induced by the nacelle and the blades. The latter (i.e. Equation 2) also has some limitations, namely there is uncertainty regarding the value of the coefficient $B$. It cannot be used when the turbine is not producing power or if there is no change...
in the power output in a given period. Use of the power and the power change mean that the rotor itself may be acting to filter turbulence at smaller scales. To evaluate the different measures of $T_I$: $T_{Ina}$ from the nacelle anemometer measurements and $T_{Ipw}$ from the wind turbine power standard deviation were compared with $T_{I_{met}}$ from the anemometer mounted on the meteorological mast (Figure 5). There is good agreement between $T_{I_{met}}$ and $T_{Ina}$ but using $B=0.9$ (as in [13]) gave values that were too high for $T_{Ipw}$ so this technique has been disregarded here. If it is to be utilized a technique for determining the value of $B$ in Equation 2 needs further investigation. Although in the following section $T_{Ina}$ is used to describe ambient turbulence intensity it is worth noting that $T_{I_{met}}$ is a better indicator of atmospheric conditions, and when plotted against $z/L$, $T_{I_{na}}$ does not vary. $T_{I_{na}}$ may be influenced by flow around the nacelle and smoothing by the rotor resulting in a value that does not vary by direction or wind speed. However, it appears from results in the northeast sector that it could be an acceptable alternative in the directions where the meteorological mast is influenced by direct wakes (339-29° and 98-117°).

Figure 5. Comparison of $T_I$ determined by different techniques. Top left: $T_I$ binned by wind speed. Top right: $T_I$ binned by wind direction. Bottom: $T_I$ binned by $z/L$. Note that $T_{I_{met}}$ has not been screened for wakes but $T_{Ipw}$ and $T_{Ina}$ are both freestream values.

4. Wake analysis

4.1 Wake behavior conditionally sampled by turbulence intensity

As noted previously [2], the main driver of wake magnitudes in approximate order of impact are 1) wind speeds (via their impact on the thrust coefficient), 2) the wind direction (as a proxy for the
number of upstream turbines, the distance to the nearest turbine, any roughness change or stability
issues) 3) turbulence intensity which is itself a function of wind speed and stability and 4) stability
which is directly related to the previous 3 variables.

In the following the freestream wind, power and turbulence intensity are taken from the turbine data
while the stability measure $z/L$ is from the meteorological mast (BJ116-70). To assess the impact of
turbulence intensity and stability conditions on wake losses we use the average power output for the
wind farm (normalized by the freestream power output by direction) calculated for each 1° directional
bin. Recall that, as shown in Figure 1, the turbines are aligned in a regular grid with turbine spacing of
11.5 D between the rows and 7.1 D within the rows. It is also worth noting that in these analyses the
direction is taken from the meteorological mast which may have an offset of 2° [14], and that wind
directions can (and should) be verified [8].

Figure 6 shows the normalized power output (total average power from all wind turbines in the array /
freestream power calculated using the power curve and freestream wind speed) by direction. It clearly
indicates the main wake directions at 139 and 319° (7-12 turbines upstream with the closest at 7.1 D).
The secondary wind turbines wakes expected at 229° and 49° based on the wind farm layout (there are
1 to 4 turbines upstream at 11.5 D and beyond in these directions) are – however – not visible, or at
least are not discernible above the general ‘wind farm wake’.

If the normalized power is conditionally sampled by both wind direction and $TI$ then it is apparent that
wake losses are larger in low turbulence conditions and vice versa. The impact on the wind farm
power output is that normalized power is slightly higher (∼0.5-1.0%) if $TI > 0.12$ and normalized
power is 7% lower if $TI < 0.06$. This is a similar value to that given for efficiency changes (relative
normalized power) at Horns Rev and Nysted wind farms of 0.98-1.4% per 1% change in turbulence

![Figure 6. Normalized power output by direction classified by turbulence intensity ($TI$) (from the
nacelle anemometer). Note the data are binned by 1° (thin gray lines) and a running mean of 3 is
applied (thicker colored lines).](image-url)
intensity [2], suggesting this may be a generalizable response function for offshore wind farms in relatively high wind speed regimes (e.g. in the seas of northern Europe).

Figure 7 shows the normalized power output (total average power from all wind turbines in the array / freestream power calculated using the power curve and freestream wind speed) conditionally sampled by both direction and stability class. This analysis indicates that observations in the stable class typically have the highest wake losses, and the near-neutral class the lowest wake losses. Unexpectedly, the unstable class appears to experience higher wake losses than the near-neutral class. However, this is not completely consistent by direction. It is possible that from 290° over north, the measurements at the meteorological mast are being impacted by wakes from the closest wind turbines.

Deconvoluting the impacts of wind speed, $TI$ and stability on wake depth, width and dissipation is confounded by their co-dependence. For example, different stability classes tend to have different distributions of wind speeds and turbulence intensity. To examine this, the data were selected for a single wind speed bin (8-10 ms$^{-1}$). Wake losses were larger due to the higher thrust coefficients in this wind speed range but the overall difference in normalized power varied by only 1% overall between the stable and near-neutral class and the unstable and near-neutral classes. Mean wind speed is close to 9 ms$^{-1}$ in all three cases, while mean $TI$ is 8.0, 8.7 and 8.5% in the stable, near-neutral and unstable classes respectively. This result is thus in contrast to our previous analyses of data from Horns Rev and Nysted that had indicated a stronger relationship between efficiency (normalized power output) changes of -8.1% to +9.7% over a range of stabilities [2].

5. Conclusions

Observations at the OWEZ wind farm have been analyzed by stability and $TI$ classes. Following previous analysis it is clear that wakes are influenced primarily by wind speeds and then by wind
direction as a proxy for both spacing and for stability. $TI$ is also shown to have a major impact on normalized power output that is of similar magnitude (about a 1% change in normalized power output for a 1% change in $TI$) as found at other offshore wind farms [2]. Analysis indicates that while $TI$ is generally lower in the stable class this assumption cannot be uniformly applied due to the wide range of $TI$ in both stable and unstable classes. Stability is also shown to have an impact on the normalized power output but the impact of stability on power losses due to wakes appears to be of lesser magnitude than $TI$, and less distinct than found for other offshore wind farms [2] which might be partly due to the height of measurements used to define stability or use of the nacelle anemometers to define turbulence intensity.

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7. References
1. Churchfield, M.J., et al. A comparison of the dynamic wake meandering model, large-eddy simulation, and field data at the Egmond aan Zee Offshore wind plant. in AIAA Science and Technology Forum and Exposition (SciTech 2015) 2015. Florida 5-9 January 2015.
2. Barthelmie, R.J., K.S. Hansen, and S.C. Pryor, Meteorological controls on wind turbine wakes. Proceedings of the IEEE, 2013. 101(4): p. 1010-1019.
3. Barthelmie, R.J., The effects of atmospheric stability on coastal wind climates. Meteorological Applications, 1998. 6: p. 39-47.
4. Sathe, A., S.-E. Gryning, and A. Peña, Comparison of the atmospheric stability and wind profiles at two wind farm sites over a long marine fetch in the North Sea. Wind Energy, 2011. 14(6): p. DOI: 10.1002/we.456.
5. Stull, R.B., An introduction to boundary layer meteorology. ISBN 90-277-2768-6 ed1988, Dordrecht: Kluwer Publications Ltd. 666.
6. Beljaars, A.C.M., A.A.M. Holtslag, and R.M. van Westrhenen, Description of a software library for the calculation of surface fluxes., 1989, KNMI: De Bilt, Netherlands.
7. Sun, J., et al., Turbulence Regimes and Turbulence Intermittency in the Stable Boundary Layer during CASES-99. Journal of the Atmospheric Sciences. 2012. 69(1): p. 338-351.
8. Larsen, T.J., et al., Validation of the Dynamic Wake Meander Model for Loads and Power Production in the Egmond aan Zee Wind Farm Wind Energy, 2012. DOI: 10.1002/we.
9. Hansen, K.S., G.C. Larsen, and S. Ott, Dependence of offshore wind turbine fatigue loads on atmospheric stratification. Journal of Physics: Conference Series 2014. 524: p. doi:10.1088/1742-6596/524/1/012165.
10. Grachev, A.A. and C.W. Fairall, Dependence of Monin-Obukhov stability parameter on the bulk Richardson number for unstable conditions over the ocean. Journal of Applied Meteorology 1997. 36: p. 406-415.
11. Motta, M., R.J. Barthelmie, and P. Volund, The influence of non-logarithmic wind speed profiles on potential power output at Danish offshore sites. Wind Energy, 2005. 8: p. 219-236.
12. Barthelmie, R.J. and L.E. Jensen, Evaluation of power losses due to wind turbine wakes at the Nysted offshore wind farm. Wind Energy, 2010. 13: p. 573-586.
13. Barthelmie, R.J., et al., Modelling and measurements of power losses and turbulence intensity in wind turbine wakes at Middelgrunden offshore wind farm. Wind Energy, 2007. 10(DOI: 10.1002/we.238): p. 217-228.
14. Alblas, L.M., Power output of offshore wind farms in relation to atmospheric stability, in Technical University of Delft in cooperation with Vestas Wind Systems A/S2012: Delft. p. 190.