IMPROVEMENT OF THE WIND FARM MODEL FLAP FOR OFFSHORE APPLICATIONS

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ABSTRACT: The wind farm program FLaP (Farm Layout Program), developed at the University of Oldenburg, has been extended to improve the description of wake development in offshore conditions, especially the low ambient turbulence and the effect of atmospheric stability. Model results have been compared with measurements from the Danish offshore wind farm Vindeby. Vertical wake profiles and mean turbulence intensities in the wake were compared for 32 scenarios of single, double and quintuple wake cases with different mean wind speed, turbulence intensity and atmospheric stability. It was found that within the measurement uncertainties the results of the wake model compares well with the measurements for the most important ambient conditions. The effect of the low turbulence intensity offshore on the wake development was modelled well. Deviations have been found when atmospheric stability deviates from near-neutral conditions. Especially for stable atmospheric conditions both the free flow model and the wake model do not give satisfying results.
Key Words: Off-Shore, Wakes, Models (Mathematical), Turbulence, Stratification (Atmospheric), Vindeby

1 INTRODUCTION

For the planning of large offshore wind farms, modelling of wake losses is an important part of the production estimation. Additionally, an estimation of turbulence intensity in the wind farm is essential for the load assumptions used in the design of the turbines. Some knowledge and considerable experience have been gained in the estimation of these wake effects from wind farms on land, which is available in wind farm models like PARK (Risø National Laboratory, Denmark), Windfarmer (Garrad, Hassan and Partners, United Kingdom) and FLaP (University of Oldenburg, Germany).

The models used for wake predictions on land have to be extended for the use in offshore conditions to incorporate the different atmospheric flow conditions. Two characteristics of the offshore conditions are of paramount importance for the wake development: Sea surface

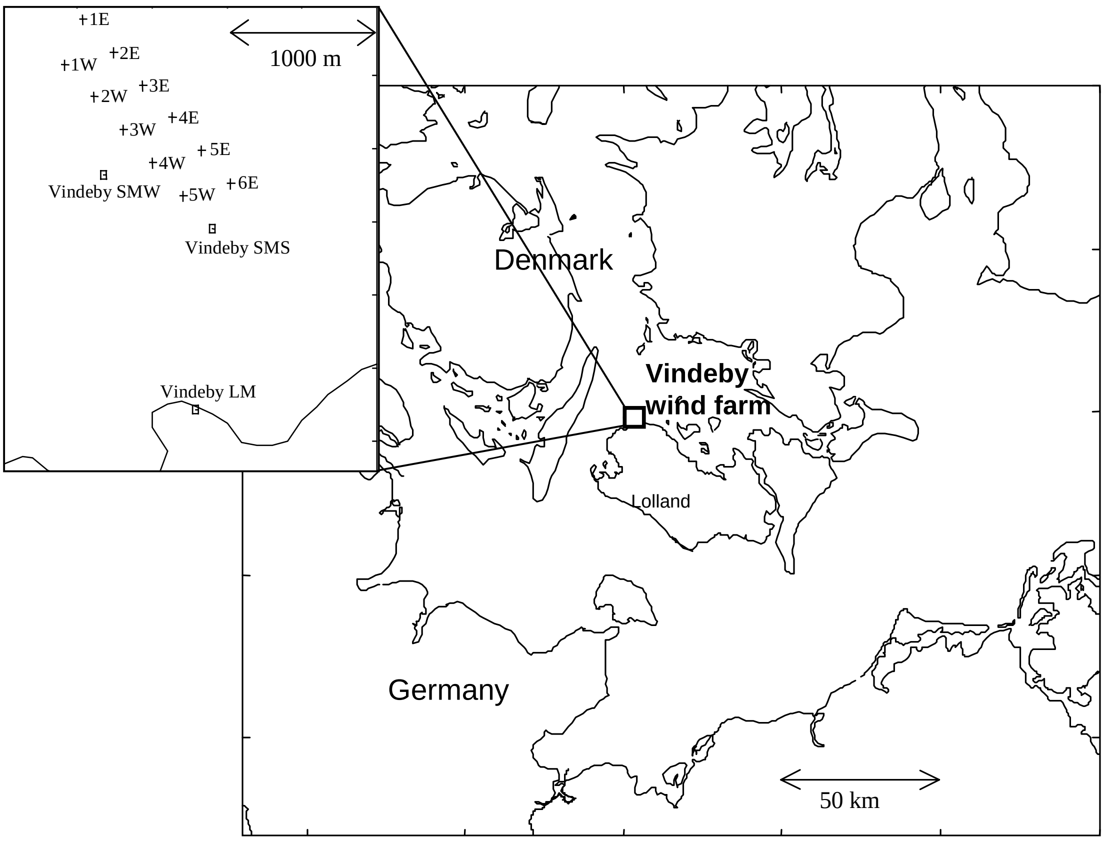

Figure 1: Location of Vindeby wind farm in the Baltic Sea in the southern part of Denmark and layout of the Vindeby wind farm and the measurement masts

roughness and atmospheric stability.
The roughness of water surfaces is different from land surfaces in that it is much smaller and dependent on the wave field, which in turn depends mainly on wind speed, but also on fetch, water depth, etc. (see e.g. (Lange et al., 2001)). This has been taken into account in the description of the ambient vertical wind speed profile. It also has important consequences for the modelling of the wake since it leads to a low and wind speed dependent turbulence intensity.
Atmospheric stability is important in offshore conditions, since atmospheric stratification departs from near neutral conditions also for higher wind speeds, which are important for wind power production, due to the land-sea temperature difference and the low roughness offshore. This has to be included in the modelling of the ambient flow, but also might have an influence on the wake development.
The wind farm modelling program FLaP has been extended with the aim to incorporate these effects in the wake modelling within the ENDOW project (Barthelmie et al., 2002). For the modelling of the ambient atmospheric flow standard Monin-Obukhov similarity theory (see e.g. Stull (1988)) has been used, employing the Charnock relation (Charnock, 1955) to estimate the sea surface roughness. A two-dimensional, axis-symmetric wake model with eddy-viscosity closure is used, based on the model described by Ainslie (1985, 1988). It has been extended to improve the modelling of the influence of turbulence intensity and atmospheric stability on the wake. Comparisons of model results with results of several other wake models and comparisons of results before and after the improvements are given in Rados et al. (2002) and Schlez et al. (2002).
Model results have been compared with measurements of the offshore wind farm Vindeby for a wide range of ambient conditions. Measurements were available for single, double and quintuple wakes for different ambient wind speed, turbulence intensity and stability. Vertical wind speed profiles in the wake and mean turbulence intensities are compared.

2 THE FLAP WIND FARM MODEL

The wind farm program FLaP (Farm Layout Program) has been developed at the University of Oldenburg since 1993. It combines an axis-symmetric wake model, describing the wake of one rotor, a free flow model for the undisturbed vertical wind speed profile and a wind farm model, which takes care of the interaction of all wakes in a wind farm. The program estimates wind speeds and turbulence intensities in wakes and their effect on the power output of the turbines in a wind farm. Noise calculations and automatic layout optimisation are additional features.
Different wake models are implemented. Here an approach based on Ainslie (1985, 1988) has been chosen. It is a two-dimensional (axis-symmetrical) model solving the simplified momentum and continuity equations with an eddy-viscosity closure. The eddy-viscosity is modelled as a combination of contributions from the ambient turbulence of the free flow and the shear generated turbulence in the wake. The model does not include the near wake directly behind the rotor. Instead, it first starts at the end of the near wake with an empirical wake profile as boundary condition.
The result is an axis-symmetric wake profile, which is than convoluted with the incident ambient wind speed profile modelled in the free flow model. For multiple wakes the wind speed incident on a rotor placed in wake(s) is calculated in a multiple wake model from the modelled wake deficits of the incident wakes.
The wake model has been extended to improve the description of wake development in offshore conditions, especially the low ambient turbulence and the effect of atmospheric stability. For a detailed description of the program and validation see Lange et al. (2002) and Waldl (1998).

3 THE VINDEBY MEASUREMENTS

Measurements from the Danish offshore wind farm Vindeby have been used for comparison with the model results. The wind farm consists of 11 stall-controlled Bonus 450 kW wind turbines with hub height 38 m and rotor diameter 35 m. They are arranged in two rows oriented along an axis of 325-145º. The distance of the turbines within the row as well as the distance between the rows is 300 m (8.6 D). Since the turbine locations are shifted in the two rows with respect to each other, the minimum distance between turbines of two rows is 335 m (9.6 D).
Three meteorological masts have been erected close to the wind farm, one on land and two offshore. The land mast is located nearly 2 km south of the most southerly turbine of the wind farm. The two offshore masts are placed at distances equal to the row and turbine spacing (335 and 300 m), one to the west and one to the south of the first row. Wind speed measurements with cup anemometers are performed at 46, 38, 20 and 7 m height at the land mast (LM) and at 48, 43, 38, 29, 20, 15 and 7 m height at SMS and SMW.
The atmospheric stability is characterised by the Monin-Obukhov-length L, which is derived from temperature and wind speed difference measurements. For a detailed description of the wind farm and measurements see (Barthelmie et al., 1994) and (Frandsen et al., 1996).
Measurements from the years 1994 and 1995 have been used. One minute averages have been calculated to reduce the effect of wake meandering due to wind direction changes during the averaging period. Four cases of direct wake interference were selected where measurements of the wind speed in the wake as well as measurements of the free wind speed are available (see Table 1).

Table 1: Measured wake cases at Vindeby wind farm

wind direction sector	measured wake	free mast	wake mast	stability determine d from
18º-28º	single	LM	SMS	LM
18º-28º	double	LM	SMW	LM
70º-78º	double	SMS	SMW	SMS
314º-323º	quintuple	SMW	SMS	LM

For each of the cases data have been classified according to the three criteria: wind speed, turbulence intensity and atmospheric stability at the free mast. Wind speed bins of 4-6m/s, 6-9m/s and 9-11m/s, turbulence intensity bins of 5-7%, 7-9% and 9-11% and atmospheric stability bins of $|L|>1000$, $0<L<1000$, $0>L>-1000$ have been used. For each case and each bin the data were averaged and normalised with the corresponding free stream wind velocity at hub height.

The comparison of measured and modelled wakes is very sensitive for measurement uncertainties in the wind speed measurements, since the wake deficit is a wind speed *difference*. As a rough estimate of the total measurement uncertainty due to systematic errors can be assumed to be in the order of 5%. This means that for a typical wake deficit of 15% the measurement uncertainty in wake deficit is about 30%.

The bin-averaged measurements are compared with model runs where the nominal (mid-bin) values of turbulence intensity, wind speed and stability are used as input. For wind direction the averaging of the measured values over a range of wind directions has been modelled by also averaging model runs for the same wind direction range in 1º steps. For multiple wakes the calculation is simplified by neglecting the effect of the increase in turbulence intensity in a wake for the modelling of the wake profile. Instead, the ambient turbulence intensity has been used for all wakes.

4 RESULTS OF THE COMPARISON

4.1 Free flow profiles

The measured wind speeds of the free mast, bin-averaged and normalised as described in section 3, are compared with the model of the free vertical wind speed profile. Data for the three different cases of wind direction sectors (18º-28º, 70º-78º and 314º-323º) are used.

A subset of the results is shown in Figure 4. Measured and modelled free flow profiles are shown for turbulence intensity 8% (bin averaged for 7-9%), wind speed 5 m/s (bin averaged for 4-6 m/s). Results for the three stability classes are compared: near-neutral stability ($|L|>1000$), stable stratification ($0<L<1000$) and unstable stratification ($0>L>-1000$).

For near-neutral and unstable atmospheric conditions the measured and modelled free flow profiles agree well. For stable conditions large deviations are found between the different measurements (wind direction sectors) and also between both measurements and the model.

4.2 Wake profiles

<u>Comparison for near neutral stability</u>

Examples of the comparison for single, double and quintuple wake situations in near-neutral atmospheric conditions are given in Figure 2 for the most frequent turbulence intensity bin, 6%, and the most frequent wind speed bins, 5 m/s and 7.5 m/s.

Model results are within the estimated measurement uncertainty for all scenarios. It can be noted, however, that larger deviations occur for the double wake situations, which are measured in two different wind direction cases. Large differences can be seen between these two measured profiles. The measurements for the 70º-78º case show large velocity deficits at low heights, even down to 7 m, while the measurements for the 18º-28º case show generally smaller wake deficits.

<u>Comparison for stable conditions</u>

Figure 3 (top) shows examples for stable atmospheric stratification for single, double and quintuple wake situations for 6% turbulence intensity and 5 m/s for single and 7.5 m/s for multiple wakes. As for the comparison of the free flow models (see section 4.1), the comparison of model results with measurements for stable stratification shows larger deviations than for near-neutral stratification.

For the single and quintuple wake cases it can be seen that the wind shear is modelled too small already the free flow. As the free flow is a part of the modelled wake this is also present in the wake model result.

In the single wake case the measured wind speed shows an unexpected profile with a maximum at 30 m height which can not be explained. For the double wake case the measured wind shear is larger than modelled. This has already be found in the near-neutral cases for this direction.

<u>Comparison for unstable conditions</u>

Figure 3 (bottom) shows examples for the comparison of single, double and quintuple wake situations with measurements for 6% turbulence intensity and 7.5 m/s mean wind speed in unstable atmospheric conditions.

As for stable conditions, the comparison of model results with measurements for unstable stratification is not as good as for near-neutral stratification. While a good agreement is found for the single wake case, double and quintuple wakes show large deviations.

For the double wake case the model overpredicts the wake deficit, while for the quintuple wake case a slight underprediction of the wake deficit can be seen. Additionally, for the quintuple wake the measured free flow profile has a larger wind shear than modelled, which was also found for stable stratification.

For the double wake in the 70º-78º wind direction the wind shear deviates between model and measurement. This was also found in near-neutral and stable stratification for this wind direction case.

4.3 Turbulence intensity

The turbulence intensity is calculated as the standard deviation of the wind speed measured in the wake divided by the mean ambient wind speed measured at the free mast. This is the definition of the turbulence intensity used in the model. It should be noted that the turbulence intensities are measured for a 1-minute averaging period rather than the usual 10 minutes. However, this has only an influence on the absolute values and not on the comparison, since the ambient turbulence intensity is measured in the same way.

The measured and modelled turbulence intensities in a single wake for the 18º-28º case of Vindeby wind farm at 38m height are compared in Table 2. For comparison the wake turbulence intensities have also been modelled with the commonly used empirical formula by Quarton and Ainslie (1990).

The measured turbulence intensities show little dependence on either wind speed, atmospheric stability or ambient turbulence intensity. The average standard deviation of the measurements within the bins is 3%, which is larger than the differences for different ambient conditions. The measured turbulence intensity can therefore be characterised by its mean value, which is 8.5%. The predicted mean turbulence intensity of the wake model is 8.9% and that of the empirical formula is 7.8%.

Both approaches predict an influence of ambient conditions on the wake turbulence intensity, especially of ambient turbulence intensity, but also of atmospheric stability and (less important) wind speed. These dependencies are the same for both models. The main difference is that the wake model generally predicts a slightly higher turbulence intensity in the wake. On average, this compares better with the measurements than the results of the empirical formula.

5 CONCLUSION

The wind farm layout program FLaP has been extended to improve the capability to model offshore wind farms. The characteristics of the offshore atmospheric flow most important for wind power utilisation have been addressed: sea surface roughness and atmospheric stability.

Model performance has been compared with measurement results from the Vindeby offshore wind farm. In total 32 scenarios of single, double and quintuple wake cases with different mean wind speed, turbulence intensity and atmospheric stability have been selected. The measurement data have been bin-averaged and compared with the model results. The measurement uncertainty for the bin-averaged wind speed measurements in narrow wind direction sectors has been estimated to be roughly in the order of 5%. Since wake deficit measurements are measurements of wind speed differences this leads to large measurement uncertainties.

Given these measurement uncertainties the FLaP model agrees well with the measurements for the atmospheric conditions, which are most important for wind power utilisation. These are the conditions with important energy content and high frequency of occurrence, i.e. moderate wind speeds, typical turbulence intensities and near-neutral stability.

The model worked well in the low turbulence intensity conditions offshore and no significant deviations were found for these situations. Modelling was less successful when atmospheric stability deviated from near-neutral conditions. This was the case both for stable and unstable stratification and both for the modelling of the free profile and the wake flow. This shows that the behaviour of free and wake flows in conditions with atmospheric stratification is not understood sufficiently and needs further investigation.

The measurements of turbulence intensity in wakes showed little dependency on ambient conditions, especially on the ambient atmospheric stability. Since a dependency on ambient conditions is usually assumed and also modelled, some deviations occur. However, the variation within the measurement is larger than the differences in question and more detailed measurements are needed here.

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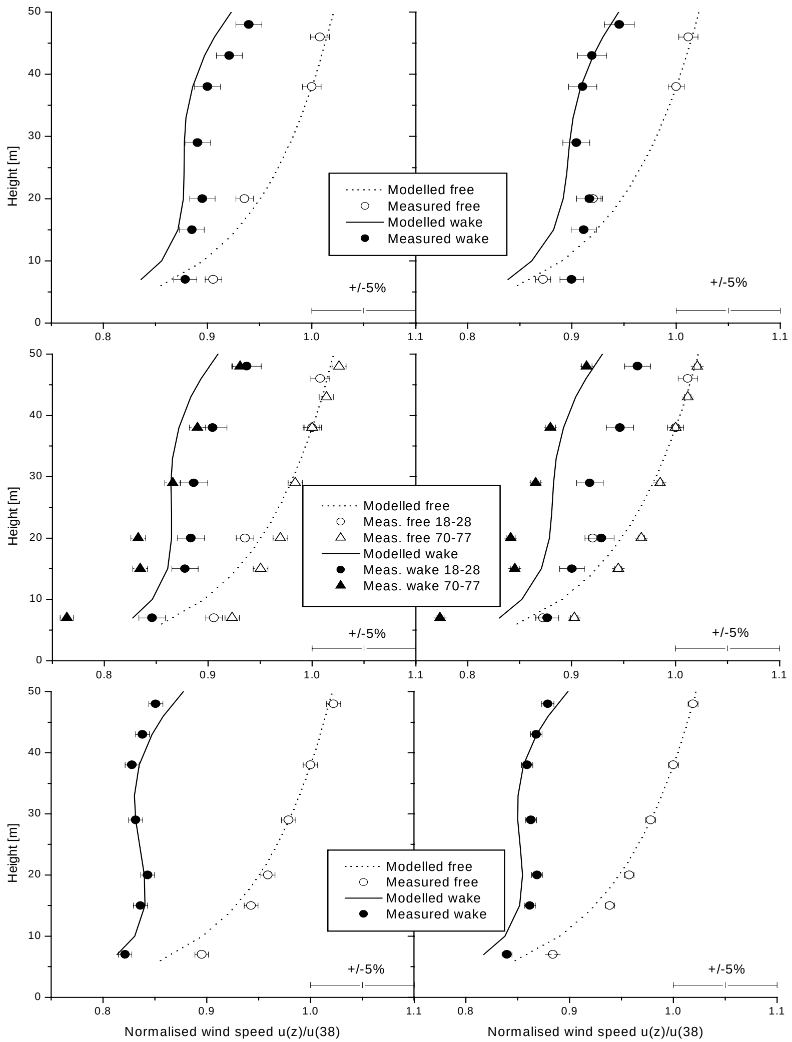

Figure 2: Vertical profiles of measured and modelled normalised wind speeds for the free and wake flow; Vindeby single (top figure), double (middle figure) and quintuple (bottom figure) wake with wind direction 314º-323º, near-neutral stability, 6% turbulence intensity, 7.5m/s (left) and 10m/s (right) mean wind speed; error bars indicate the standard errors

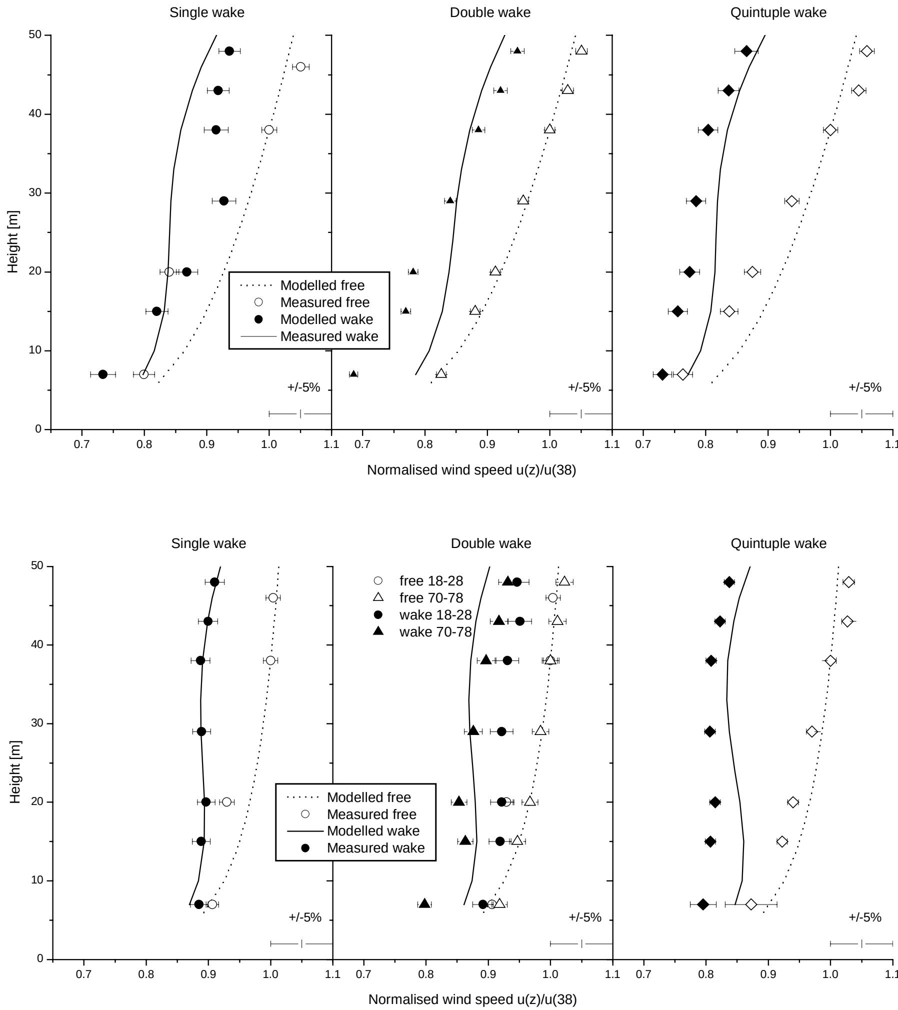

Figure 3: Vertical profiles of measured and modelled normalised wind speeds for the free and wake flow; Vindeby single, double and quintuple wakes, stable (top figure) and unstable (bottom figure) stratification, 6% turbulence intensity, 7.5m/s mean wind speed (except single wake stable: 5m/s); error bars indicate the standard errors

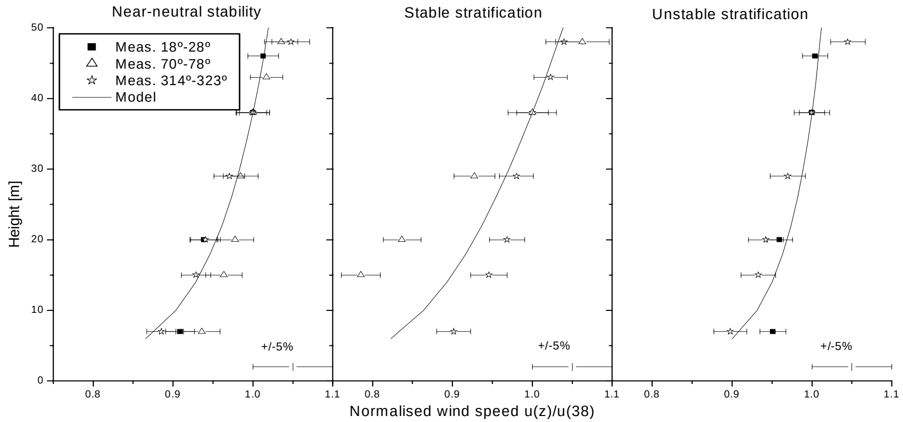

Figure 4: Measured and modelled free vertical wind speed profile for near neutral stratification (|L|>1000)(left), stable stratification (0<L<1000) (middle) and unstable stratification (0>L>-1000); turbulence intensity bin 8% (7-9%), wind speed bin 5ms-1 (4-6ms-1), wind direction sectors as used for wake comparisons; error bars indicate the standard errors

Table 2: Measured and modelled (m=measured, w=wake model, e=empirical formula) turbulence intensities in the single wake at Vindeby wind farm; 18º-28º case, 9.6D distance, 38m height

		5ms-1			7.5ms-1			10ms-1			15ms-1		
		m	w	e	m	w	e	m	w	e	m	w	e
6%	neutral	9	8	7	8	8	7	8	8	7	9	7	6
	stable	8	7	7									
	unstable	7	9	8	8	9	7						
8%	neutral	10	10	9	9	10	9				9	9	8
	stable												
	unstable	8	11	10	9	11	9						