WAKE MODEL EVALUATION METRICS AND THE VIRTUAL WAKES LABORATORY

RJ Barthelmie and SC Pryor
Atmospheric Science Program, Department of Geological Sciences, Indiana University
Email: rbarthel@indiana.edu

ABSTRACT

As evidenced by the recent development of IEA Wind Task 31 WAKEBENCH [1], there is a need to improve wake models for use in designing/operating large wind farms that are currently being built primarily offshore in Europe and on land in the USA. Establishing model credibility in a robust way is critically contingent on evaluation of model skill from a process-level perspective using appropriate, robust and reliable statistical metrics. Thus this paper will focus on providing:

1) A context for wake model evaluation that ensures models and measurements are being compared on an equivalent basis
2) A list of simple and readily quantifiable (robust) metrics to quantify discrepancies between measurements and models, and can diagnose model performance and serve to indicate whether model performance is improving
3) An open access resource of available/public data that can be used to develop and evaluate wake and wind farm models

1 Introduction

Challenges to evaluating wind turbine wake models are manifold. A number of potential approaches have been adopted in model evaluation studies including the use of case studies, and use of average composites, and any approach is likely a compromise between model type (statistical or prognostic), data availability and time constraints. Irrespective of the nature of the model evaluation exercise, model evaluation must be based on a quantitative metrics to objectively assess and diagnose model performance. Hence, in conjunction with the obvious need for robust frameworks under which to conduct model performance analyses, there is also a need for high quality data for use in model evaluation, such as are available from the open access on-line repository called the Virtual Wakes Laboratory. We describe this repository and provide example analyses based on these data with a focus on skill metrics and diagnostic analyses of wake models.

2 Observations

2.1 A context for wake model evaluation: Observational challenges

A major issue in quantifying wind turbine wakes and the physical controls on wake properties derive from challenges to making sufficiently precise and accurate measurements. Thus prior to discussing appropriate methods for wake model evaluation it is important to acknowledge some of the challenges to providing in situ measurements against which the models can be compared.

Given the velocity deficit in wakes is quantified by comparison with freestream conditions, one of the most important issues is correct characterization of the freestream wind and turbulence profile [2]. Additionally, the freestream flow will change over time or be non-homogeneous over the area of the wind farm [3]. Thus, despite the emphasis placed on accurate measurements of wind speed in wakes, the most important measurement by far is that of the freestream flow. Without an accurate freestream wind speed profile, all subsequent analysis will have uncertainties that are at least the equivalent of the uncertainty in the velocity deficit (except perhaps that of the near-wake under moderate wind speed conditions where the velocity deficit may be as much as 60% of the freestream wind speed at hub-height [4]). Even in superficially homogeneous environments, given the scale of wind farms being built there is likely to be variability in the freestream wind speed across the wind farm. So in addition to capturing temporal variability that is introduced from situations such as the passage of fronts, spatial variability in the freestream wind speed must be incorporated into wake calculations. Gradients of wind speed in coastal areas [3] can introduce large-scale variability that is non-trivial and can even be of similar magnitude to more obvious inhomogeneities generated by complex terrain. Figure 1 illustrates the complexity of interpreting measurements from the first offshore wind farm located in Vindeby, Denmark. The mean wind speed distribution is mainly a function of the large scale synoptic flow with higher wind speeds from the southwest. The wind speed reduction at Sea Mast South (SMS) from wakes at 8.6 rotor diameters (D) from the single turbine 6E at 22º and from the row of turbines 1W to 5W at 320º is clear. However, in the absence of topography and impacts from wind turbine wakes it might be anticipated that the normalized wind speed would be equal to 1 in all wind directions. The large ratio of wind speeds at the SMS relative to the LM occurs for wind directions centered at approximately 85º and 220º which arise from the wind speed increase over the sea to SMS whereas the fetch to the land mast (LM) is over land. These kinds of gradients in wind speed at the coast can have an impact over much larger distances than the 2 km indicated here. Modeling and measurements from Nysted indicate gradients in hub-height wind speed extend and are detectable over at least 15 km, and further in stable conditions [3]. Thus over a large wind farm it is unlikely that even un-waked turbines (e.g. along the edge of an array) will experience a single inflow wind speed and turbulence profile. This issue is even more pronounced in complex terrain.

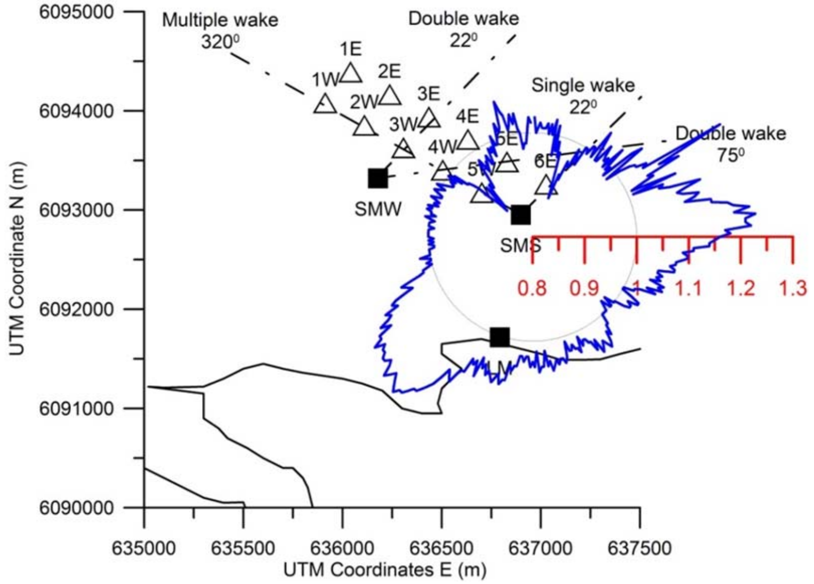

Figure 1. Hub-height (38 m) wind speed at Sea Mast South (SMS) normalized by wind speeds at the Land Mast for the period 1993-1996.

In addition to the freestream wind speed at turbine hub-height, wake behavior is also a function of the wind speed profile and turbulence intensity [5]. It has previously been demonstrated that vertical shear across the wind turbine blades not only influences the power production of a turbine [6] but the level of ambient turbulence is also a critical control on the transfer of momentum into the wake and thus the 'wake recovery' [5]. Recent improvements to remote sensing technologies have improved comparability of the resulting data to traditional anemometry for both wind speeds and turbulence [7-9], and offer the potential to obtain more vertical detail in profiles (of wind speed and turbulence) than can typically be obtained using instrumentation deployed on meteorological masts, and thus offer the potential for improved characterization of both freestream and wake conditions. However, there is need for further evaluation of these technologies to ensure data quality [10].

Given that the wind and turbulence characteristics in the wake are non-linear function of the wind turbine power and thrust coefficients (which are function of incident wind speed at turbine hub-height and the wind shear across the blades), for model evaluation exercises these must be known, bearing in mind that the onsite power curve may not be equivalent to the manufacturer's power curve. Realistically, the turbine power curve that is likely to be available to potential end users will likely be the manufacturer's power curve rather than the onsite power curve, although substantial deviations have been observed in the field [11] which may influence momentum extraction and turbine added turbulence intensity, and thus impact downstream wake behavior.

Further confounding issues to data interpretation and identification of appropriate initial and lateral boundary conditions for models arise from; (i) measurement errors in the wind direction (and thus the angle at which a wake impacts downstream turbines) or wind turbine yaw alignment errors and (ii) the role of atmospheric stability in dictating wake expansion and/or meandering. A frequent problem in use on in situ data for wake quantification is that wind direction measurements have bias issues (due to the difficulty of correctly aligning the direction measurement at installation on a meteorological mast), or that yaw measurements or the yaw control mechanism on individual turbines are imperfect. Alternatively the wind direction measurement (which typically derives from a wind vane) can drift over time, or under light wind speeds, the wind direction can change over the distance between the meteorological mast measurement and the turbine. As has been discussed previously [2] wake models typically assume one wind direction with no standard deviation of direction and hence overestimate wake losses because they focus on the wake center maximum velocity deficit, while the measurements contain directional variability due to stochastic effects in the atmosphere, and thus typically show a wider but shallower wake profile.

2.2 The Virtual Wakes Laboratory

A major bottle-neck confronting attempts to quantify the physical and dynamical controls on wind turbine wakes and to evaluate and improve wind turbine wake models (and wind farm models) is access to high quality observational data sets. The Virtual Wakes Laboratory (VWL) was designed to meet at least some of this need (Figure 2). The Virtual Wakes Laboratory is a freely accessible resource that currently contains wake and wind farm data that have been made available by a number of agencies. At present the VWL contains the data sets shown in Table 1 and can be accessed through: http://mypage.iu.edu/~rbarthel/Welcome.pdf. To gain access to the site potential users are required to register but there-after access to all data is provided.

Table 1. Data sets currently available in the Virtual Wake Laboratory

Type	Period	Site	Source	Reference
SCADA data for turbines with array presented as time series (2 data sets)	2001-2004	Middelgrunden	Middelgrunden Wind Turbine Cooperative	[11]
SCADA data for turbines with array presented as time series (2 data sets)	1996-2004	Vindeby	Originally from SEAS	[12, 13]
Case studies of wind and turbulence conditions in and out of wakes data collected with ship-mounted sodar	2001	Vindeby	ENDOW project	[14]
SCADA data for case studies of wake characteristics for specific wind direction and wind speed classes	2004-2006	Nysted	DONG/Vattenfall	[15]
SCADA data for case studies of wake characteristics for specific wind direction and wind speed classes	2005	Horns Rev	DONG/Vattenfall	[16]

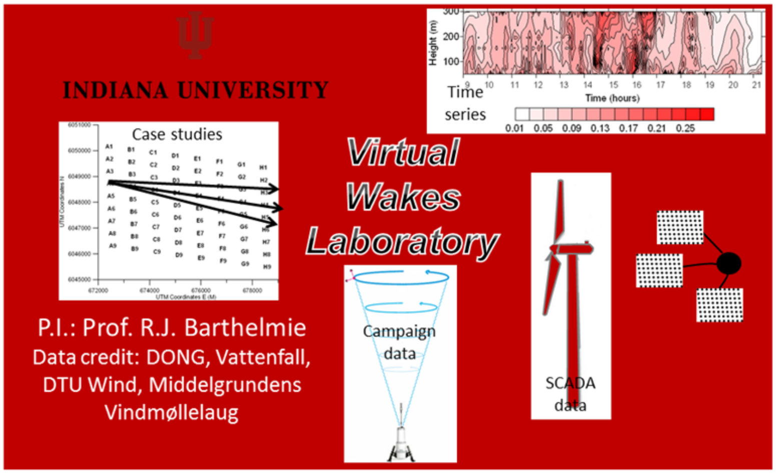

Figure 2. Interface for the Virtual Wakes Laboratory (http://mypage.iu.edu/~rbarthel/)

2.3 Model evaluation

Many previous wake model evaluation exercises have relied upon visual inspection of time series of velocity deficits downstream of wind turbines, but such analyses lack performance metrics and error attribution. A new approach is needed that addresses the following questions:

- What is the goal when comparing models with measurements?
- Which variables should agree, and to what level of precision and accuracy?
- What can or does the model simulate? Is this the same identical quantity under the same circumstances as is given in the measurements? If not, to what degree could they be expected to agree?
- Where models are shown to deviate from the observations, what types of model diagnostics can be undertaken to facilitate error attribution (and ultimately model improvement)?

In the following we present methods that can be applied to address at least some of the questions (see Table 2).

On the most fundamental level an individual wind turbine wake can be quantified using the following descriptors; the wake location (centerline), the wake magnitude (i.e. maximum velocity deficit at the centerline), and a wake width. Thus key evaluation metrics should include the wake depth (maximum velocity deficit for the wake center) at a given distance and the wake width (distance across the wake at which a reduction in the freestream wind speed can be detected) (Table 2 and Figure 3). Naturally, both metrics require that the freestream velocity profile is known. Since the normalized velocity will not be 1 in reality but might be lower or higher due to inhomogeneous in the flow or to wake 'shoulders' (over-speeding at the edges of wakes), it is necessary to set a threshold for recovery (that could be e.g. 95% of the freestream) that describes the 'wake edge'. A more systematic approach to determining wake metrics might be to assume a Gaussian distribution of velocity deficit and to determine the wake width and depth in terms of the standard deviation of distribution. If at a fixed point downstream from a turbine, one could define a wind direction associated with direct flow from the upstream wind turbine to the observational point. However, for slight variations in wind direction from this direction, the meteorological mast (or remote sensing volume) is impinged upon not by the centerline of the wake but a peripheral part of the wake, and thus by conditionally sampling the wind speed data for slight variations in the wind direction a picture such as that shown in Figure 3 can be developed. One standard deviation of wind direction around the centerline would contain 68% of observations inside the wake and correspond to a recovery of about 95% of the maximum velocity deficit at the center while two standard deviations would contain 95% of observations and about 0.99 of the maximum velocity deficit. Thus a robust estimate of true wake width can be derived.

Table 2. Wind turbine wake model evaluation. The first columns provides a summary of approaches for wind turbine wake model evaluation. The second column shows sample quantities that can be measured/modeled for comparison. The third columns summarizes statistical (skill) metrics to be used to quantify model-measurement agreement

Approaches		Quantities		Statistical Metric
Mean (time average)		Turbine power output		Standard deviation
Mean (statistics of similar cases)		Wind speed/turbulence intensity at hub-height		Root Mean Square Error
Case studies		Wake width and wake depth		Bias
Dynamic cases		Momentum deficits through the wind speed profile		Standard error

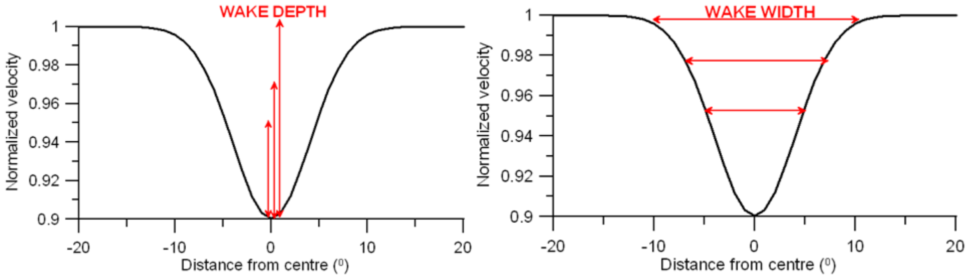

Figure 3. Possible wake model evaluation metrics - wake depth and wake width.

An alternative integrative metric for determining wake recovery is the momentum deficit at individual points across the wake or integrated across the wake (see example in Figure 4) [2].

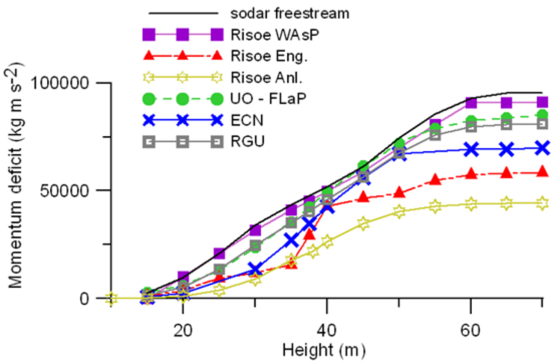

Figure 4. Comparison of the cumulative momentum deficit across the rotor plane for a single wake experiment (at 2.8 D downstream) in the Vindeby wind farm. In this analysis the freestream wind profile and the wake profile were measured using a boat-mounted sodar, and the models were initialized with the sodar derived freestream wind profile [2]. The measurements of the actual cumulative momentum deficit is shown by the curve denoted sodar freestream – where the same sodar was used to determine the freestream profile and the wake profile). The colored lines show momentum deficits computed from a variety of different wake models (with varying complexity). As shown, even at this short downstream distance some models under-predict the wake width and the momentum deficit, indicating too rapid wake recovery.

These types of evaluations provide a more systematic framework for wake model evaluation, are useful in terms of identifying model biases, and can be coupled with quantitative ‘skill’ metrics such as Root Mean Square Error if the comparisons can be undertaken across a range of – for example, wind speed classes, ambient turbulence intensity conditions etc. They can also be leveraged to more diagnostic approaches that can be used to attribute model error (or to diagnose the occurrence of compensating errors). An example of this type of analysis is given below in the context of the components that contribute to an observed wake width and depth [17]. The actual wake width measured at some distance downstream from a turbine is comprised of contributions from; (i) the rotor diameter plus (ii) wake expansion (due to momentum transfer) plus (iii) meander (wind direction variability) (Figure 5). Quantifying these components rather than examining one wake width metric facilitates understanding of whether models are correctly parameterizing the components of wake width and therefore be more useful in terms of diagnosing the effectiveness of different parameterizations.

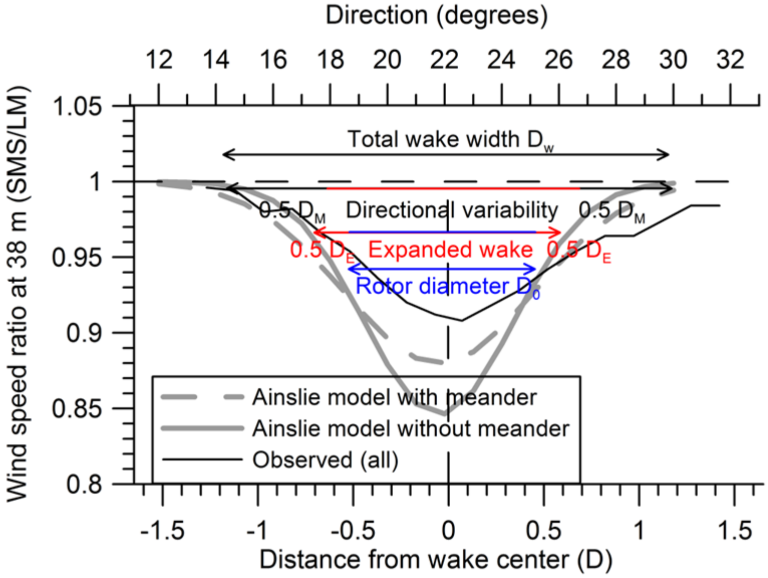

Figure 5. The ratio of wind speed at Vindeby mast SMS to mast LM by direction for the single wake (black line). Horizontal lines indicate the approximate contributions of the rotor diameter (D_0), wake expansion (D_E) and wake meandering (D_M) to the total wake width (D_W). The wake profiles of Ainslie [18] with and without wake meandering are shown in grey (Adapted from [17]).

The examples given above implicitly presume that the evaluation is cast in a framework where multiple case studies are conducted. That is each simulation is for conditions during a relatively short time window during which stationary can be assumed, and that these simulations are conducted for a realistic range of initial conditions (e.g. classes of wind speed, direction, ambient turbulence intensity, stability etc.). Obviously not all wake and wind farm models are suitable for this type of dynamic evaluation, for example some of the more parameterized models seek to describe the statistical properties of wakes rather than instantaneous realizations thereof, while some of the more computationally demanding models are more suited to a limited number of case studies than to producing large statistical ensembles. In either case we argue that a more quantitative approach is needed that does not simply compare, for example, the mean velocity deficit at the wake centerline, but includes some estimates of, for example, the standard deviation or the bias of model v. measurement agreement across a range of simulation conditions that can be objectively used to determine how closely models and measurements match.

When moving beyond evaluation of the simulations of individual wind turbine wakes, other approaches need to be adopted to evaluate wake models. Model complexes that take into account not only individual wakes, but wake-wake interactions and wind farm-atmosphere interactions are needed to fully capture the complexity of the flow fields [19]. Approaches to evaluating key aspects of models that capture wake-wake interactions include, but are not limited to:

(i) ‘Down-a-row’ (i.e. embedded wakes). In these analyses model-measurement comparisons have been conducted using a range of approaches to define the free-stream conditions, but then conditionally sampling by wind direction to select flow such that each turbine is in a direct wake of upstream turbine(s). The power output from each turbine is then normalized by the turbine that experienced free-stream condition for comparison with wake models (e.g. [16]) compared with observations. Such comparisons are useful to assessing some aspects of wake-wake interactions, and represent a worst-case scenario in terms of wake related power-loss, but again are not trivial to interpret since the ambient data will always incorporate some directional variability within a wind speed class whereas most models assign zero directional variability.

(ii) Evaluation of overall wind farm efficiency [5]. In this approach the power produced over the entire wind farm can be integrated and compared to values from a wind farm model. This is useful in terms of perhaps best representing the apriori expectations for a given wind farm layout. However, in order to diagnose actual model performance it is necessary to disaggregate to individual turbines in order to determine whether the model is representing the actual power production gradients (and thus getting the right answer for the right reason). An example of the spatial variability of power output (normalized to the mean of all turbines within an array) is given in Figure 6 from Nysted, Denmark [20].

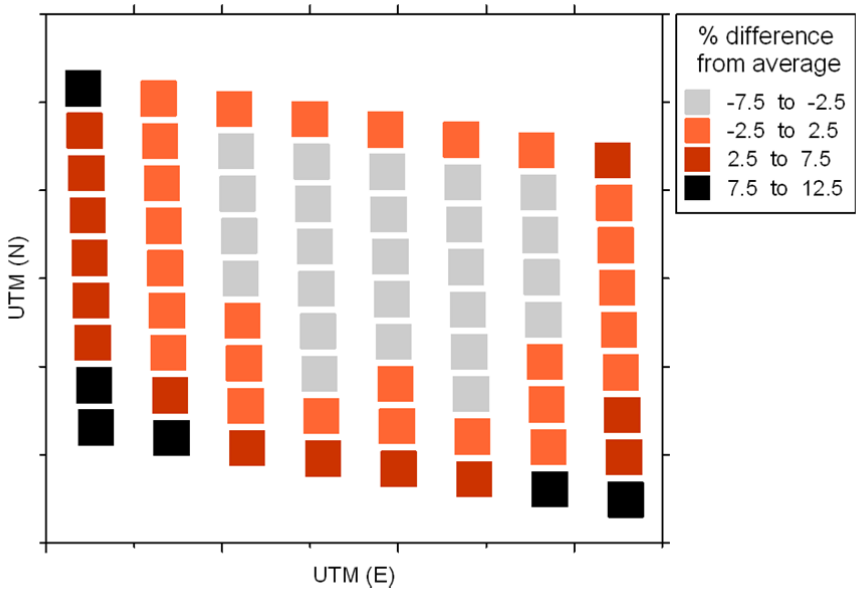

Figure 6. Example of the average wake losses by turbine from Nysted, Denmark, where the wake loss at each turbine is shown as the difference in power from the average for the whole wind farm (%) [20].

3 Summary

It is difficult at present to answer the question ‘What is a successful outcome in terms of wake model evaluation?’ or ‘How much of the uncertainty is due to random noise rather than measurement or model error?’ Until these questions can be addressed, wake modeling continues to be less quantitative than is needed to move forward in terms of optimization of wind farm layouts. This paper discusses the context for evaluating wake and wind farm models and measurements and focuses on moving away from visual inspection to defining a set of metrics that set out to describe and quantify model agreement with measurements based on a more systematic approach to the evaluation (e.g. as used in short-term forecasting). The paper advocates a greater focus on (i) dynamic studies, (ii) process-level experiments (and error attribution analyses) and (iii) quantitative metrics for model evaluation. As an aid to wake model evaluation the Virtual Wake Model Laboratory is described that is an open access resource that provides wake and wind farm data.

4 Acknowledgements

We would like to acknowledge funding from the National Science Foundation (#1067007), Dept. of Energy (#EE0005379), European Commission (EERA-DTOC 282797). Data in the Virtual Wakes Laboratory have been provided by DONG Energy, Vattenfall and Middelgrundens Vindmøllelaug.

5 References

1. Sanz Rodrigo, J. and P. Moriarty, *TASK 31. Benchmarking of wind farm flow models. Progress Report to ExCo 69. Trondheim May 22-24, 2012*, 2012.
2. Barthelmie, R.J., et al., *Comparison of wake model simulations with offshore wind turbine wake profiles measured by sodar.* Journal of Atmospheric and Oceanic Technology, 2006. **23(7)**: p. 888-901.
3. Barthelmie, R.J., et al., *Wind speed gradients in the coastal offshore environment: Issues pertaining to design and development of large offshore wind farms.* Wind Engineering, 2007. **31**(6): p. 369-382.
4. Whale, J., et al., *A study of the near wake structure of a wind turbine comparing measurements from a laboratory and full scale experiments.* Solar Energy, 1996. **56**: p. 621-633.
5. Barthelmie, R.J., K.S. Hansen, and S.C. Pryor, *Meteorological controls on wind turbine wakes.* Proceedings of the IEEE, 2012. **99**: p. 1-10. DOI: 10.1109/JPROC.2012.2204029
6. Wagner, R., et al., *Accounting for the speed shear in wind turbine power performance measurement.* Wind Energy, 2011. **14**(8): p. 993-1004.
7. Friedrich, K., et al., *Stability and turbulence in the atmospheric boundary layer: A comparison of remote sensing and tower observations.* Geophysical Research Letters, 2012. **VOL. 39, L03801**: p. doi:10.1029/2011GL050413, 2012.
8. Peña, A., et al., *Offshore Wind Profiling Using Light Detection and Ranging Measurements.* Wind Energy, 2009. **12**(2): p. 105-124.
9. Sathe, A., et al., *Can Wind Lidars Measure Turbulence?* Journal of Atmospheric and Oceanic Technology, 2011. **28**(7): p. 853-868.
10. Gottschall, J., et al., *Lidar profilers in the context of wind energy – A verification procedure for traceable measurements.* Wind Energy, 2012. **15**: p. 147-159.
11. 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.
12. Barthelmie, R.J., et al., *Meteorological aspects of offshore wind energy - observations from the Vindeby wind farm.* Journal of Wind Engineering and Industrial Aerodynamics, 1996. **62**(2-3): p. 191-211.
13. Frandsen, S., et al. *Measurements on and modelling of offshore wind farms*. 1996. 101 DOI: Risø-R-903(EN).
14. Barthelmie, R.J., et al., *Offshore wind turbine wakes measured by SODAR.* Journal of Atmospheric and Oceanic Technology, 2003. **30**: p. 466-477.
15. Barthelmie, R.J., et al., *Modelling and measuring flow and wind turbine wakes in large wind farms offshore.* Wind Energy, 2009. **12**(5): p. 431-444. DOI: 10.1002/we.348.
16. Barthelmie, R.J., et al., *Quantifying the impact of wind turbine wakes on power output at offshore wind farms.* Journal of Atmospheric and Oceanic Technology, 2010. **27**(8): p. 1302-1317.
17. Barthelmie, R.J. and S.C. Pryor, *Wake model evaluation using data from the Virtual Wakes Laboratory.* Applied Energy, 2013. **104**: p. 834-844.
18. Ainslie, J.F., *Calculating the flow field in the wake of wind turbines.* Journal of Wind Engineering and Industrial Aerodynamics, 1988. **27**: p. 213-224.

19. Frandsen, S., et al., *The making of a second-generation wind farm efficiency model-complex.* Wind Energy, 2009. **12**: p. 431-444.
20. 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.