Offshore Wind Turbine Wakes Measured by Sodar

R. J. BARTHELMIE,* L. FOLKERTS,+ F. T. ORMEL,# P. SANDERHOFF,* P. J. EECEN,# O. STOBBE,@ AND
N. M. NIELSEN*

**Wind Energy Department, Risoe National Laboratory, Roskilde, Denmark*
+*Ecofys bv, Utrecht, Netherlands*
#*Wind Energy Department, Energy Research Centre of the Netherlands, Petten, Netherlands*
@*Ecofys Energieberatung und Handelsgesellschaft mbH, Cologne, Germany*

(Manuscript received 14 February 2002, in final form 18 September 2002)

ABSTRACT

A ship-mounted sodar was used to measure wind turbine wakes in an offshore wind farm in Denmark. The wake magnitude and vertical extent were determined by measuring the wind speed profile behind an operating turbine, then shutting down the turbine and measuring the freestream wind profile. These measurements were compared with meteorological measurements on two offshore and one coastal mast at the same site. The main purposes of the experiment were to evaluate the utility of sodar for determining wind speed profiles offshore and to provide the first offshore wake measurements with varying distance from a wind turbine. Over the course of a week, 36 experiments were conducted in total. After quality control of the data (mainly to exclude rain periods), 13 turbine-on, turbine-off pairs were analyzed to provide the velocity deficit at hub height as a function of the distance from the turbine. The results are presented in the context of wake measurements at other coastal locations. The velocity deficit is predicted with an empirical model derived from onshore measurements based on transport time dependent on surface roughness. The measurements are closer to those predicted using an onshore rather than an offshore roughness despite the relatively low turbulence experienced during the experiments.

1. Introduction

Offshore wind energy developments are under way in many European countries (DEA/CADDET 2000) with planned projects of several thousand megawatts to be installed in the first decade of the new millennium (Barthelmie 1999a; Barthelmie et al. 2000). In this context, the term ‘‘offshore wind farm’’ indicates that the wind turbines are erected with their foundations in water. While experience gained through the offshore wind farm demonstration projects currently operating (Barthelmie et al. 1996), (Lange et al. 1999) is valuable, a major uncertainty in estimating power production in large offshore wind farms lies in the prediction of the dynamic interaction between the atmosphere and wind turbines. Planned offshore wind farms consist of up to 80 turbines giving complex wake effects (defined as the velocity decrease, turbulence increase downstream of a wind turbine rotor). Crespo et al. (1999) describe the development of wind turbine wakes and their decay downwind of the turbine rotor. Outside of the near-wake region the main parameter in determining wake decay is ambient turbulence. Given that turbulence offshore is typically lower than onshore, it is hypothesized that wake effects are propagated over larger distances downstream offshore than over land and that atmospheric stability will play a larger role in determining the downstream wake decay. The likely result is that in order to optimize power output, offshore wind farms will require larger distances between turbine rows than is common in the design of onshore wind farms. This has a major economic disadvantage because undersea grid connections and connections between turbines are proportionally more expensive than their cost and installation at land sites. Model simulations suggest that power loss due to reduced wind speeds at the turbine rotor can be more than 5% in large wind farms. Improved understanding of wake propagation offshore is an essential part of design to minimize these losses.

The measurements of wind speed profiles in an offshore wind farm described in this paper are designed to assist understanding of wake development offshore. Measurements of wind speed profiles at fixed distances from the wind turbines have been made at the wind farm over a long period on meteorological masts (Barthelmie et al. 1996; Frandsen et al. 1996), but the disadvantages are that the measurements extend only 12 m above the turbine hub height and the variability of

---

Corresponding author address: Dr. R. J. Barthelmie, Dept. of Wind Energy and Atmospheric Physics, Risoe National Laboratory, Roskilde 4000, Denmark.
E-mail: r.barthelmie@risoe.dk

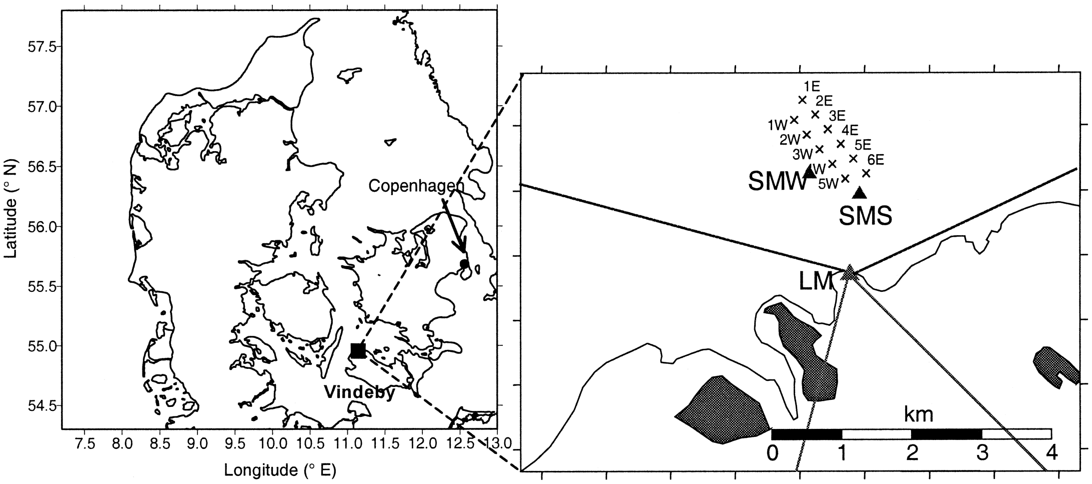

FIG. 1. Location of the Vindeby wind farm in Denmark. SMS and SMW are the southern and western meteorological sea masts, respectively; LM is the land-based meteorological mast.

the wake with distance to the turbine cannot be assessed. Hence an experiment was conducted to provide additional data for offshore wakes (especially in near-wake situations for which very few datasets are available even for land sites) and to form part of the evaluation process for wake models within the Efficient Development of Offshore Windfarms (ENDOW) project (Barthelmie et al. 2001).

For the first time, a sodar mounted on a ship was used to measure wind speed profiles in the turbine wake in an offshore wind farm. While sodar has a long history of use at land sites (Crescenti 1997) and has many advantages (Vogt and Thomas 1994) for boundary layer and air pollution studies, the instrument has had less exposure in marine-based studies (e.g., Otterstein et al. 1974; Petenko et al. 1996) and has not been extensively employed in wind energy work (see, e.g., Hogström et al. 1988). Although minisodars have been used to assess wind energy sites, there is little documentation available. In the experiment described here, selective operation of turbines in different conditions reflecting wind speed and direction (influencing the fetch variation) allowed the direct impact of turbine operation on wake effects to be measured at varying distances from the turbine (here 1.7–7.4 rotor diameters, *D*). Use of a sodar provided wind speed profiles to hub and rotor heights of offshore wind turbines currently being developed, which were supplemented by ongoing measurements on meteorological masts.

The main objectives of the experiment were to evaluate whether the sodar could operate successfully when mounted on a ship and whether the noise from a wind turbine would interfere with the sodar wake measurement. If successful in these regards, the priorities of the experiment were to measure near-wakes at a range of distances from the turbine and, assuming favorable wind directions, single and double wakes.

2. Experimental details

a. Experiment design

The measurement campaign was conducted at the 5-MW offshore wind farm at Vindeby, Denmark (Fig. 1). Note that the wind farm is relatively close to the coast (about 2 km). The site was chosen because it is one of very few operating offshore wind farms and has three monitoring masts [two offshore, referred to hereafter as sea mast south (SMS) and sea mast west (SMW), and one at the coast, hereafter land mast (LM)] providing detailed meteorological measurements to 48-m height. The wind farm, which has been operating since 1991, consists of 11 BONUS (Bonus Energy A/S, Brande, Denmark) 450-kW turbines in two rows oriented toward the southwest (prevailing wind direction). The hub height is 38 m and the rotor diameter is 35.5 m. Layout of the wind farm and the two offshore masts is also shown in Fig. 1. The site has the advantage of shallow water (2–5 m) with relatively low wave heights and swell compared to more exposed sites.

April was chosen for the experiment to avoid periods of very high wind speeds (which mainly occur in winter). However, to measure wakes, wind speeds also have to be above turbine cut-in wind speeds of 4 m s^{-1} making summer months less attractive. The mean wind speed measured at 10 m above mean sea level at SMW in April for the period 1996–99 inclusive is 7.4 m s^{-1} with mean air temperatures of 5.9°C and a mean water temperature of 5.8°C.

The sodar was mounted on the *Seaworker,* which is a highly stable ship with regard to both tilt and position. The *Seaworker* is equipped with four anchors although during most experiments only three were used. The two front anchors were used to position the ship in the direct wake of the turbine. By moving one (the rear) anchor, the ship could be repositioned at different distances from

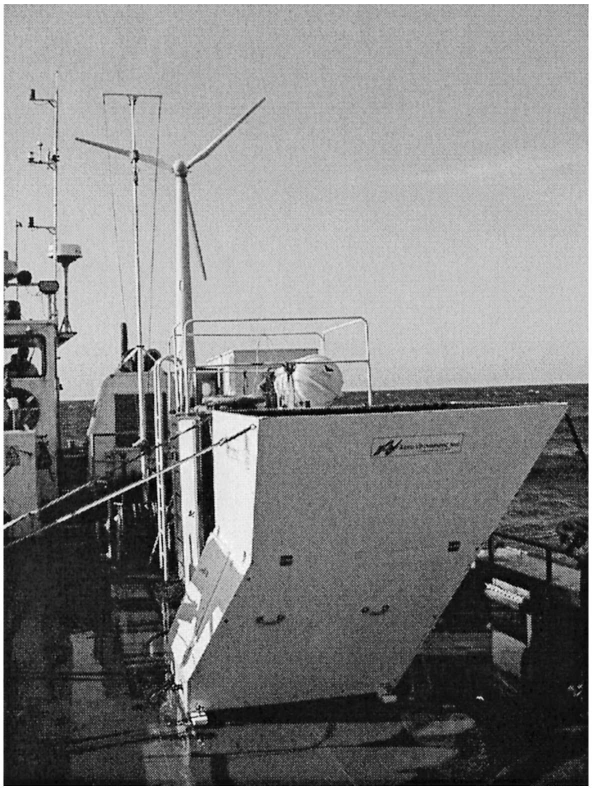

FIG. 2. Photograph of the sodar on the *Seaworker* behind a wind turbine.

the turbine providing a transect for the measurements. Given that a large proportion of the experiment time was spent positioning the ship, being able to measure at three wake distances over a distance of 150–200 m without having to take up all three anchors was an advantage. Further requirements were 1) that the equipment used to operate the sodar could be protected from the weather and high waves, 2) that sufficient power was available when the ship's engine was turned off (to reduce noise that interferes with the sodar signal), and 3) that structure of the ship was low enough not to provide a barrier causing noise reflections. Although the *Seaworker* is equipped with several cranes, these were lowered onto the deck during measurements. The rear boom could not be lowered to the deck but lowering it a few meters proved adequate. The *Seaworker* also had sufficient room for the sodar on the deck (Fig. 2) and lastly had an extremely low draft of about 1.5 m, which is important at Vindeby since the water depth is around 2 m to the south of the wind farm. The level of the deck is close to the water line and so the height of the sodar-measured wind speeds have not been corrected with respect to mean sea level. The first three range gates (15, 20, and 25 m) were excluded because of the poor number of returns. This may be related to the structures on the boat but was also noted during a sodar experiment on an offshore platform (Coelingh et al. 2000).

During the experiment period 21–28 April 2001 wind speeds were lower than expected allowing the *Seaworker* to sail each day. However, measurements were limited by periods of rain (wind speed profiles measured during rain had unacceptably large standard deviations). The experiment was also limited by periods in which wind speeds at the turbine hub height dropped below 4 m s^{-1}. In this situation turbines stop operating and there are therefore no wakes. A further disadvantage of lower than expected wind speeds was the directional variability of the wind. While the *Seaworker* could be accurately positioned in the direct wake of a wind turbine, shifts of wind direction sometimes occurred during measurements, which meant that the sodar was no longer measuring in the direct wake. Since repositioning the boat in the direct wake took approximately 40 min, this directional variability limited the number of experiments that could be conducted each day.

Further matters which had to be considered concerned the operation of the sodar accounting for the movement of the ship and accurately determining the position and angle of the ship. The positions of the ship and turbines were measured using a GPS to an accuracy of ±4 m. As in Fairall et al. (1997) recordings of the tilt and yaw were made. Data were discarded if the tilt angle exceeded ±4°. A major consideration was whether the wind turbines themselves would distort the sodar signal due to noise during their operation. As indicated by the Danish Wind Energy Industry Association (available online at www.windpower.dk), at a distance of 3 rotor diameters (*D*), the sound level of a wind turbine is expected to be below 45 dB (*A*) and even at 1 *D* is less than common noise levels in cities. Crescenti (1998) indicates noise levels less than 50 dB(*A*) are acceptable for sodar measurements. Hogström et al. (1988) found good agreement between sodar measured wake velocity deficit and data from a nearby tower or kites suggesting that noise was not an issue at 2 *D*. Although the recorded noise level increased during the near-wake experiments (1–2 *D*) described in this paper, it remained below acceptable levels and the sodar gave wind speed profiles with standard deviations that were not distinguishable from the freestream measurements behind the nonoperating wind turbine. In contrast to the experience of Fairall et al. (1997) the performance of the sodar on the ship experiment at Vindeby was not significantly different than during land-based or offshore fixed-base experiments, which had been conducted previously with the same instrument (Coelingh et al. 2000). This may be because the requirement during the Vindeby experiment was to maintain a fixed position (with engines turned off) rather than to operate under sail.

b. Sodar specifications

The main characteristics of the sodar used at Vindeby are shown in Table 1. This Aerovironment 4000 minisodar uses sound to measure wind speed and wind di-

TABLE 1. Characteristics of the Aeroenvironment 4000 minisodar operated during the Vindeby experiment.

Characteristic	Specification
Max sampling altitude	200 m
Min sampling altitude	15 m
Height resolution	5 m
Transmit frequency	4500 Hz
Tilt angle of the beams	16°
Averaging interval	1–60 min
Wind speed range	0–35 m s^{-1}
Wind speed accuracy (wind speed >2 m s^{-1})	<0.50 m s^{-1}
Wind direction accuracy (wind speed >2 m s^{-1})	±5°
Power output (acoustic average)	40 W

rection over a range of heights (15–200 m) with a resolution of 5 m. The instrument consists of an antenna with a speaker array with 32 piezoelectric speakers, an acoustic signal processor, an audio amplifier, and a controlling PC. The speaker array emits a sound pulse about once per second at a frequency of 4500 Hz, which is amplified and transmitted into the air. By a phased array technique the sound beam is alternately steered in one of three directions u, v, or w, where the w direction is vertical whereas the u and v directions have an inclination of 74° (tilt angle of 16°) and are mutually separated by a 90° azimuth angle (see Fig. 3). Sound pulses are backscattered to the antenna by air density differences mainly caused by temperature variations. Air velocities along measurement paths are measured by frequency shifts between the transmitted and received signals (Doppler effect) and the range to sound-reflecting air parcels is detected by the time lag between pulse emission and return signal. The time distribution of the returned pulse enables velocity estimates for several heights above the ground, and measurements along the three paths are translated into a three-dimensional wind vector.

1) ORIENTATION OF THE SODAR

The sodar was mounted on the *Seaworker* with the u beam oriented sideward toward the port side and the v beam forward toward the bow. By positioning the ship with the stern into the wind (using its three anchors) the v beam is oriented along-wind and the u beam is oriented crosswind. The major advantage of this orientation is that the main part of the wind speed can be obtained from one beam, the v beam. The u and the v beams sample separate volumes of the wake. Because of the tilt angles of these beams (16° of vertical), the shift in the point of actual sampling increases with height, with about 10.5 m (0.3 D) at hub height. This distance has been added to the distances determined using GPS. In terms of the accuracy of the distance between the rotor and the sodar measurements, 4.9 m should be added to the uncertainty [calculated as the position shift over half the rotor diameter ($=35.5/2 \times \sin 16$)]. Since the v beam is aligned with the mean wind, the measured wind speed profile still accurately represents the velocity deficit downwind of the turbine.

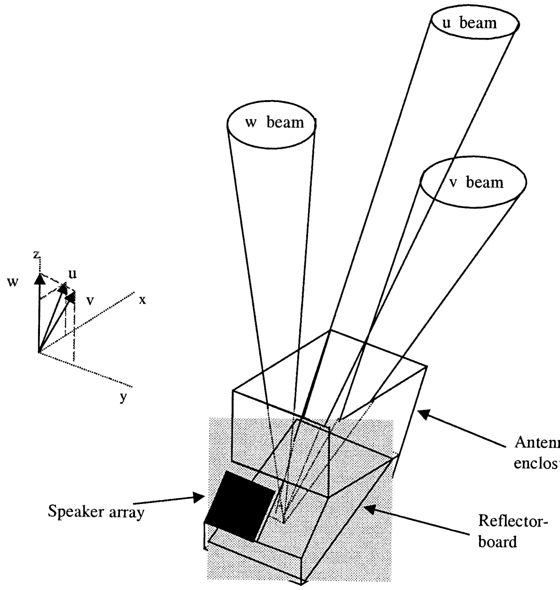

FIG. 3. The minisodar and its sound beams.

In the analysis of the sodar data, two different methods were compared to check the secondary relevance of the u beam in this orientation. The standard method is to calculate the wind speed as the vector mean using the three beams. The alternative method, valid with the v beam aligned with the mean wind, is using only the v beam and the w beam (vertical), and ignoring the crosswind u beam. In this method, small misalignments of the sodar were corrected using the wind direction from SMW. The two methods yield nearly identical results, confirming the marginal importance of the u beam.

c. Mast data

Instrumentation installed at the Vindeby masts used here (LM and SMW) is shown in Table 2. All three masts are purpose-built meteorological masts of 45 m standing on bases of approximately 2.5 m above mean sea level or 2 m on land. Heights in Table 2 are above ground or above mean sea level. Additional instrumentation at LM includes a barometer, net radiometer, and a precipitation detector, while water temperatures are

TABLE 2. Instrumentation at the Vindeby masts in spring 2001. Heights are above ground or above mean sea level.

	LM	SMW
Min time resolution	1 min	1 min
Heights of instrumentation (m)		
Wind speed	47, 30.9, 9.8	47.5, 28.7, 10
Wind direction	20.9, 33.9	18.5, 42.8
Temp	9.7	10
Temp difference	46.5–9.7, 19–9.7	47–10, 22.8–10

TABLE 3. Details of single wake experiments. Relative velocity deficit is calculated from sodar wind speed profiles using a height of 40 m. Freestream wind (U) at 48 m and direction (dir) are measurements from the meteorological mast, L is the Monin–Obukhov length, and x is the distance to the turbine expressed as number of rotor diameters D. Max disp is the largest distance from the center of the wake due to the directional variability of the wind during each experiment (expressed as a fraction of rotor diameters). Here C_T is the thrust coefficient for the specific wind speed (characteristic of the wind turbine at Vindeby) and t is the transport time. Wake-generated turbulence I_{added} calculated from Frandsen et al. (1996) is compared with ambient turbulence I_0 (%).

No.	$\Delta U/U$	U (m s^{-1}) at 48 m	Dir (°)	L (m)	D	Max disp.	C_T	t (s)	I_0 (%)	I_{add} (%)	I_{total} (%)	No. wake	No. non-wake
1*	0.36	10.54 ± 0.30	336.4 ± 0.9	2156	3.8	0.3	0.55	11.8	5.8	3.2	6.6	32	32
2*	0.13	8.76 ± 0.43	341.2 ± 2.3	−3088	6.5	0.75	0.67	24.9	8.0	1.6	8.2	40	41
3*	0.53	8.76 ± 0.43	342.8 ± 1.9	−3088	4.1	0.3	0.67	14.4	7.6	3.6	8.4	40	44
4	0.37	5.74 ± 0.20	226.6 ± 1.1	130	2.8	0.3	0.85	15.2	4.2	8.7	9.7	27	36
5	0.30	5.74 ± 0.20	226.6 ± 1.1	130	3.6	0.5	0.86	20.4	4.2	5.2	6.7	27	26
6	0.21	5.74 ± 0.20	226.6 ± 1.1	130	4.5	0.5	0.86	26.0	4.2	3.4	5.4	27	21
7	0.24	6.37 ± 0.25	152.2 ± 3.1	668	3.4	0.5	0.82	17.3	7.7	5.6	9.5	31	30
8	0.32	3.76 ± 0.33	133.1 ± 4.8	332	4.1	0.5	0.93**	35.9	5.3	4.4	6.9	22	18
9	0.44	6.90 ± 0.59	219.6 ± 2.3	380	1.7	0.3	0.82	7.9	7.7	25.6	26.7	22	34
A	0.35	7.54 ± 0.45	205.8 ± 3.3	1103	2.9	0.5	0.76	12.2	9.0	7.3	11.6	17	22
B	0.11	6.12 ± 0.74	207.8 ± 3.2	231	7.4	0.5	0.76	33.5	15.1	1.4	15.2	17	21
C	0.27	8.19 ± 0.46	221.9 ± 3.0	900	3.4	0.3	0.70	13.0	8.7	4.9	10.0	35	29
D	0.22	8.19 ± 0.46	221.9 ± 3.0	900	5.0	0.5	0.70	19.7	8.7	2.4	9.0	35	31

* Reference wind speed and turbulence for these experiments is LM but wind direction and L are taken from SMW. In all other cases data are from SMW. Some expt pairs use the same turbine-off measurements, e.g., expts 2 and 3, 12 and 13.

** The turbine is not operating at this wind speed so the thrust coefficient is estimated based on winds of 4 m s^{-1}.

also measured at SMW. Data from LM and SMW are synchronized and are available as 1-min averages. Data from SMS have not been used because they are not time synchronized with the other masts. All times are Danish standard time (UTC + 1).

d. Data processing and quality control

1) SODAR DATA

The sodar data were recorded on a 1-min basis and have been processed to give averages for each experimental period with a minimum of 15 min. The following steps were taken to exclude selected individual profiles from the average.

- *Noise level.* A noise level was recorded for every 1-min wind profile. Higher noise levels could be traced to disturbances recorded in the logbook, such as the proximity of another ship. In the analysis a threshold was set to exclude data above a certain noise level defined using the background noise level for the day's experiments.
- *Inclination.* The angle of inclination of the ship was recorded during the experiment. A maximum amplitude of ±2° in the ship's movement during a minute is used to exclude periods of larger swing. The exception was for the first experiment when the angle was not measured and during experiments 2 and 3 during periods of higher wind speed when the cutoff was set to ±4°.
- *Directional variation.* During wake measurements (turbine on), variation in the wind direction meant that the sodar profile was taken at various distances from the center of the wake. In the analysis a gate was set to only include profiles near the center of the wake. The maximum displacement from the wake center allowed is given in Table 3.

Resulting wind profiles were composed by averaging over each single height in the 1-min profiles. The resulting standard deviation on the averaged wind speeds consists of both actual variation in the wind speed as well as deviations resulting from the measuring technique.

2) METEOROLOGICAL DATA

During parts of the experiment the anemometer at 30-m height at Vindeby SMW operated intermittently. These periods were removed from the database. For comparison with the sodar a dataset of 1-min averages was prepared. Stability information was required and this was provided by calculating the Monin–Obukhov length (L) from wind speed and temperature data using the method of Beljaars et al. (1989). The Monin–Obukhov length is initially estimated using the temperature profile at SMW, and then an iteration procedure is used to calculate the friction velocity and temperature scale including the wind speed measured at one level. During the experimental period, conditions were more stable than neutral (only observed during the first three experiments) at both the LM and SMW as expected at this site in April (Barthelmie 1999b). A median of the 1-min data is given for each experiment in Table 3. There can be small shifts in the median Monin–Obukhov length between the wake and nonwake periods, but these are of the order 30 m and do not affect the broad stability class. The meteorological data are used to provide an

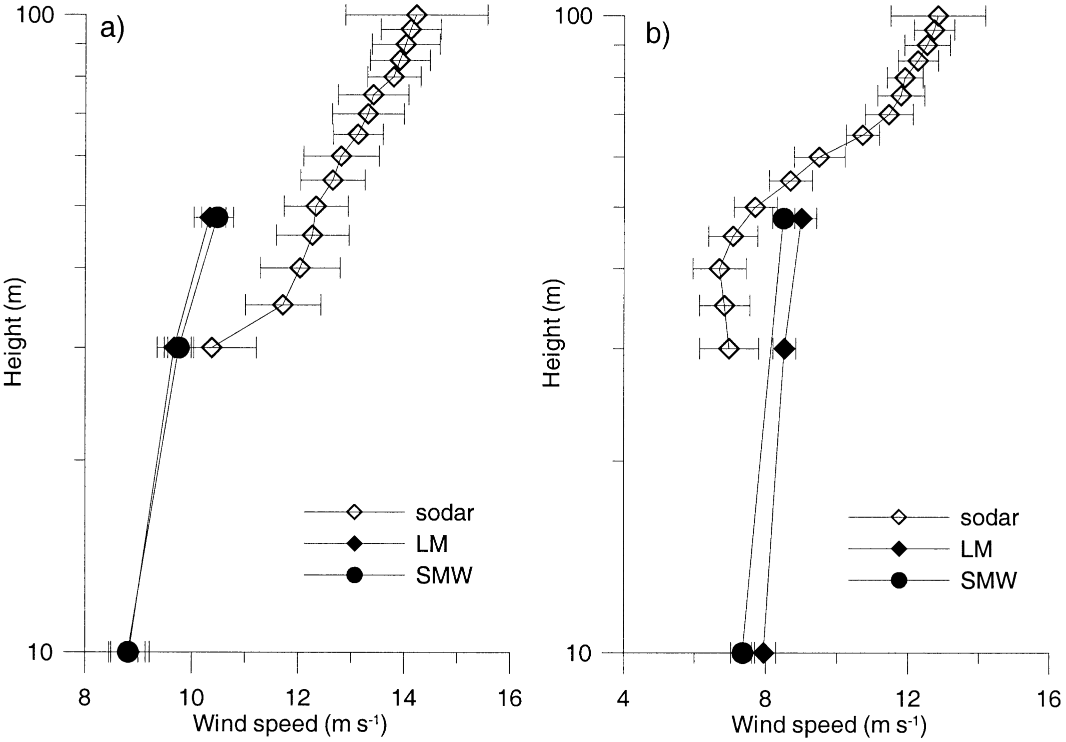

FIG. 4. Measurement of the (a) freestream wind and (b) offshore wake profile by sodar compared with mast data (expt 1 from Table 3). Error bars shown are 1 std dev on each side of the mean.

absolute reference for sodar-derived wind speeds during both wake and nonwake experiments. The measurements of freestream wind speeds are taken from LM if SMW is in the wake of the wind farm (directions from 320° to 110° over north, first three experiments) and from SMW if the wind direction is between 110° and 320° (remaining experiments).

3) DATA CORRECTION

Slight shifts in wind speed between the wake and nonwake periods had to be accounted for. Assuming that the freestream wind at 50 m measured on one of the meteorological masts (U_{mast}) was the baseline, a correction factor (CF) between the two (wake and nonwake) periods was determined:

$$\mathrm{CF} = U_{\mathrm{mast\ (nonwake\ period)}}/U_{\mathrm{mast\ (wake\ period)}}. \qquad (1)$$

This correction factor was then applied to the nonwake wind speed measured by the sodar. The velocity deficit was then calculated using the corrected wind speed profile.

3. Results: Specific experiments

In the first experiment, the freestream wind was measured for comparison with data from one of the meteorological masts. In the remaining experiments turbine-on, turbine-off experiments (of ≈ 30 min) were conducted (see Table 3). All times (meteorological masts and sodar) are synchronized to the nearest minute. At the beginning of the experiment, the wind direction was north-northeasterly, wind speeds were fairly high, and conditions tended toward neutral. Subsequently, the direction changed to south-southwesterly and the wind speed dropped giving slightly stable conditions. In experiments 4–6, conditions were strongly stable and the ambient turbulence intensity was very low. In the remaining experiments, turbulence intensity was between 5% and 15% at 48-m height. Two specific experiments are described in detail below and the results of all the experiments are shown in Table 3.

Table 3 shows the relative velocity deficit calculated for all the single wake pairs of experiments where both freestream (nonwake) and wake wind speed profiles are available from the sodar and the masts. Velocity deficit ΔU is defined in Hogström et al. (1988) as

$$\Delta U = U_{\mathrm{freestream}} - U_{\mathrm{min}}, \qquad (2)$$

where U_{min} is the minimum wind speed at any height. Here $U_{\mathrm{freestream}}$ is the wind speed measured by the sodar at 40-m height with the turbine switched off and the velocity deficit is defined at 40 m, which is the closest measurement to the turbine hub height of 38 m:

$$\Delta U = U_{\mathrm{freestream}} - U_{\mathrm{wake}}. \qquad (3)$$

As indicated in Table 3 the distance (x) to the turbine was measured using GPS and is expressed in number of rotor diameters *D* where the rotor diameter of the turbine is 35.5 m.

a. Freestream and one wake measurement

The first experiment (1 in Table 3) consisted of a comparison of the sodar wind speed profile with the measurements from SMW and LM. The *Seaworker* was anchored close to SMW during a period of fairly strong winds and the wind speed profile was measured for 40 min. During this period the wind direction remained steady with a direction 340.9° ± 1.1°. As shown in Fig. 1, when winds are from the north, both SMW and SMS are in the shadow of the wind farm. Wind speed and direction measurements from LM represent the regional wind field with more accuracy. For this 30-min period the stability (as determined by the Monin–Obukhov length based on the temperature profile) was near neutral and this is confirmed by the log-linear relationship shown by the wind profiles. Turbulence intensity (σ_U/U) as determined at 48 m was 5.8%. After measurements close to SMW, the *Seaworker* was repositioned at 3.8 *D* in the direct wake of turbine 1W and the wake measured with the sodar for approximately 30 min. During this period the wind direction was 342.9° ± 1.9° and the stability at LM was near neutral. Turbulence intensity was 5.9%. Figure 4 shows the average wind speed profiles for these two periods. Error bars shown are one standard deviation on either side of the mean value, showing little variability in the wind speed measured either by sodar or on the masts. While there is good agreement between the sodar and the mast measurements at 30 m (Fig. 4), the sodar gives rather higher wind speeds than the mast measurements at 48 m in the first period. The freestream and wake profiles are shown in Fig. 5, together with the corrected relative velocity deficit $\Delta U/U_{\text{freestream}}$, which has a maximum at 40 m.

b. One wake turbine-on, turbine-off measurements

During this experiment (7 in Table 3) the ship was positioned approximately 100 m (3.4 *D*) behind turbine 6E in light southeasterly winds. The wind direction was 146.50° ± 3.6° at LM and 145.7° ± 2.4° at SMW. Measurements at all three masts are affected by the land fetch to the south from this direction as shown in Fig. 1 and the sea masts give a better representation of the freestream wind speed. The distance to SMS is approximately 1.6 km and to SMW about 2.3 km, hence the distance from the coast to the ship was about 1.9 km. Turbulence intensity at 48 m at SMW was 5.9%. Stability was slightly unstable at LM ($L \sim 440$ m) and slightly stable at SMW ($L \sim 668$ m). The height of the internal boundary layer is expected to be close to 90 m [calculated using the formula in Bergström et al. (1988)]. However, it is not evident from the measured wind speed profiles (Fig. 6).

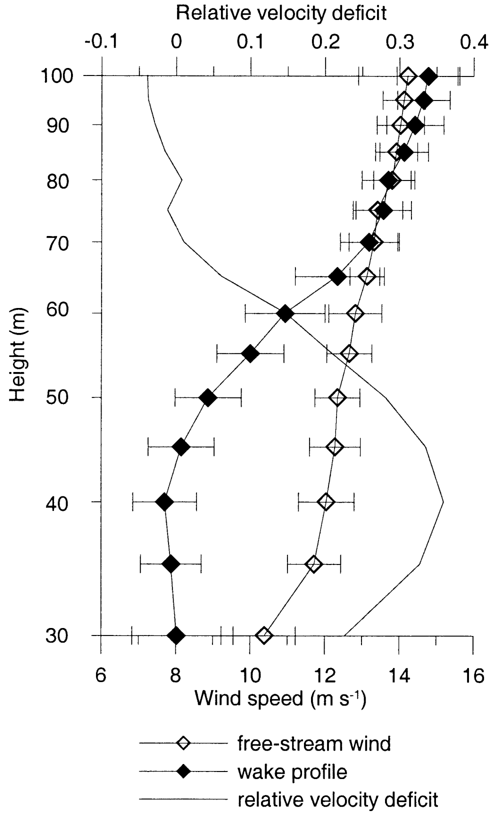

FIG. 5. Corrected freestream and wake profiles and relative velocity deficit measured by sodar (expt 1 in Table 3). Error bars shown are 1 std dev on each side of the mean.

As expected wind speeds at LM are lower than at the sea masts. There is good agreement between wind speeds measured at the sea masts and between the sea mast and sodar data during the nonwake measurements. The ratio between the measured wind speeds at 48 m between the masts and the sodar is 0.96 at SMW, and there was no measurable wind speed shift during the two periods at either LM or SMW. Figure 7 shows the corrected relative velocity deficit profile with a maximum between 35 and 40 m.

c. Single wake experiments

In total 13 wake experiments were conducted where both freestream and wake measurements passed quality controls. Figure 8 shows the relative velocity deficit profiles and details are given in Table 3. In Fig. 8 the velocity deficit profiles have been grouped according to distance from the turbine (expressed as number of rotor diameters *D*). Out of the three near-wake experiments (4 and 9) two show a distinct minimum at the height of the turbine nacelle and maximum at the midpoints of the blades (29 and 48 m). This is not so evident in the third experiment (A), which was also at less than 3 *D*. Of the five experiments between 3.3 and 3.9 *D*, all except experiment 5 show a similarly shaped profile with a maximum velocity deficit close to 40-m height.

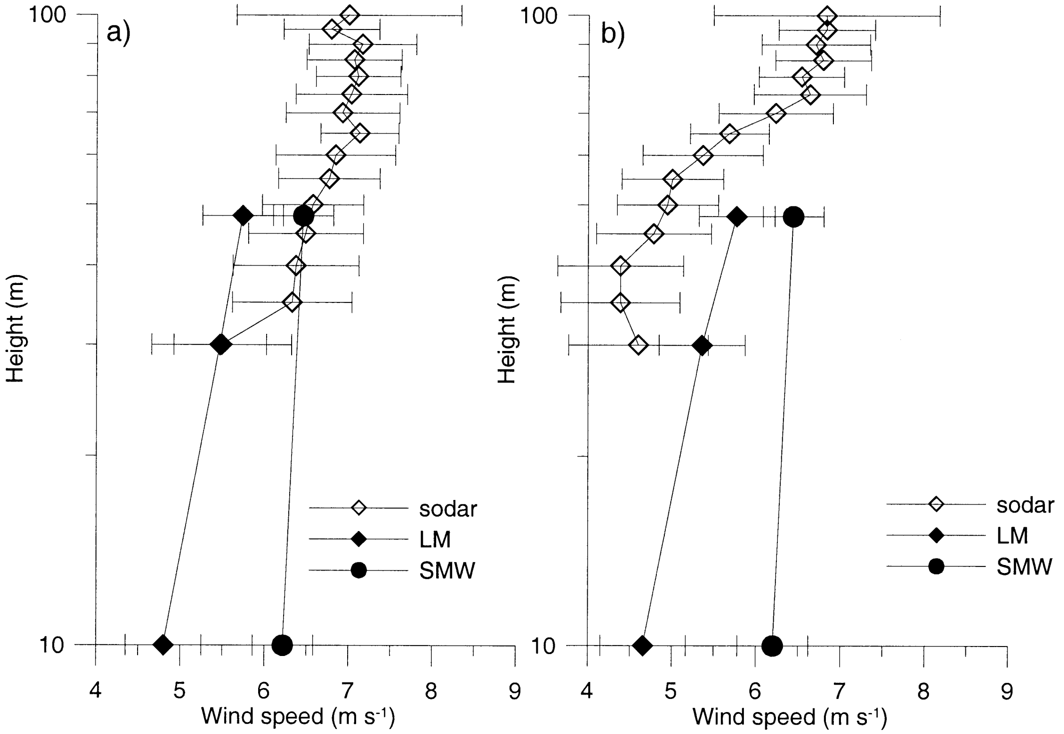

FIG. 6. Wind speed profiles for the (a) turbine-off, (b) turbine-on experiment at turbine 6E at Vindeby (expt 7 in Table 3). Error bars shown are 1 std dev on each side of the mean.

However, there is quite a large variation in the velocity deficits and the two experiments conducted in near-neutral conditions (1 and 3) have the highest velocity deficits. Theory predicts that wake recovery should be faster in near-neutral conditions. Three experiments were conducted at distances of 4.1–5.0 D and these show a fairly flat profile. There are two ''far wake'' experiments ($D > 6$), which show good agreement in the velocity deficit profile.

The velocity deficit profile depends on a number of factors including wind speed profile for wake recovery, the wind speed–related thrust coefficient of the wind turbine, ambient (mechanical and thermal) and turbine-generated turbulence, and the possible presence of an internal boundary layer or nonequilibrium conditions as flow adjusts in the coastal area. Hence it is difficult to analyze the data further without use of wake/meteorological models. In the next section, the experimental data are compared with results from an empirical model that predicts the velocity deficit based on the transport time.

4. Comparison of sodar data with previous wake measurements and an empirical model

One of the major concerns regarding offshore wind farm development is that wakes will decay more slowly offshore due to lower turbulence requiring larger spacing of offshore turbines than is the case on land. This has major financial implications due to the cost of undersea cabling. Hence it is of interest to examine wake decay with distance from the turbine and to compare this with similar data from land sites. Wake measurements have been made previously at offshore wind farms at Vindeby and at Bockstigen, but since these are mast measurements they are at specific, fixed distances from the turbines. One of the main objectives of using the ship for the sodar measurements was to determine the velocity deficit at different wake distances.

Magnusson and Smedman (1994) summarized wake data from a number of coastal (onshore) and inland sites. Rather than repeat this exercise we show here (Fig. 9) the relative velocity deficit against D from the sodar experiment with a regression line estimated from the data in Magnusson and Smedman (1994) as

$$\frac{\Delta U}{U_{\text{freestream}}} = 1.03\left(\frac{x}{D^{-0.97}}\right). \qquad (4)$$

Relative velocity deficits from the sodar experiment (Table 3) are also shown in Fig. 9. Regression of these data give the following fit:

$$\frac{\Delta U}{U_{\text{freestream}}} = 0.98\left(\frac{x}{D^{-0.96}}\right). \qquad (5)$$

Correlation coefficient for this fit (relative velocity deficit vs distance in rotor diameters) is 0.79. Although the velocity deficits from the sodar experiment are smaller

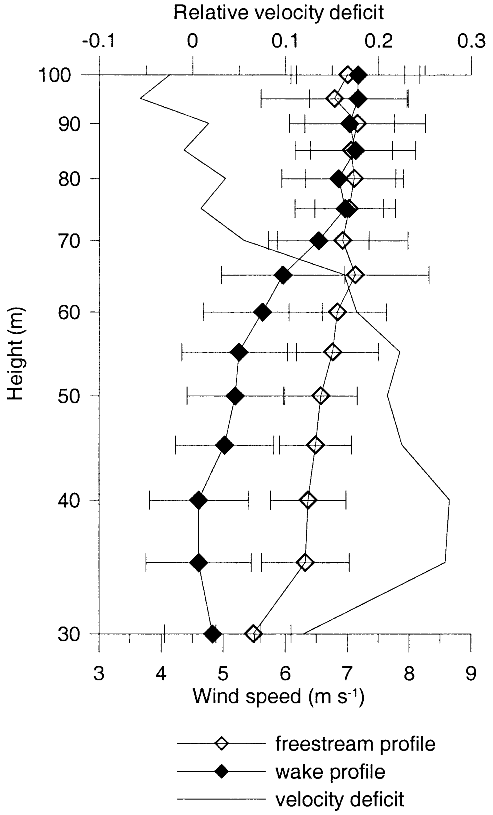

FIG. 7. Corrected freestream and wake profiles and relative velocity deficit measured by sodar (expt 7 in Table 3). Error bars shown are 1 std dev on each side of the mean.

than those from Magnusson and Smedman (1994) (for the same distance), the difference is small compared to the uncertainty in the measurements. The agreement between the distance decay of the velocity deficit from the offshore Vindeby experiment and the onshore data from Magnusson and Smedman (1994) may also partly reflect the coastal location of the majority of the measurement sites used in that study.

There does not seem to be any particular feature that determines whether the relative velocity deficit for each experiment lies close to the predicted value. For example, the three higher wind speed cases (experiments 1–3) lie on either side of the line; the three most stable cases (experiments 4–6) lie close to the line, but the experiment B with a similar Monin–Obukhov length does not. Nor can the predictability of the experimental results be grouped in terms of ambient or total turbulence.

A simple model defined by Magnusson and Smedman (1996) gives the decay of the relative velocity deficit $\Delta U/U_{\text{freestream}}$ as

$$\frac{\Delta U}{U_{\text{freestream}}} = 0.4 \ln\left(\frac{t_0}{t}\right) + C_T, \quad t > t_0 \tag{6}$$

where C_T is the thrust coefficient, t_0 is a timescale, and t is the transport time defined as $x/U_{\text{freestream}}$ where x is the distance in meters.

Equation (6) cannot be used for large t if the absolute value of $0.4 \ln(t_0/t) > C_T$.

The timescale t_0 can be defined for near-neutral conditions by

$$t_0 = \frac{1}{f} \ln\left(\frac{H}{z_0}\right)\frac{R}{H}, \tag{7}$$

where f is the rotational frequency, R is the radius of the rotor, H is the hub height, and z_0 is the roughness length.

The parameters for the Vindeby wind farm are $f = 0.59$ Hz, $R = 17.8$ m, $H = 38$ m. To provide the first estimates of t_0, z_0 is assumed to be 0.05 m over land giving $t_0 = 5.3$ s and $z_0 = 0.0002$ m over sea giving $t_0 = 9.7$ s. [Note these are similar to those given for Alsvik in Magnusson and Smedman (1996) ~5.25 s.] From rearranging Eq. (6) the calculated relative velocity deficit (in near-neutral conditions) is

$$\frac{\Delta U}{U} - C_T = 0.4 \ln\left(\frac{t_0}{t}\right). \tag{8}$$

For the same turbine (known C_T), a velocity deficit can then be determined for on- and offshore situations (where the difference is the surface roughness) and these are shown against transport time in Fig. 10. To compare this with the results of the sodar experiment, a transport time was calculated for each relative velocity deficit and this is also shown in Fig. 10. The results lie close to the curve derived from onshore roughness—implying that the wake decay at Vindeby can be predicted using a roughness more typical of coastal than offshore environments.

For the period 1996–2001, average turbulence intensity at 48-m height at LM is 12% compared with 10% at SMW. Although the turbulence level at SMW is increased by the presence of the wind farm (removing these sectors gives a turbulence intensity of 9%), these results suggest that the turbulence level in the first few kilometers from the coast is not significantly lower than at coastal sites. Turbulence level calculated using data from the same period at 48-m height at a similar mast 11 km offshore from the coast was 6.5%. However, the turbulence intensity at SMW during the sodar experiments was 9% or less in all but one case, lower than would be expected for a land site.

The question arises whether the turbine added turbulence I_{added} is more significant to the wake development than the ambient turbulence I_0. The turbulence experienced at each turbine I_{total} can be estimated using the following equation from Frandsen et al. (1996):

$$I^2_{\text{total}} = I^2_0 + I^2_{\text{added}}. \tag{9}$$

The turbine added turbulence intensity is determined using the thrust coefficient and turbine separation [see Frandsen et al. (1996) and Eq. (10)] and ambient tur-

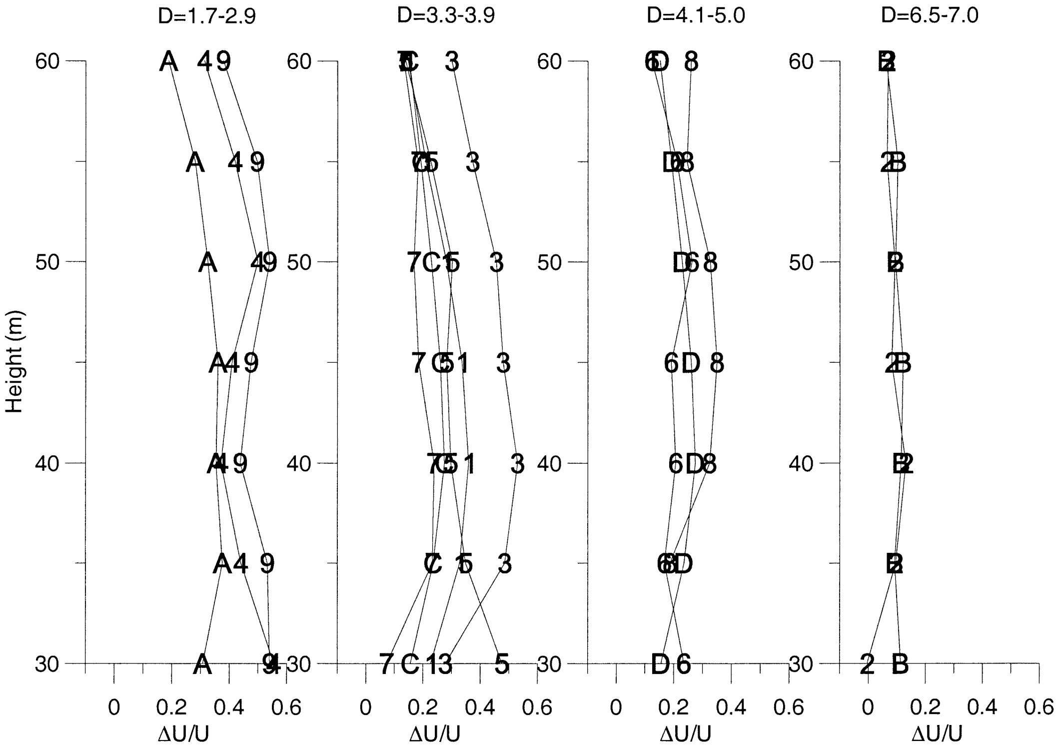

FIG. 8. Relative velocity deficit profiles for each of the 13 experiments grouped by distance of the measurements to the turbine (expressed as number of rotor diameters). Numbers shown refer to the experiment designations given in Table 3.

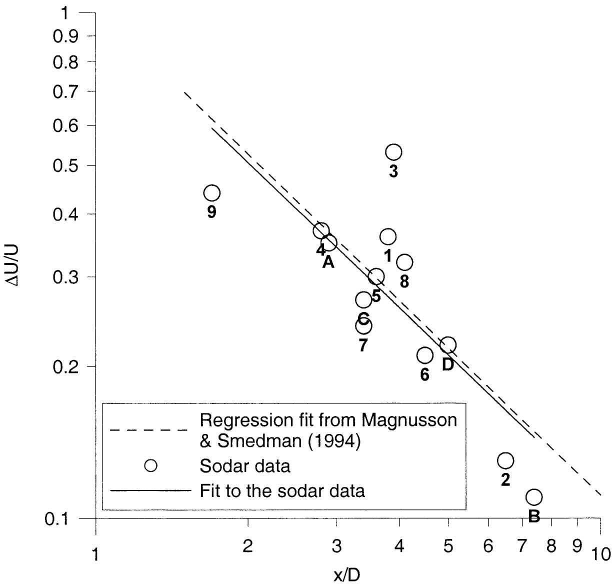

FIG. 9. Relative velocity deficit by distance (shown here as number of rotor diameters D). The relative velocity deficit is defined as $(U_{\text{ambient}} - U_{\text{hub height}}/U_{\text{ambient}})$. The dashed line shows a regression fit to data from Magnusson and Smedman (1994). Numbers shown refer to the experiment designations given in Table 3.

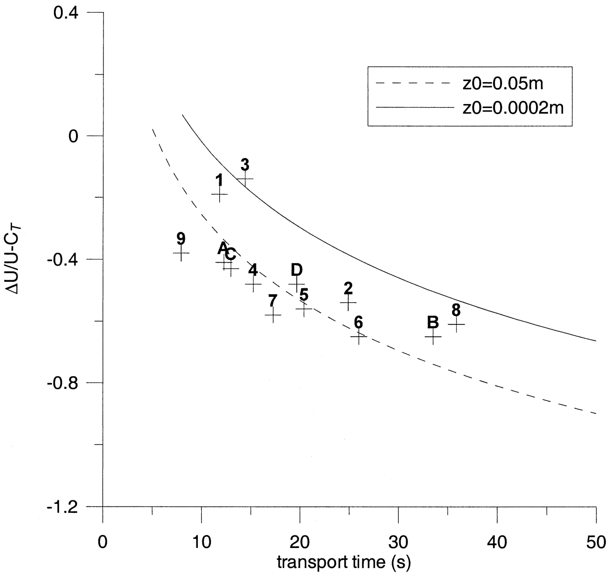

FIG. 10. Relative velocity deficit and transport time calculated for two different roughnesses [representing onshore (0.05 m) and offshore (0.0002 m) and from the sodar data]. Numbers shown refer to the experiment designations given in Table 3.

bulence intensity is calculated as the 10-min standard deviation of the wind speed divided by the 10-min average wind speed. Hence the total turbulence intensity is given by

$$I_{\text{total}} = \sqrt{I_0^2 + \frac{1.2C_T}{s_t^2}}, \tag{10}$$

where I_0 is the ambient turbulence calculated as σ_v/U and σ_U is the standard deviation of wind speed and s_t is the turbine separation (expressed in rotor diameters).

Given that the ambient turbulence is known, the equation is applied here for each experiment and the results shown in Table 3. The added turbulence is significant when D is less than $\sim$4.

The analyses presented indicate that the wake decay measured at Vindeby (coastal offshore) is not substantially different than that measured at other coastal (onshore) sites despite observed lower ambient turbulence. This requires further investigation using both datasets from onshore wind farms and by conducting further sodar measurements at a far offshore site.

5. Conclusions

The main objectives of the sodar experiment described here were to evaluate the operation of the sodar when mounted on a ship offshore and to investigate whether the noise of the operating wind turbine impacted the vertical profile of wind speed as measured by the sodar. These objectives were met with the sodar operating well. Vertical profiles measured by the sodar gave good agreement with the mast data. Sodar wind speeds were within 2%–15% of mast measured wind speeds (at 48-m height). In the situation of the Vindeby wind farm in relatively shallow water and with low wave heights, it proved possible to measure wind speed profiles that clearly showed a deficit in wind speed close to hub height during turbine operation, which disappeared when turbine operation was stopped. The noise of the wind turbine did not prove a barrier to successful monitoring of the wind speed profile up to 100-m height. Wake profiles were clearly measured as a reduction in the wind speed (centered on the hub height of the wind turbine). The relative centerline velocity deficit was calculated and the decay of the wake (with distance or transport time) was shown to be similar to those determined by other wake studies in coastal (onshore) environments despite the relatively low turbulence. Compared with an empirical model of relative velocity deficit versus transport time, results from the sodar experiment were closer to predicted velocity deficit over a roughness of 0.05 m than to predictions using an offshore roughness of 0.0002 m. This may indicate that offshore wind farms in coastal environments (up to 3 km from the coast) can be effectively modeled with wake model designed for onshore wind farms. The results of the sodar experiment are now being compared with physical wake models [e.g., based on Ainslie (1988)], which can also account for the variation in turbulence intensity.

The experience from the experiment may prove useful in current plans to use sodar operated from floating platforms for wind monitoring in the North Sea. Although wave heights were comparatively low during the experiment, it was possible to measure the longitudinal and transverse tilt angles at high time resolution, which could potentially be used to correct the sodar signal in future experiments.

Acknowledgments. Financial support for this research was given in part by the European Commission's Fifth Framework Programme under the Energy, Environment and Sustainable Development Program. Project reference: ERK6-1999-00001 ENDOW. Meteorological measurements at Vindeby are funded by SEAS. We would also like to acknowledge PM Diving's *Seaworker* crew Carsten Johannesen, Gregers Glensdorf, Lars Jensen, and Flemming Carlsen and Bent Christiansen of Vindeby. Weather forecasts were provided by the National Environmental Research Institute of Denmark with thanks to Bjarne Jensen. Dr. Sara Pryor of Indiana University is acknowledged for useful comments on the manuscript. The comments and suggestions of three anonymous reviewers have improved the clarity of the paper.

REFERENCES

Ainslie, J. F., 1988: Calculating the flow field in the wake of wind turbines. *J. Wind Eng. Ind. Aerodyn.,* **27,** 213–224.

Barthelmie, R. J., 1999a: A brief review of offshore wind energy activity in the 1990s. *Wind Eng.,* **22,** 265–274.

——, 1999b: The effects of atmospheric stability on coastal wind climates. *Meteor. Appl.,* **6,** 39–48.

——, M. S. Courtney, J. Højstrup, and S. E. Larsen, 1996: Meteorological aspects of offshore wind energy—Observations from the Vindeby wind farm. *J. Wind Eng. Ind. Aerodyn.,* **62,** 191–211.

——, I. Bryden, J. Coelingh, and S. C. Pryor, 2000: Energy from the oceans: Wind, wave and tidal. *Seas at the Millennium,* C. Sheppard, Ed., Elsevier, 303–321.

——, and Coauthors, 2001: Efficient development of offshore windfarms: A new project for investigating wake and boundary-layer interactions. *Proc. 2001 European Wind Energy Conf. and Exhibition,* Copenhagen, Denmark, WIP-Renewable Energies, 657–660.

Beljaars, A. C. M., A. A. M. Holtslag, and R. M. van Westrhenen, 1989: Description of a software library for the calculation of surface fluxes. Tech. Rep. TR-112, KNMI, De Bilt, Netherlands, 32 pp.

Bergström, H., P.-E. Johansson, and A.-S. Smedman, 1988: A study of wind speed modification and internal boundary-layer heights in a coastal region. *Bound.-Layer Meteor.,* **42,** 313–335.

Coelingh, J., L. Folkerts, G. Wiegerinck, and E. van Zuylen, 2000: Study of the offshore wind climate using a sodar. *Offshore Wind Energy in Mediterranean and other European Seas,* ATENA, 61–70.

Crescenti, G. H., 1997: A look back on two decades of Doppler sodar comparison studies. *Bull. Amer. Meteor. Soc.,* **78,** 651–673.

——, 1998: The degradation of Doppler sodar performance due to noise: A review. *Atmos. Environ.,* **32,** 1499–1509.

Crespo, A., J. Hernandez, and S. Frandsen, 1999: Survey and modelling methods for wind turbine wakes and wind farms. *Wind Energy,* **2,** 1–24.

DEA/CADDET, 2000: Electricity from offshore wind. Danish Energy Agency and IEA CADDET Renewable Energy Programme, ETSU, Harwell, United Kingdom, 102 pp.

Fairall, C. W., A. B. White, J. B. Edson, and J. E. Hare, 1997: Integrated shipboard measurements of the marine boundary layer. *J. Atmos. Oceanic Technol.,* **14,** 338–359.

Frandsen, S., and Coauthors, 1996: Measurements on and modelling of offshore wind farms. Risø-R-903(EN), Risø National Laboratory, Denmark, 100 pp.

Hogström, U., D. N. Asimakopoulos, H. Kambezidis, C. Helmis, and A. Smedman, 1988: A field study of the wake behind a 2 MW wind turbine. *Atmos. Environ,* **22,** 803–820.

Lange, B., E. Aagard, P. E. Andersen, A. Møller, S. Niklassen, and A. Wickman, 1999: Offshore wind farm Bockstigen—Installation and operation experience. *Proc. 1999 European Wind Energy Conference and Exhibition,* Nice, France, 300–303.

Magnusson, M., and A. S. Smedman, 1994: Influence of atmospheric stability on wind turbine wakes. *Wind Eng.,* **18,** 139–151.

——, and ——, 1996: A practical method to estimate wind turbine wake characteristics from turbine data and routine wind measurements. *Wind Eng.,* **20,** 73–91.

Otterstein, H., M. Hurtig, G. Stilke, B. Brummer, and G. Peters, 1974: Shipbourne sodar measurements during JONSWAP 2. *J. Geophys. Res.,* **79,** 5573–5584.

Petenko, I. V., A. N. Bedulin, and E. A. Shurygin, 1996: Sodar observations of the atmospheric boundary layer over the ocean during ASTEX-91. *Bound.-Layer Meteor.,* **81,** 63–73.

Vogt, S., and P. Thomas, 1994: Sodar—A useful remote sounder to measure wind and turbulence. *J. Wind Eng. Ind. Aerodyn.,* **54/55,** 163–172.