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Laser measurements of flow over a forest

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Abstract. It is estimated that 20-30% of the total European wind energy growth takes place in areas where the wind flow is affected by forests. The description of the wind conditions near and above forests poses a challenge, since assumptions of classical boundary-layer theory are violated. Turbines are designed for a maximal turbulence intensity and wind profile gradient. In forested areas, these limits are often violated possibly leading to reduced turbine life-time. In this paper we investigate the mean wind profile and turbulence statistics above an 85 years old dense beech forest by use of a laser Doppler anemometer and compare the profiles with a CFD model specifically made for the modeling of flow over vegetation canopies.

1. Introduction

Wind turbine sites in or near forest are problematic because of the high turbulence intensity, implying larger structural loads, and lower average winds. However, the advantage is less visual impact and lower prices of the land, and despite the drawbacks an increasing number of turbines are erected in or close to forests. In northern Europe more than half of all turbines are erected in forested areas.

Over ordinary land surfaces the mixing length is proportional to the distance to the surface, but over a forest the situation is more complicated. Also the correlation coefficient of the horizontal and vertical velocity fluctuations is larger right over the forest compared to an ordinary surface (Raupach et al. 1996). The purpose of this work is to quantify properties of the atmospheric flow over a forest relevant for loads on wind turbines by an atmospheric field experiment using sophisticated laser anemometry and to compare them to a $k$-$\varepsilon$ models of Sogachev & Panferov (2006).

2. Experiment and analysis method

Two experiments are a part of our effort to understand aspects of flow over forest with relevance for wind turbines. One is described in this paper and the next will take place in 2008 concerning flow right at the forest edge.

2.1. Site and experimental setup

The Søro site is located in an 85 year old beech forest called Lille Bøgeskov ($55^{°}29^{9}9.00^{°}$N, $11^{°}38^{4}40.73^{°}$E) on the island Zealand, Denmark. The forest extends 1 km in the east-west direction and 2 km in the north-south direction (see figure 2, left). The area surrounding the forest is dominated by agricultural fields and the area is flat. The western sector of the Søro site is homogeneous with relatively constant tree top height and is the sector chosen for modeling (see section 2.2.1). The 57 m tall mast is located in the middle of the forest with a fetch of...
Figure 1. Left: Sketch of the field experiment with a met mast and laser anemometer situated 0.5 km from the nearest forest edge. IBL: internal boundary layer, RS: roughness sub-layer, IEL: internal equilibrium layer. Right: The experimental site seen from above with the platform for the lidar to the right.

Figure 2. Left: Map of the Lille Bogeskov with the experimental site indicated by a cross. Right: Doppler wind spectra as a function of direction fitted to (1). The arrows indicate the standard deviation of the radial wind speed in the upwind and downwind directions respectively.

approximately 500 m both to the west and the east. The beech trees are on average 25 m tall, but the forest also contains scattered stands of conifers. Mean leaf area index for the main footprint of the forest is 5 m²/m². The leaf area index is approximately constant between June and September and drops slowly during the autumn. Displacement height and roughness length are \( d = 20.6 \pm 4 \text{m} \) and \( z_0 = 1.8 \pm 0.7 \text{m} \) (Dellwik & Jensen 2005) based on measurements taken during early autumn.

Next to the mast there is a 24m tall scaffolding tower, where the QinetiQ ZephIR Doppler lidar was placed at the level of the tree tops, see figure 1. This lidar will be described in more detail in section 2.2.

Wind measurements in the mast consist of cup anemometers at 37, 41, 48 and 57 m above ground level (Cup P2244, Risø National Laboratory, Denmark). Two sonic anemometers are mounted at 43 and 48 m (Solent 1012R2, Gill Instruments Ltd., Lymington, UK). Wind vanes (Risø National Laboratory, Denmark) are placed at 43 m and 57 m height.

Information on other measurements taken at the Sorø site can be found in Pilegaard et al. (2003).
2.2. Laser instrument

We use the prototype version of QinetiQ’s ZephIR lidar (Smith et al. 2006) to measure the winds up to 180 m. The instrument essentially assesses the radial velocity at the point of focus. We use it in the conical scanning mode, where the laser beam is deflected an angle \( \phi \) from the vertical by a prism, and the prism is making one full turn every second. The along beam or radial velocity component of the wind is thus measured on a circle as indicated on figure 1 (left). For each focus height the beam rotate three times before the instrument changes focus to the next height. Wind in eight height are measured in this way.

Assuming the flow field to be roughly homogeneous over the averaging circle (see figure 1, left) with a mean \((u, v, w)\) the radial velocity in the direction of the laser beam \( v_r \) is

\[
v_r = |u \sin \phi \cos \theta + v \sin \phi \sin \theta + w \cos \phi|,
\]

where \( \theta \) is the horizontal angle from the downwind direction, and \( \phi \approx 30.6^\circ \) is the half opening angle of the cone. The absolute value on the right hand side is there because the instrument can only measure the absolute value of the Doppler shift, see Smith et al. (2006). All three velocity components can be obtained through fitting equation (1) to the Doppler spectra, as shown as the thin, black curve in figure 2. There are several different ways of doing this, but we will not go into details in the present contribution.

The Doppler velocity measured is not exactly from the focus point, but rather weighted in space along the laser beam by

\[
\varphi(s) = \frac{1}{\pi} \frac{L}{L^2 + s^2}
\]

where \( s \) is the distance along the laser beam from the focus point, and \( L \) is the half width at half maximum length (Sonnenschein & Horrigan 1971). For a focus distance of 100 m \( L \) is approximately 12 m for the QinetiQ system and \( L \) varies quadratically with the focus distance. This implies \( L \approx 3 \) m at a focus distance of 50 m and \( L \approx 50 \) m at 200 m.

The Doppler spectral density subtracted the background noise spectrum \( S(v_r) \) may thus by approximated by

\[
S(v_r) = \int_{-\infty}^{\infty} \varphi(s) \delta(v_r - v_r(s)) ds,
\]

where we have ignored several effects. We now use the identity \( \langle \delta(v_r - v_r(s)) \rangle = p(v_r; s) \) where \( \langle \rangle \) means averaging and where \( p(v_r; s) \) is the probability density function (pdf) of the radial
velocity at position \( s \), and get

\[
\langle S(v_r) \rangle = \int_{-\infty}^{\infty} \varphi(s)p(v_r; s) ds \approx p(v_r),
\]

where the last approximation assumes that the pdf of radial velocities does not depend on distance. This means that the lidar can measure the pdf of the unfiltered velocity no matter how large \( L \) is, as long as we take a sufficient number of spectra to make a reasonable average. The variance can thus also be obtained.

We now turn our attention to the expected variances of the radial velocity when the lidar is pointing up- and down-wind, while still maintaining the half opening angle \( \phi \) of 30.6°. The fluctuations in the upwind (\( \theta = \pi \)) and downwind (\( \theta = 0 \)) directions can be derived from (1):

\[
\begin{align*}
\sigma^2(v_{r,up}) &= \sigma_u^2 \sin^2 \phi + \sigma_w^2 \cos^2 \phi - 2 \sin \phi \cos \phi \langle u'w' \rangle \\
\sigma^2(v_{r,down}) &= \sigma_u^2 \sin^2 \phi + \sigma_w^2 \cos^2 \phi + 2 \sin \phi \cos \phi \langle u'w' \rangle 
\end{align*}
\]

so subtracting these equations the momentum flux \( \langle u'w' \rangle \) can be obtained. \( \pm \sigma(v_{r,up}) \) and \( \pm \sigma(v_{r,down}) \) are indicated by arrows in figure 2, and it can be seen that \( \sigma(v_{r,up}) \) at direction \( \approx 2 \) is the larger implying a negative \( \langle u'w' \rangle \), as expected.

2.2.1. The comparison run. From December 2006 and the first half of January 2007 we select a number of half hour periods in order to compare the measured flow with the model. We select neutral atmospheric stratification \( |(z - d)/L| < 0.05 \), where the displacement length \( d \) is 20.6 m. We choose a narrow westerly sector defined by the 57 m vane readings being between 270° and 290°. Moderately strong winds are selected: The cup 57 m measures a half hour mean wind speed between 6 and 8 m/s. The lidar measuring heights are 48, 57, 65, 76, 92, 113, 140, 175 m. We had to exclude data from one day in December due to lacking lidar data at high altitude. The reason of this absence of data is currently not known. This selection procedure leaves us with 78 half hour periods.

The average spectra of all half hour runs as functions of direction are shown in figure 4. Clearly, the wind speed increases with height because the amplitude of the “rectified cosine” increases. In figure 3 the wind speeds of individual half hour runs are shown together with the corresponding directions. The heights are chosen such that if the wind profile is logarithmic the wind speeds will be spaced equidistantly. This seems often to be the case. The wind directions are seen to turn slightly clockwise as height increases for most of the half hour runs. This is qualitatively what should be expected from the Ekman turning. It is an unforeseen advantage of the instrument that it can measure this very tiny direction shift with height. It would be difficult, if not impossible, to align ordinary vanes in a mast to measure the same, and it is something that can be compared with model calculations, if these include a Coriolis force.

Some problems occasionally occur in the analysis when clouds or rain is present. These runs have not been omitted from the analysis, but as the half hour run in figure 5 (left) shows, low clouds can give spurious effects. It is seen that the cloud (thin rectified cosine above the main signal) moves at a higher speed and roughly 25° clockwise to the wind at 175 m. Much analysis remains to assess these uncertainties.

3. CFD model description
SCADIS, which is an acronym for Scalar Distribution, is a \( k - \epsilon \) type flow model for the time averaged Navier–Stokes equations. It has mainly been used for estimation of the source area, the so called footprint, for scalar measurements of carbon dioxide. For this study we disregard the footprint calculator and focus on the flow model output. The SCADIS flow
Figure 4. Average spectra at eight heights above ground level shown as functions of direction in ° and radial wind speed in m/s. The upwind direction is around 270°.

Figure 5. Left: Lidar Doppler spectra from 175 m a.g.l. where clouds echoes can be seen. Right: SCADIS 2D calculations of wind speed in m/s for the winter conditions. The extend canopy is shown with a dashed line.

model is especially designed for modeling the flow in and above vegetation canopies. It is well documented in the scientific literature (Sogachev et al. 2002, Sogachev, Leclerc, Karipot, Zhang & Vesala 2005, Sogachev, Panferov, Gravenhorst & Vesala 2005, Sogachev & Panferov 2006) and has been verified against numerous field measurements. The model exists in both a 2D and a 3D version. The user-friendly 2D version can be run at a normal PC, where a model run takes approximately an hour. The vertical domain and resolution, which both are fixed, are 0-3025 m and 75 points respectively. The default horizontal resolution is 50 m and the PC version allows for 50 points.

Model input is one sided total leaf area index (LAI), LAI vertical distribution, vegetation height and ground/soil roughness length. This information is given for each vegetation type.
Table 1. Input parameters for SCADIS runs. Run 1 and 2 correspond to typical winter and summer conditions respectively. The LAI is given in m²/m², leaf area distribution (LAD) in m²/m³ and the number corresponds to a fix setting in SCADIS, $h$ is vegetation height in m and $z_0$ is the ground/soil roughness length also in m.

| Run | Agricultural fields | Forest |
|-----|---------------------|--------|
|     | LAI     | LAD    | $h$ | $z_0$ | LAI   | LAD  | $h$ | $z_0$ |
| 1   | 0 0     | 0.05   | 1.5 | 5     | 25    | 0.1  |
| 2   | 4 3     | 0.5    | 0.1 | 5     | 5     | 25   | 0.1 |

Figure 6. Left: Measured half hour mean wind speeds (dots) compared to SCADIS calculations for winter conditions (solid, blue) and summer conditions (dashed, red). Middle: Mean wind directions compared to simulations. Right: Momentum flux measurements. The blue lower point is from a sonic, while the rest of the points are from the lidar. The the broad solid curve is another way of calculating the momentum flux from the lidar data. SCADIS simulations also shown.

in the modeling domain. Subsequently the different vegetation types are placed on a matrix, representing a map.

Model input for the western sector of the Sorø site is given in table 1. We model both a typical winter case and a summer case with a higher LAI in order to improve our understanding of how the LAI parameter affects the flow.

Choosing the appropriate LAI for the winter period is not a straight forward matter. On one hand the measured and actual leaf area is low, but on the other hand the supporting structure of the leaves (trunks, branches, and twigs) which absorb most of the momentum in the flow, is the same all year round. In this sense, one could argue that it is the leaf area’s supporting structure which is the most relevant parameter. The effect of the leaves on the flow is poorly investigated and more research is needed.
4. Results
The average of all comparison runs are shown in figure 6. We are quite confident about the mean wind speed and direction profiles, but the momentum flux needs some discussion. First of all, it seems that the lidar overestimates slightly the momentum flux as compared to the sonic. We have made a similar comparison of momentum fluxes at another site (Høvsøre) with a newer version of the lidar, which indicates the same. More detailed analysis is needed to explain the difference. Another obvious difference between lidar and sonic momentum fluxes is the scatter. The standard deviation of all half hour runs is shown as a horizontal line for both instruments. The shorter interval is the standard deviation of the mean, i.e. the standard deviation divided by the square root of the number of half hour runs. The standard deviation of the lidar is twice as large as the sonic. One cause for this could be that the lidar measures only for less than three minutes at each height for each half hour run, which must imply are larger uncertainty.

The SCADIS simulations compare very well with the mean wind speed and direction profiles. Two curves are shown in figure 6; one for winter conditions, which is most relevant to compare to the measurements, and one for summer conditions. The momentum flux profiles compare less well.

5. Conclusion
We can measure profiles with a lidar both of the mean wind speed, the wind direction, and, with more uncertainty, the momentum flux. Interesting work remains to be done on the ways to analyze the lidar data.

The calculations with the SCADIS model are very encouraging. Especially the mean wind and direction profiles are predicted well.

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