Variations of the wake height over the Bolund escarpment

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Variations of the wake height over the Bolund escarpment

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1 Abstract

The here presented results are part of a paper that is submitted and accepted with minor revisions by the Boundary-Layer Meteorology journal.

The wake zone behind the escarpment of the Bolund peninsula in the Roskilde Fjord, Denmark, has been investigated with the help of a continuous-wave Doppler lidar. The instrument measures the line-of-sight wind speed 390 times per second in highly resolved 7-m tall profiles by rapidly changing the focus distance and beam direction. The profiles reveal the detailed and rapidly changing structure of the wake induced by the Bolund escarpment. The wake grows with distance from the escarpment, with the wake height depending strongly on the wind direction, such that the minimum height appears when the flow is perpendicular to the escarpment. The wake increases by 10% to 70% when the wind direction deviates ± 15° from perpendicular depending on the distance to the edge and to a lesser degree on the method by which the wake height is determined.

Keywords: Bolund, Wake height, Complex flow, WindScanner

2 Introduction

To obtain high quality results in numerical and physical modelling for wind energy purposes, is it important to verify these models with reliable real world measurements [1, 2, 3, 4, 5, 6]. Bolund, an isolated flat-topped hill with steep sides in the Roskilde Fjord, Denmark, (Fig. 1) serves as such a baseline reference for various studies with respect to numerical and physical modelling since a mast based atmospheric experiment was conducted by DTU Wind Energy during winter 2007-2008 [7, 8]. To obtain a more comprehensive understanding of the flow pattern over the Bolund peninsula, especially close to the surface, a complementary field experiment on the Bolund peninsula was conducted. In October 2011 a laser anemometer, in the following called WindScanner [9, 10], was placed on the peninsula 20 m inland from the westward facing escarpment.

3 Approach

The WindScanner, aligned on the 270° axis, was operated during westerly wind conditions to scan the area downstream of the Bolund edge. The atmospheric flow was measured in seven, 7-m high vertical profiles with distances between 8 m and 31 m from the scanning lidar (Fig. 2). In addition to the seven vertical profiles a horizontal arc extending ± 60° was scanned 120 m away from the instrument. The line-of-sight wind speeds of the eighth profile were used to determine the undisturbed inflow wind speed and wind direction.

While westerly wind directions prevailed, lidar measurements were recorded continuously during an almost 24 hour long measurement period.

Figure 1: Photo of Bolund, taken south of the peninsula.

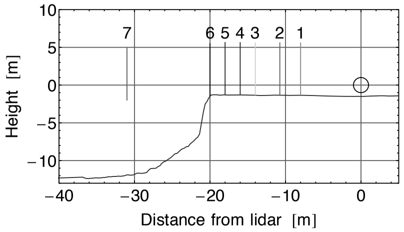

Figure 2: The position and height of the 7 vertical profiles scanned by the lidar relative to the Bolund escarpment. The position of the WindScanner itself is indicated by the circle.

4 Method

The characteristic of the escarpment-induced wake height is further investigated by identifying the boundary between the turbulent wake layer and the freestream flow above. Due to the high measurement-sampling rate a precise determination of the interface between the two distinctly different layers is possible. We determine the wake height δ using three different methods.

1. The first approach determines the displacement thickness, δ_1, that is defined as the distance that the boundary layer is displaced to compensate for the reduction in flow rate on account of the wake formation, where $u(z)$ is the line-of-sight wind speed at height z and u_0 is the freestream velocity [11]

$$\delta_1 = \int_0^\infty \left(1 - \frac{u(z)}{u_0}\right) dz. \tag{1}$$

2. The second approach identifies the height of the maximum gradient of the line-of-sight wind speed, δ_2, of each vertical scan [12, Sect. 2.2.2]

$$\delta_2 = \arg\max_z \left[\frac{du(z)}{dz}\right]. \tag{2}$$

3. The third approach identifies the height at which the average between the integral of the two atmospheric layers is the greatest, δ_3, which resembles [13] and [12, Sect. 2.2.3]. Here, z_{top} is the top of the profile,

$$\delta_3 = \arg\max_z \left[\frac{1}{z_{top} - z} \int_z^{z_{top}} u(z)dz - \frac{1}{z}\int_0^z u(z)dz\right]. \tag{3}$$

The results of the wake height identifications of all three methods are presented in Fig. 3. All three methods manage to identify a wake height, although the actual height differs between the methods. Method 1 gives the highest value of the wake heights.

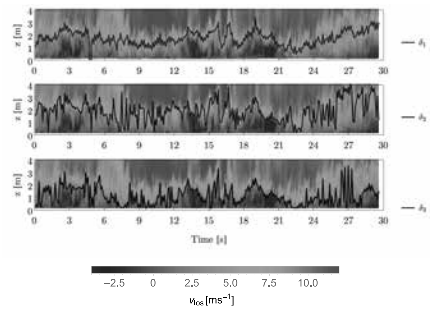

Figure 3: The line-of-sight projected wind speed of profile 3, 12 m away from the WindScanner lasting for 30 s with the defined wake heights using three different methods.

The calculated wake height for each profile location can be placed in relation to the undisturbed wind direction and speed (Fig. 4). With increasing distance from the escarpment, the wake heights show a stronger dependence on the wind direction. The lowest wake heights of every profile is located at a wind direction of 270°. Depending on the distance from the escarpment the wake height increases between 10% and 80% when the wind direction deviates from west, either to the north or the south ± 15°. At larger direction deviations the height seems constant.

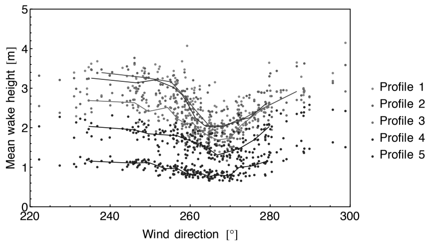

Figure 4: Dependence of the determined wake height and the wind direction. The solid lines depict the average wake height. The profile number increases with increasing distance from the WindScanner. The wake height is calculated through the definition of the displacement thickness.

5 Conclusion

The new remote sensing based wind profile measurements provide a unique data set for validation of unsteady flow modelling over complex terrain for wind energy. Based on the analysis of the high frequency atmospheric measurements with a rapidly scanning continuous-wave Doppler lidar a relationship between the escarpment induced wake height and the wind direction could be shown.

References

[1] P.S. Jackson and J.C.R Hunt. Turbulent flow over a low hill. *Quarterly Journal of the Royal Meteorological Society*, 101:929–955, 1975.

[2] J.C.R. Hunt, S. Leibovich, and K.J. Richards. Turbulent shear flows over low hills. *Quarterly Journal of the Royal Meteorological Society*, 114:1435–1470, 1988.

[3] Fotini Katopodes Chow and Robert L. Street. Evaluation of Turbulence Closure Models for Large-Eddy Simulation over Complex Terrain: Flow over Askervein Hill. *Journal of Applied Meteorology and Climatology*, 48(5):1050–1065, May 2009.

[4] F. A. Castro, J. M. L. M. Palma, and A. Silva Lopes. Simulation of the Askervein Flow. Part 1: Reynolds Averaged Navier–Stokes Equations (ke Turbulence Model). *Boundary-Layer Meteorology*, 107(3):501–530, 2003.

[5] A. Silva Lopes, J. M. L. M. Palma, and F. A. Castro. Simulation of the Askervein flow. Part 2: Large-eddy simulations. *Boundary-Layer Meteorology*, 125(1):85–108, July 2007.

[6] B. Conan. *WindResource Assessment in Complex Terrain by Wind Tunnel Modelling.* PhD thesis, 2012.

[7] A. Bechmann, J. Berg, M.S. Courtney, H.E. Jørgensen, J. Mann, and N.N. Sørensen. The Bolund Experiment : Overview and Background Risø-R-Report. Technical Report July, 2009.

[8] J. Berg, J. Mann, A. Bechmann, M.S. Courtney, and H.E. Jørgensen. The Bolund Experiment, Part I: Flow Over a Steep, Three-Dimensional Hill. *Boundary-Layer Meteorology*, 141(2):219–243, July 2011.

[9] M. Sjöholm, N. Angelou, P. Hansen, K. H. Hansen, T. Mikkelsen, S. Haga, J.A. Silgjerd, and N. Starsmore. Two-Dimensional Rotorcraft Downwash Flow Field Measurements by Lidar-Based Wind Scanners with Agile Beam Steering. *Journal of Atmospheric and Oceanic Technology*, 31(4):930–937, April 2014.

[10] N. Angelou, J. Mann, M. Sjöholm, and M. Courtney. Direct measurement of the spectral transfer function of a laser based anemometer. *Review of Scientific Instruments*, 83(3):33111, 2012.

[11] J.O. Hinze. *Turbulence*. McGraw-Hill series in mechanical engineering, 1975. ISBN: 0070290377.

[12] S. Emeis, H.P. Frank, and F. Fiedler. Modification of air flow over an escarpment. Results from the Hjardemål experiment. *Boundary-Layer Meteorology*, 74(1-2):131–161, April 1995.

[13] K. J. Davis, N. Gamage, C. R. Hagelberg, C. Kiemle, D. H. Lenschow, and P. P. Sullivan. An Objective Method for Deriving Atmospheric Structure from Airborne Lidar Observations. *J Atmos Ocean.*, 17(11):1455–1468, November 2000.