The Tall Wind project - wind profile and boundary-layer height

S.-E. Gryning[1], E. Batchvarova[1,2], B. Brümmer[3], S. Emeis[4], L. Gulstad[5], N. Lee[6]
[1]Risoe DTU, Roskilde, Denmark, sveg@risoe.dtu.dk, [2]NIMH, Sofia, Bulgaria
[3]Hamburg University, Germany, [4]Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
[5]Vestas Wind Systems A/S, Denmark, [6]DONG Energy Power, Denmark

ABSTRACT

Predicting the wind at typical heights of to-days and future wind turbines and thus the energy potential for the new generation of wind turbines is a considerable scientific challenge. Presently applied models are accurate within the surface layer. New measurements and instrument synergies are necessary as basis for developing new wind models and understanding the physical processes that form the wind profile in order to describe the wind profile above it.

Analysis of the wind and turbulence profiles from a meteorological mast at heights up to 160 meters and wind lidars up to 300 meters at the National test station at Høvsøre, Denmark, shows deviations of the wind profile above 80 meters from the traditional profile used so far near the surface. It also reveals the importance of the boundary-layer height as a physical parameter for the description of the wind profile.

In the *Tall Wind project*, mast and lidar measurements of wind and fluxes will be combined with monitoring of the boundary-layer height by use of an aerosol lidar. At the main project monitoring sites (Høvsøre in Denmark and Hamburg in Germany) long term monitoring programmes on tall masts (160 and 300 meters) already exists and will be intensified. As part of the project the wind profile will be measured up to 1000 to 1500 meters by a wind lidar and the boundary-layer height by an aerosol lidar. The new data sets can be used for theoretical developments and evaluation of meso-scale meteorological models.

1. INTRODUCTION

Recent research at Risø-DTU suggests that the wind profile above 50-80 meters height is influenced by both the surface conditions as well as the height of the boundary layer and the conditions at the top of it. It also suggests that the parameterisation of the wind profile depends on the surface roughness in a new and not yet explored way, being different over the sea, in rural areas and over a city/forest. An instrument package is suggested within the Tall Wind project to study the wind profile and its dependence on processes at the top of the boundary layer. The instrument package is deployed at the test station for wind turbines at Høvsøre starting in April 2010 and will be in operation there for a period of about 1 year. Then the equipment will be moved to a meteorological site in Hamburg for one year. Finally, it will be used as a supplement for measurements over the sea carried out at Horns Rev 2 offshore site. Fig. 1 shows the measuring sites. The measurements will further be analysed by use of LES (large eddy simulation) modelling, mixing length theory and by the modelling performed by different industrial groups.

Figure 1. *The location of the 3 measuring sites.*

The Tall wind Project aims at:

- Providing and deploying a new “wind profiler” instrument package for wind profile research at heights up to 1000 meters and above based on a newly available commercial pulsed Lidar for wind profiles. As the boundary layer height is proved to play an essential role in the processes within the boundary layer, it will be measured by use of an aerosol lidar. Intensive measurements campaigns will be organized performing high resolution in space and time radiosonde measurements for comparison with standard methods. The instrument package will be used at sites with tall towers already instrumented with turbulence measurements.
- Carrying out measurements over surfaces with different roughness (urban, land and sea).
- Performing modelling by use of i. e. LES of the wind profile and its dependence on the boundary-layer height and parameters in the free atmosphere above the boundary layer.

This combined instrument set up will provide a unique data set for further use on scientific different topics outside the Tall Wind Project objectives.

2. RESEARCH CHALLENGES

In [1] it has been established that the wind profile over land above the surface layer (lowest 50 to 80 meters) exhibits a dependence on the boundary-layer height in such a way that the wind speed becomes larger as compared to the traditional used logarithmic wind profile, Figure 2. In [2] the effect was found to be less pronounced off-shore.

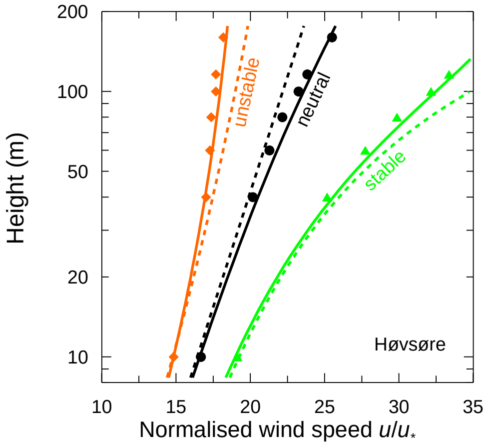


Figure 2. *Wind profile dependence on atmospheric stability and boundary-layer height. Dashed line is the traditional surface layer wind profile, the full line the parameterization of the wind profile suggested in [1] that includes the effect of the boundary-layer height, and the filled circles are measurements.*

However the dependence is only rudimentarily established and it seems that the suggested parameterisation in [1] is conservative in such a way that the deviation from the logarithmic wind profile is even larger. These new findings are based on a recent 2 months campaign at Høvsøre in January and February 2008, where the wind profile was successfully measured with a commercial pulsed Lidar (Wind Cube – WSL7 made by Leosphere) up to 300 meters.

The study of the wind profile over flat homogeneous terrain in The Tall Wind project is based on a combination of measurements, data analysis and modelling. The idea is to supplement existing long-term measurements of turbulence and wind speed at tall well instrumented meteorological masts (at Høvsøre to reflect low roughness over rural area; and at Hamburg to reflect high roughness such as urban conditions) and at Horns Rev 2 (off-shore, not instrumented with turbulence instruments). Additional measurements will address the wind profile up to 500 to 1000 meters by use of a newly developed commercial pulsed wind Lidar (WSL70). The height of the planetary boundary layer will be determined from aerosol backscatter with a new meteorological Lidar (ASL 300). Campaigns with radiosoundings will provide instantaneous measurements of the structure of the boundary layer and above. The turbulence profile measured at the tall masts will keep the link to known behavior and findings.

However, not only the height of the boundary layer is controlling the wind profile. Recent modelling studies indicate a significant dependence on the vertical temperature gradient in the atmosphere above the boundary layer (Brunt Vaisala frequency, N) and baroclinicity (horizontal temperature gradient) as discussed in [4]. The theoretical dependency is illustrated below, where L_{mbl} together with the height of the boundary layer, is the parameter that controls the shape of the wind profile. It illustrates that the shape of the wind profile depends on N in such a way that large values of N is associated with small values of L_{mbl}, it can also be observed that L_{mbl} increases for decreasing surface roughness. This dependence on N is purely theoretical at the moment however a recent analysis of data from Hamburg and Høvsøre and Horns Rev 2 ([1], [2], [3]) supports the dependence on the surface roughness.

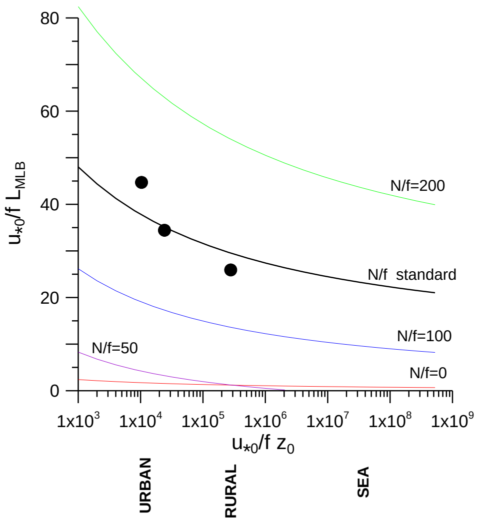


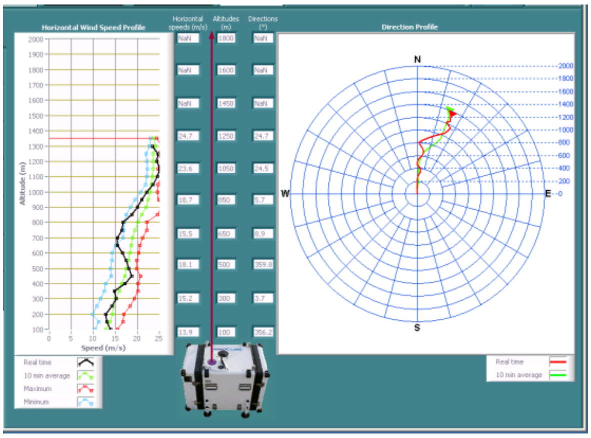
Figure 3. *Length scale L_{mbl} dependence on Brunt Vaisala frequency, N.*

The natural tool to investigate such a complex problem is to apply a modelling framework. The modelling will be performed by use of traditional mixing length theory along the lines of [1], as well as by use of LES (large eddy simulations), a relative new and very promising modelling tool. The advantage of using LES as compared to the more traditional RANS modelling (Reynold Averaged Navier-Stokes) lies in the lesser demand for the parameterizations. In a way a LES model produces most of the turbulence itself and only a small part is due to the parameterization - contrary to RANS type models. Both the mixing length and LES work can be considered state of the art.

The ultimate goal is to come up with recommendations for parameterizations for applied use of the wind profile above the surface layer as well as recommendations for the measurements and instruments requirements that can provide the necessary input for yield assessments and constitute a design load basis for wind turbines. It is realized that this is a very ambitious goal but the data set we hope to achieve will be internationally unique and an excellent basis for the research leading to better tools for the prediction of the energy yield and design basis for to-days large wind turbines.

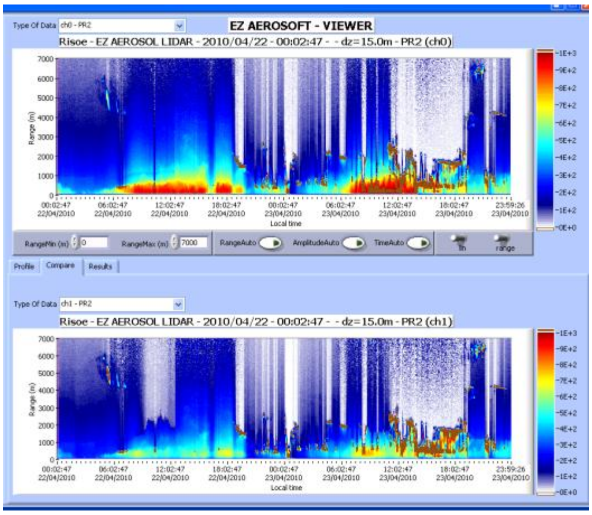
3. EXAMPLES OF MEASUREMENTS SET UP

After being tested for several months at Risoe DTU premises in Roskilde, Denmark the pulsed wind lidar (WSL70) and the aerosol lidar (ASL300) started operation in the end of April 2010 at Høvsøre Test site. In Figures 3 and 4 the regime of measurements is demonstrated.



Horizontal speeds (m/s)	Altitudes (m)	Directions (°)
NaN	1800	NaN
NaN	1600	NaN
NaN	1450	NaN
24.7	1250	24.7
23.6	1050	24.5
18.7	850	5.7
15.5	650	8.9
18.1	500	359.8
15.2	300	3.7
13.9	100	356.2

Figure 4. *Wind profile at Høvsøre (25 April 2010).*


EZ AEROSOFT - VIEWER

Type Of Data: ch0 - PR2

Risoe - EZ AEROSOL LIDAR - 2010/04/22 - 00:02:47 - - dz=15.0m - PR2 (ch0)

RangeMin (m): 0

RangeMax (m): 7000

Type Of Data: ch1 - PR2

Risoe - EZ AEROSOL LIDAR - 2010/04/22 - 00:02:47 - - dz=15.0m - PR2 (ch1)

Figure 5. *Aerosol Back scatter at Høvsøre (22-23 April 2010).*

It is clearly seen from Figures 3 and 4 that the suggested measurement strategy will serve well the purposes of the project. The wind profile lidar signal reaches in this case 1300 m but has been found to reach to 2 km during clear sky days. The aerosol lidar is depicting clearly the atmospheric boundary layer depth.

The aerosol lidar works both with polarised and no polarised beam, which allows to distinguish between spherical (water) and non spherical (ash, for example) particles. Thus, more complex structure and composition of the atmosphere are revealed and the data already now have additional value. The boundary layer is marked clearly with red and yellow colours in the non-polarised channel (upper panel in Figure 4). The appearance of the volcano ash cloud on 22 of April is recognised in the polarised signal (lower panel in Figure 4).

4. TOOLS EMPLYED IN TALL WIND PROJECT

4.1 Instruments

Aerosol Lidar for boundary-layer height determination
Traditionally the boundary-layer height was realized by techniques such as SODARS (sound detection and ranging), tethered balloons, radiosondes and ceilometers, but these techniques has severe limitations. In this project we will test and use a powerful Lidar (ASL 300) by Leosphere for measurements of the vertical aerosol distribution. The planetary boundary-layer contains most of the atmospheric aerosols. The height of the boundary layer can be taken as the height of a jump in aerosol concentration. The aerosol Lidar is designed for atmospheric boundary layer research, proving the vertical aerosol distribution up to 10 km with an adequate resolution (5 metre is possible). It is eye-safe, mobile and is thus ideal for use in boundary-layer experiments.

The company Leosphere introduced in 2006 a wind lidar named “Wind Cube” aimed at the wind energy market. The Wind Cube (WSL7) is a pulsed lidar with a fixed focus. The prism holds still whilst the lidar sends a stream of pulses (5000-10000) in a given direction, recording the backscatter in a number of range gates (fixed time delays) triggered by the end of each pulse. Having sent the required number of pulses, the prism rotates to the next azimuth angle to be scanned, each separated by 90°. A full rotation takes about 6 seconds. For the Wind Cube, the spatial measuring resolution depends on the pulse length and gate-open time and is constant with sensing range. The radial range resolution of a 1.55 μm pulsed wind Lidar with identical pulse and gate-open times (200 ns in this case) has been estimated to be about ~ 36 meters. The latest developments and improvements during 2009-2010 of the wind lidar (called WSL70) are used in this project.

4.2 Experimental sites

Existing sites will be supplemented with wind profile and boundary layer height measurements. Campaigns with releases of radiosondes will also be performed.

4.2.1 Hamburg - urban

The Hamburg site is located 5 km south-east of downtown Hamburg. Wind speed, direction and turbulence were measured with three-dimensional sonic anemometers at 50, 110 175 and 250 meter height on a TV-tower and at 12 meters height at a small mast nearby. The analysis will deal with measurements that are representative for a residential and an urban part of the city. The sector 225-330º covers the urban part of Hamburg, sectors 15-135º and 165-225º represents residential areas.

4.2.2 Høvsøre - rural

The Høvsøre site is located in a rural area near the west coast of Jutland, [1]. Towards the east the upwind land area is flat and homogeneous and the measurements are not influenced by the water west and south of the mast or the wind turbines. Profile measurements of wind speed and direction are measured up to 160 meter by cup-anemometers and wind vanes. Atmospheric turbulent fluxes of heat and momentum are obtained from three-dimensional sonic anemometers at 10, 20, 40, 60, 80, 116 and 160 meters height.

4.2.3 Horns Rev 2 offshore

The Horns Rev 2 is a new off-shore wind farm in the North-Sea that will be built and operated through DONG. In connection with the wind farm a tall platform for instruments will be erected. The platform will serve as basis for the wind and aerosol measurements by Lidars. It might even be possible, in connection with the Norsewind project, to obtain the wind profile with both a pulsed and continuous lidar.

4.3 Modelling

The measurements will form the basis for the modelling efforts. The traditional way of modeling the wind profile is based on mixing length theory. The parameters that control the mixing length are not known and the goal is to improve the existing parameterisations, such as [1]. The theory formed the basis for the famous logarithmic wind-profile, and has been applied in [1] and [3]. The theory will be further elaborated due to the new and improved measurements that will be obtained in this project. The theory is closely connected to RANS (Reynolds Averaged Navier-Stokes) modelling where the results are very depending on the parameterisations in the model. In RANS modeling the length scale is formed from parameterized quantities or it is parameterized. The RANS modelling is widespread in the meteorological and wind energy community both as a research tool as well as in applied modelling, such as CFD (small scales) and WRF (large scales).

LES is considered one of the best techniques we have today for studying turbulence processes in the boundary layer. It is based on the observation that the largest eddies are responsible for most of the turbulent transport of momentum, heat and matter, which are most important meteorological effects of PBL turbulence. In contrast, the behavior of the smaller scale eddies are generally assumed to be more independent and thus statistically similar in turbulent flows. This forms the basis for the large-eddy simulation (LES) techniques. In principle, LES allows us to examine problems that would otherwise be beyond our computing resources. It is generally believed that by choosing the computational grid spacing small enough so that the largest eddies are explicitly resolved and the net effect of the small scales on the large eddies are treated by a more or less simple parameterization (the so-called sub-grid model), the turbulent PBL flow can be described in sufficient detail and accuracy. LES can be used to perform "controlled" numerical experiments to isolate individual physical processes.

5. INTERNATIONAL AND INDUSTRY ACADEMIA COLLABORATION

Through the collaboration on the project of Hamburg University, Forschungszentrum Karlsruhe and Academy of Sciences in Bulgaria, the project is secured cooperation with very experienced experimental groups in the field of boundary-layer meteorology and on the determination of the boundary-layer height. Vestas Wind Systems A/S, Denmark, one of the biggest wind turbine producers worldwide and DONG Energy Power, Denmark, one of the main energy providers in Denmark participate the project with research and measurement platforms.

ACKNOWLEDGEMENT

The study is supported by the Danish Council for Strategic Research, Sagsnr. 2104-08-0025 and the EU FP7 Marie Curie Fellowship VSABLA.

REFERENCES

[1] Gryning, S.-E., E. Batchvarova, B. Brümmer, H. Jørgensen, S. Larsen, 2007: The extention of the wind profile over homogeneous terrain beyond the surface boundary layer, *Boundary-Layer Meteorol*., **124**, pp. 251-268.

[2] Pena A. and S.-E. Gryning, 2008: Charnock's roughness length model and non-dimensional wind profiles over the sea, *Boundary-Layer Meteorol.,* **128**, pp. 191-203.

[3] Pena A., S.-E. Gryning, C. B. Hasager, 2008: Measurements and modeling of the wind speed profile in the Marine Atmospheric Boundary Layer, *Boundary-Layer Meteorol.,* **129**, pp. 479-495.

[4] Zilitinkevich S. S., N. Esau, 2005: Resistance and heat-transfer laws for stable and neutral planetary boundary layers: old theory advanced and re-evaluated, *Quart. J. Roy. Meteorol. Soc.,* **131**, pp. 1863-1892.