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SOME CHALLENGES OF WIND MODELLING FOR MODERN WIND TURBINES: THE WEIBULL DISTRIBUTION

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ABSTRACT

Wind power assessments, as well as forecast of wind energy production, are key issues in wind energy and grid related studies. However the hub height of today's wind turbines is well above the surface layer. Wind profiles studies based on mast data show that the wind profile above the surface layer depends on the planetary boundary layer (PBL) structure and height, thus parameters that are not accounted for in today's traditional applied flow simulation models and parameterizations.

Here we report on one year of measurements of the wind profile performed by use of a long range wind lidar (WSL 70) up to a height of 600 meters with 50 meters resolution. The lidar is located at a flat coastal site.

The applicability of the WRF model to predict some of the important parameters for wind energy has been investigated. In this presentation, some general results on the ability of WRF to predict the wind profile and the turning of the wind direction with height will be touched upon, but we mainly will discuss the long term distribution of the wind speed, which is often represented by a Weibull distribution. It was found that above 100 meters both the measured scale (A) and shape (k) parameter are larger than predicted by WRF. The under prediction of scale parameter is in accordance with the general underestimation of the wind speed by WRF. The consequence for wind energy is discussed and a simple parameterization for the shape parameter is put forward.

1. SITE AND MEASUREMENTS

The measurements were carried out at the Danish National Test Station of Wind Turbines at Høvsøre, which is located at the western coast of Jutland, Fig. 1. Except for the presence of the North Sea to the west, the terrain is flat and homogeneous consisting of grass, various agricultural crops and a few shrubs. The intensively instrumented 116.5 m high reference meteorological mast is located about 1.8 km east of the coastline and south of the closest wind turbine stands. Wind speed is measured at 10, 40, 60, 80, 100, 116.5 m with Risø cup anemometers and the wind direction at 10, 60 and 100 m. with wind vanes. Observations from the 160 m top level at the nearby light tower are also used. Both the light tower and the meteorological mast are instrumented with METEK Scientific USA-1 sonic anemometers installed at heights: 10, 20, 40, 60, 80, 100 and 160 m. The three-dimensional wind speeds are measured with a frequency of 20 Hz and then reduced to 10-min statistics of linearly de-trended mean values, variances and co-variances.

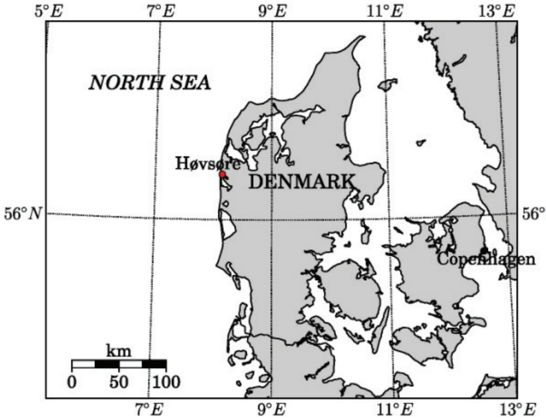

Figure 1 Geographical location of the Høvsøre site.

In addition a pulsed wind lidar (WLS70) has been operating near the meteorological mast between April 2010 and March 2011. The wind lidar is equipped with a rotating silicon prism providing an optical scanning cone of 15 degrees to zenith. The lidar scans the atmosphere at four azimuth angles separated by 90°. One 360 degree full scan (rotation) is performed about every 30 s. The wind lidars Doppler shift based measurements of the wind are available measures from 100 m above the ground and every 50 m up till 1 to 2 km height dependent on the attainable 10-min averaged Carrier to Noise (CNR) ratio. The upper measuring height is often determined by the cloud base where the lidar signal (1.55 nm) largely weaken.

2. NUMERICAL MODELLING

Wind profiles were predicted using a research real-time forecast system based on the WRF ARW model version 3.2.1, developed by the National Centre for Atmospheric Research (NCAR), [1]. It is a numerical weather prediction and atmospheric simulation system designed for both research and operational applications. Data for initial and boundary conditions come from the Final Analyses (FNL, Global Final Analysis Data) of the National Center for Environmental Prediction (NCEP, USA) global model. The physical options of model setup include the Noah land surface scheme [1] and the Thompson microphysics scheme [2]. The WRF model calculates the meteorological parameters at 41 vertical levels from the surface to pressure level 100 hPa. Eight of these levels are within the height range of 600 m that is analyzed in this study and the first model level is at 14 m.

When the model is run in analysis mode as in this study, it uses the NCEP Final Analysis (FNL) global boundary conditions that are available every 6 hours on a 1 x 1 degree grid. Two domains with a horizontal grid size of 18 and 6 km respectively are used. The simulations are initialized every 10 days at 12:00 and after a spin up of 24 hours a time series of 10 minutes simulated meteorological forecast data from 25 to 264 hours is generated. In order to prevent the model from drifting away from the large scale features of the flow, the model is nudged towards the FNL analysis. Nudging is applied for the wind, temperature and humidity above the 10th model level, which approximately corresponds to 1400 m, on the outermost model domain during the whole simulation period.

3. WEIBULL DISTRIBUTION

The long-term frequency distribution of the horizontal wind speed is often presented in the form of a two parameter Weibull distribution. This distribution has received considerable attention in relation to assessment of wind energy from meteorological observations.

The Weibull distribution of the horizontal wind speed can be expressed as:

$$\mathrm{f(u)} = \frac{\mathrm{k}}{\mathrm{A}}\left(\frac{\mathrm{u}}{\mathrm{A}}\right)^{\mathrm{k}-1} \exp\left(-\left(\frac{\mathrm{u}}{\mathrm{A}}\right)^{\mathrm{k}}\right) \tag{1}$$

where $f(u)$ is the frequency of occurrence of the wind speed u. In the Weibull distribution the scale parameter A has units of the wind speed. It is proportional to the average wind speed $\langle u \rangle$ for the entire distribution. It is related to the wind speed through:

$$\langle u \rangle = A\,\Gamma(1 + 1/k) \tag{2}$$

where Γ represents the gamma function and k is the shape parameter in the Weibull distribution: for typical wind speed distributions over homogeneous terrain k is in the range 2 to 3. For decreasing k the mode of the distribution shifts towards lower values of the wind speed at the same time as the probability for higher wind speeds increases.

From the measurements and simulations of the wind speed the A and k parameters in the Weibull distribution were derived by use of the Climate Analyst which is a part of the Wind Atlas Analysis and Application Program (WAsP).

3.1 Scale parameter

The comparison of the modeled A parameter with measurements shows similarities with the wind speed. Below 60 meters the WRF predicts well the A parameter. Above 60 meters the simulated scale parameter is gradually underestimating the measurements more and more, Fig. 2.

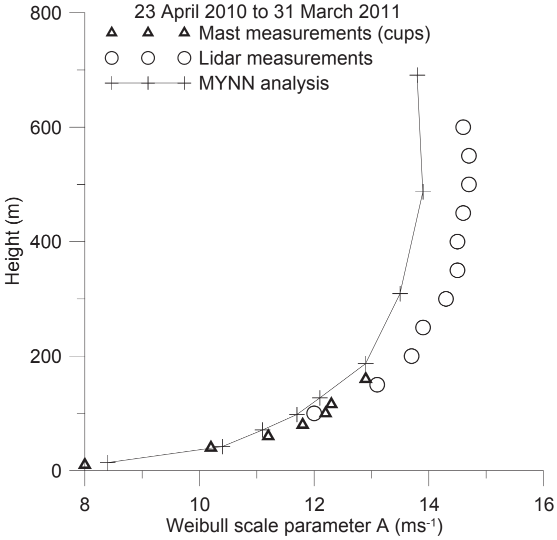

Figure 2. Profiles of the scale parameter in the Weibull distribution estimated from measurements and simulations.

3.2 Shape parameter

Contrary to the scale parameter, which has a rather smooth vertical profile, the shape parameter k has a very distinct form. Investigations over land have revealed [3] and[4] that k is controlled by 2 regimes of the atmosphere, the large-scale wind climate and the local boundary-layer. This results in a characteristic vertical profile of the shape parameter. It increases from its value near the ground up to a maximum located at around 100 to 200 meters height, in dependence of the balance between the diurnal variation of the local meteorological conditions and the variability of the synoptic conditions prevailing in the region. The height of the maximum in the k profile is associated with the height of the stable boundary-layer as well as the reversal of the wind regime that occur in stable nights where the diffusion of momentum is inhibited, resulting in low wind surface winds while the wind speed above the stable boundary-layer increases.

It is found that the WRF simulations agrees well with the measurements up to 100 meters, while above that height the model generally underestimates the k parameter. The height of the maximum in the k-profile from measurements is about 200 m while it is lower for the model simulations, being about 120m.

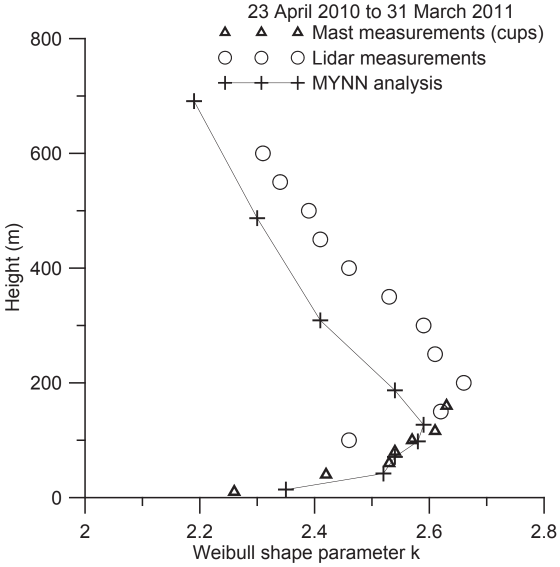

Figure 3. Profiles of the shape parameter in the Weibull distribution estimated from measurements and simulations.

3.3 Parameterization of k

Here is suggested a simple parameterization of the k-profile. Both the measurements and the modeling simulations show that the k parameter has a very distinct profile at Høvsøre. Similar profiles have been reported by [4]. The suggested relationship have 3 external parameters, the value of k in the surface layer, k_s, at a specific height z_s; the value of k in the free troposphere k_t and the height of the maximum in the k profile, z_r, sometime named the reversal height. The suggested simple parameterization for $z>=z_s$ reads:

$$k = c\,\frac{z-z_s}{z_r-z_s}\;exp\left(-\frac{z-z_s}{z_r-z_s}\right) + k_s - (k_s - k_t)\,\exp\left(-\frac{z_t}{z-z_s}\right) \qquad (3)$$

which has a maximum near z_r and will asymptotically approach the value of k_t in the upper part of the planetary boundary layer. The best fit value of c is near one, that of z_t is around 1000 meters and likely connected to the height of the convective boundary layer and the values of k_t is around 2, see Table 1. The application of the suggested parameterization is shown in Fig. 4.

Near the surface and well below z_r, the k-profile is almost linear, therefore for $z<z_s$ it is suggested to apply linear extrapolation. The derivative of the expression for the k profile reads:

$$\frac{dk}{dz} = c\,\frac{z_r - z}{(z_r - z_s)^2}\,exp\left(-\frac{z - z_s}{zr - zs}\right) \qquad (4)$$

where the right hand side of Eq. (3), the part dealing with the tropospheric adaption, has been neglected.

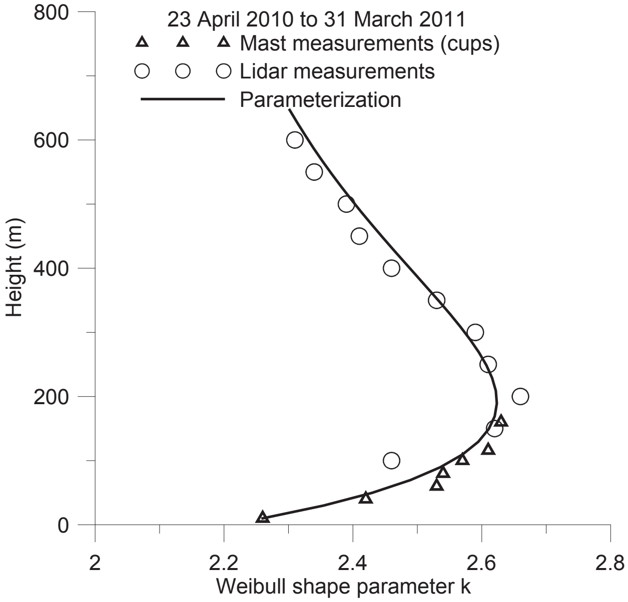

Figure 4. Measured k profile and the suggested parameterization in Equation (3). The parameterization is plottet for z_s=10 meter where k_s in this case can be seen to be 2.26, z_r=200 m and z_t is taken as 1000 m with k_t=2.

Table 2. Values of the parameters in Equation. (3) determined from the measurements.

c	k_t	z_r	z_t
1.0	2.0	200	1000

4. DISCUSSION

In this study a full year of measurements of the wind profile performed at a coastal site in a windy climate has been analyzed and compared to a simulations carried out with the WRF model. The measurements were carried out with a novel wind lidar that permitted wind profiles up to 2 km in favorable conditions in combination with a tall meteorological mast. Reference [5] found very good agreement with wind speed measurements carried out a with cup anemometer at 100 meters height and simultaneous wind lidar observations. The agreement deteriorates as the signal to noise become worse. A CNR ratio of -22 dB was found to be a fair compromise between the need for high quality measurements and a good height coverage of the wind profile. By filtering the observations with this CNR value and allowing for a number of technical problems resulted in data coverage of 31% where the missing data are distributed over the whole year. The wind rose from the wind lidar indicated predominantly westerly winds, i.e. from the sea.

The dominance of westerly winds has as consequence that the results from the analysis are influenced by the internal boundary-layer that forms downwind of the abrupt change between sea and land. The height of the internal boundary layer is typical 100 meters at the measuring site, it is shallower in stable conditions and higher at unstable atmospheric conditions [6] and thus comparable to the height of the maximum in the shape parameter in the Weibull distribution.

In this study the focus is on the wind profile and its Weibull distribution. Performing a WRF simulation requires a choice among the many parameterizations that are available in the WRF package. Presently there does not exists a generally accepted set of parameterizations for overall use, but the literature is still at a stage where specific set-up's is suggested in dependence of the climatic region and the specific parameters that the user wishes to model.

Other modeling aspects such as surface roughness, atmospheric stability and enhanced diffusion in the surface layer are discussed in [7]. Additional aspects rarely dealt although important for many practical applications are eddy diffusivity, turbulence kinetic energy, mixing length, temperature profiles and boundary-layer height just to mention a few [8].

The 1.5 order closure MYNN PBL scheme was used in this study and it was found that the WRF simulation predicts the general profile of the shape parameter quite well although it underestimates its value. It can be mentioned that the first order closure YSU PBL scheme is unable to predict the characteristic profile of the shape parameter, but this aspect is not shown here.

5. OUTLOOK

In the Tall Wind project one year data-sets of wind and aerosol profiles were created from measurements by remote sensing instruments and instrumented tall meteorological masts for two sites - Høvsøre in Denmark and Hamburg in Germany. The data are available for the COST ES0702 community through the participation of several Tall Wind project partners in EG-CLIMET. COST Action ES0702 aims at operational use of remote sensing technology in weather and climate models and all related applications. The present study is related to the evaluation of meso-scale models wind profile against long range wind lidar data at one of the sites. The outcome is important for the use of meso-scale models in wind climate applications and the downscaling studies on wind power potential.

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