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“Tall” wind profiles and related issues

Mark Kelly*, Sven-Erik Gryning, Ib Troen, Andrea Hahmann, Rogier Floors

Meteorology Group, Wind Energy Division, Risoe DTU

Frederiksbergvej 399, P.O. Box 49--Building 125, Roskilde 4000

**corresponding author*: mkel@risoe.dtu.dk ; tel.(+45) 4677 5020 , fax(+45)4677 5083

Summary

Recent progress in the theoretical extension and application of models for "tall" wind profiles, as well as re-evaluation of accepted atmospheric surface-layer parameterizations, have both clarified the need for various research-grade data to further evaluate and develop current wind models; they also highlight the need for scrutiny of commonly-used models' limits. We elucidate some current needs and progress in extended wind profile modelling within the context of various contemporary wind models. The final emphasis is upon the use of measurements to drive tall-wind predictions, as well as to facilitate the development and mutual use of mesoscale and microscale models.

Introduction

The increase in wind turbine hub heights has led to a greater need to characterize the wind field well beyond the atmospheric surface layer, for reasons including estimation of production and loads. Typically wind siting engineers obtain wind speed and direction statistics at some height(s) below hub height, as well as a surface description. But obtaining relevant long-term wind statistics for heights above 80–100 m based on measurements below these heights—in order to more reliably estimate the production for today’s tall turbines—one needs to account for phenomena other than surface effects.

Finite extent of the Atmospheric Boundary Layer

The atmospheric boundary layer (ABL) is the turbulent portion of the atmosphere in contact with the surface, which extends to some spatially and temporally varying height above which the flow tends to be non-turbulent.[1] Typical ABL depths can vary from roughly 100 m (e.g. night, winter) to 1–2 km (e.g. sunny day over land). A number of physical mechanisms and processes can influence the wind statistics and their vertical profile in the upper ABL; among these are the temperature profile characterizing the ABL “top” and environment above, shear instability, gravity waves, entrainment (clouds), low-level jets, baroclinic shear, and the time-varying finite extent of the ABL itself—which is influenced by the surface. For example, the influence of baroclinity, that is the geostrophic wind shear caused by large-scale horizontal temperature gradients (over tens of km), is seen in Figure 1. The figure displays dimensionless wind profiles measured by tall tower and LIDAR at the Høvsøre test station on the west coast of Denmark for 6 months, grouped by baroclinity computed from corresponding runs of the mesoscale model WRF; note the different mean wind profiles and shears corresponding to each baroclinic class.

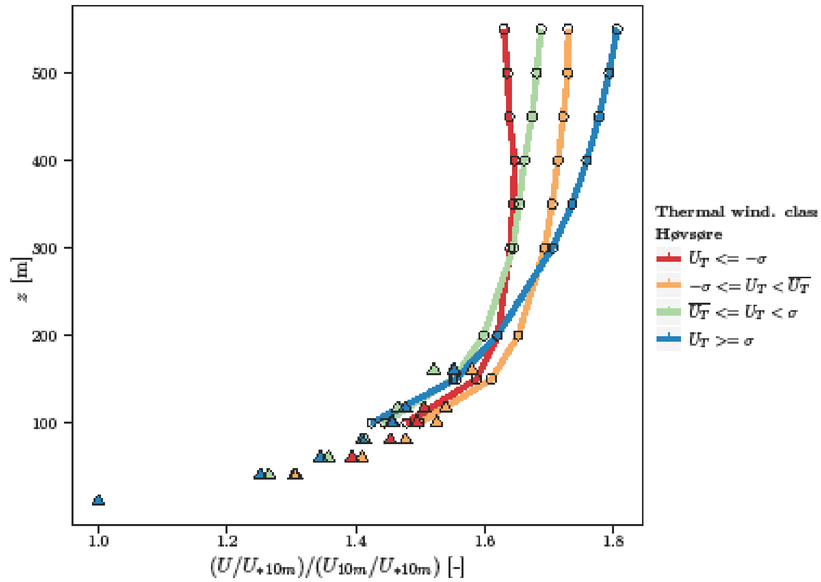

Figure 1: Observed mean wind profile at Høvsøre (triangles from mast, circles are LIDAR), broken into baroclinity classes taken from corresponding WRF runs.

The ABL top and upper-ABL phenomena mentioned above can impact turbines in a number of ways. Large (or negative) shear and greater shear variability tend to become more common at heights approaching the minimum ABL depth, as seen in Figure 2 for recent observations taken from 60 and 116.5 m at Høvsøre. At this coastal location the ABL depth can often drop below 150 m, particularly in winter; as a consequence, the shear exponent exceeds the accepted IEC-61400-1 value during most of the 4 days shown in the figure. The wind also tends to turn in the upper ABL, affecting turbines via directional shear. As seen in Figure 3, which shows the wind directions at Høvsøre for 60 m and 100 m during the last day of data shown in Figure 2, differences of 20–30° or more can persist for hours across a relatively small (40 m) rotor. The presence of the ABL top further affects the amplitudes of turbulent fluctuations and fluxes, alters the length scales inherent in the wind profile and turbulence, as well as the three-dimensional turbulent structure (i.e. cross-spectra). Thus the ABL top generally changes the wind distribution and power density, as well as expected loads and fatigue.

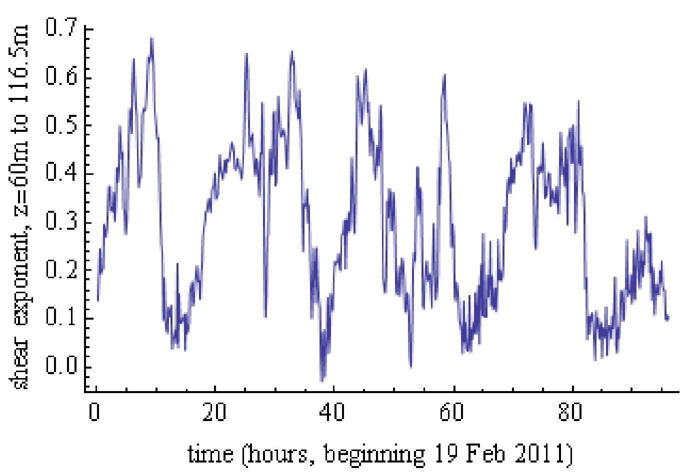

Figure 2: Observed shear exponent from 60–116.5 m at Høvsøre for 19–22 Feb 2011.

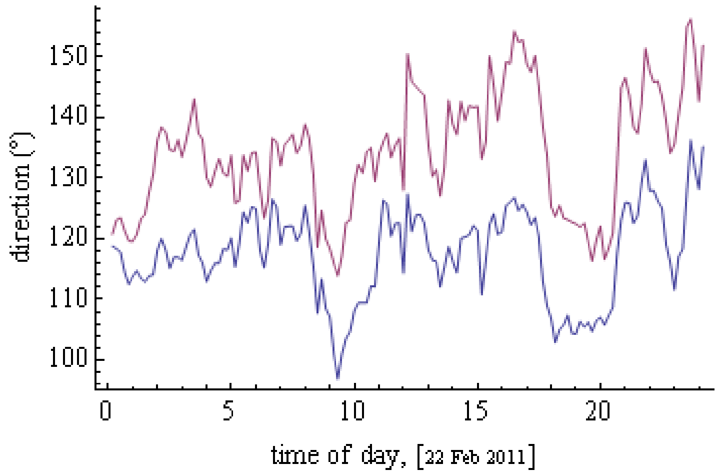

Figure 3: Observed wind directions at 60 m (magenta) and 100 m (blue) at Høvsøre, corresponding to final 24 hours of Figure 2.

Modelling issues

Because there are generally insufficient measurements taken above 100 m for most wind projects, and due to the non-trivial combination of top-down processes at play in the upper ABL as outlined above, wind engineers are increasingly turning to computational models—with limited or no local observations—in order to estimate the wind resource for taller turbines. The two methods most commonly used today in this context are mesoscale (numerical weather prediction) models and microscale computational fluid dynamics (CFD) models.

As of 2011 the CFD models used in the wind industry are generally limited to be Reynolds-averaged Navier-Stokes (RANS) models, which solve the mean fluid equations and parameterize the mean turbulence in a domain extending a few tens of kilometers. A small number of these RANS models account for the effects of stability, and even fewer incorporate measured winds. These limitations having been stated, more importantly RANS models for wind do not (yet) include the ABL depth or its effects[†]. Further, due in part to resource limitations (computational/time), RANS models used for wind generally do not include realistic variable forcing—in nature the horizontal pressure gradients which drive the ABL vary in both space and in time [1]. In addition, the turbulence parameterizations used by wind-industry RANS are limited in effect to a single characteristic length scale (see e.g. [3]), which limits their ability to treat turbulence interacting with complex terrain (or with modelled turbines). Another feature lacking from CFD applied to wind is

[†] with one partial exception, which unfortunately does not fully treat surface heat fluxes, but does include an above-ABL temperature gradient [2]

the interaction between scales larger and smaller than the domain, and such RANS models do not account for larger-scale effects such as baroclinic shear.

Mesoscale models, on the other hand, do a good job capturing phenomena such as baroclinic shear and the variable pressure gradients which drive ABL winds. However, mesoscale models are limited to effective resolutions on the order of 5–20 km (~5–7 times the grid spacing [4]), and must parameterize all motions and physics at scales smaller than this. Moreover mesoscale models are typically configured to employ planetary boundary layer (PBL) schemes to parameterize ABL- and surface fluxes, doing so in a reduced-dimensional manner (i.e. not 3-D). The schemes give ABL heights and behaviour which are not necessarily physically representative, but which are tuned to give reliable results for weather prediction; they possess restricted capability in reproducing statistics associated with the ABL top. Common PBL schemes are not optimized for wind prediction, and can give unrepresentative stability and surface interactions that affect wind profiles and distributions—and hence wind power estimates—more adversely than they affect other fields important for weather prediction. An example of this is given in Figure 4, which displays the distribution of shear exponent (from10-60m) predicted by the mesoscale model WRF using the most popular PBL scheme (YSU, [9]) at a resolution of 2 km, versus observations over a one month period at the Høvsøre test station on the western Danish coast. The figure starkly demonstrates mesoscale predictions of shear exponents that appear to satisfy the IEC standard, in contrast to the observations which show significant violation of the standard.

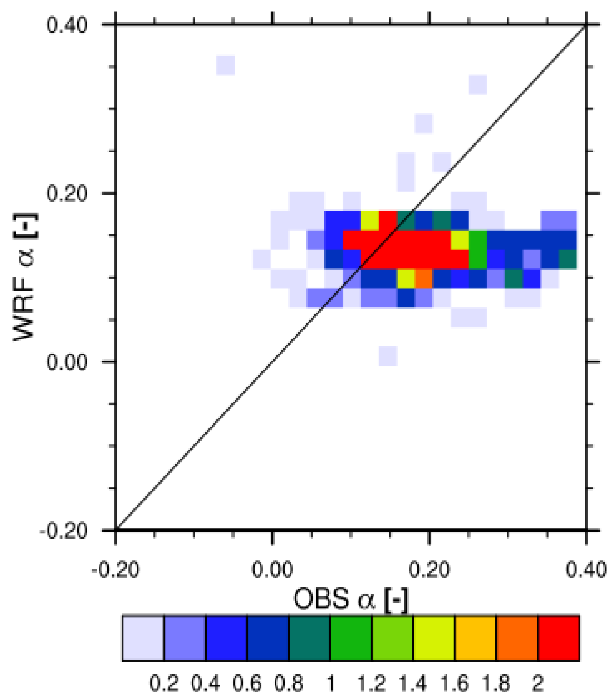

Figure 4: Distributions of shear exponent from WRF, using popular PBL scheme, vs. observed distribution at site on western Danish coast.

Applied modelling for wind energy: profiles driven by observations

Given that a number of physical mechanisms contribute in a complex and highly variable (and interacting) way to the upper-ABL flow field, and given the inability of mesoscale and RANS wind models to reliably characterize these mechanisms and their statistical effect upon the modelled wind beyond the atmospheric surface layer, it is reasonable to build upon observation-driven modelling which produces appropriate wind statistics in the lower ABL. By incorporating representative estimated statistics of relevant upper-ABL processes along with measured statistics below, we can produce wind statistics applicable for tall turbines.

Surface-layer similarity theory for wind profiles has recently been adapted for long-term wind statistics [5], including a framework which adapts a model [6] accounting for ABL depth. A sample application of such a model can be found in Figure 5, which shows the observed dimensionless wind profile at the Høvsøre mast for a 4-year period, the profile modelled via conventional surface-layer theory using mean stability, and the "tall" model (green) where the effective mean boundary layer depth is taken into account plus the long-term mean stability based on sonic anemometer (heat and momentum flux) measurements. Note the classic theory using a mean stability fails even in the surface layer, because long-term *variations* in stability dominate. The long-term baroclinity has not been accounted for here, but an expression for the wind profile including the effective mean baroclinic shear has been derived after [5] and is given by

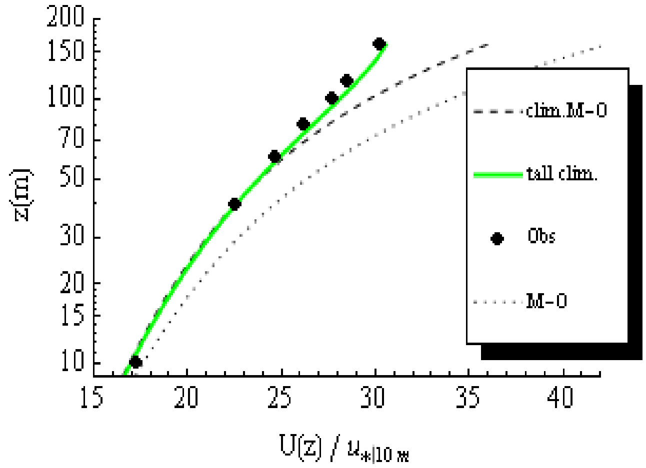

Figure 5: Dimensionless mean wind profile at Høvsøre over 4-year period. Dotted line is standard similarity theory, dashes are adapted surface-layer theory, green line is adapted tall theory [5], black dots are observations.

$$\left\langle \frac{kU}{u_{*0}} \right\rangle = \ln\left(\frac{z}{z_{0m}}\right) - \langle\psi\rangle(z) - \frac{z}{h_{\mathrm{eff}}}\left[\overline{\langle\psi\rangle_z} - \langle\psi\rangle(z)\right] + \frac{h_{\mathrm{eff}}}{2\ell_{\mathrm{mid}}^{\mathrm{eff}}}\left[1-\left(1-\frac{z}{h_{\mathrm{eff}}}\right)^2\right] + \frac{z}{h_{\mathrm{eff}}}\left(\langle s\rangle - 1\right)$$

where s is the dimensionless baroclinic shear and angle brackets denote long-term mean values; the climatological values of roughness, ABL depth and matching scale $\{z_{0m}, h_{\mathrm{eff}}, \ell_{\mathrm{eff}}\}$ are given in [5]. At Høvsøre the effective long-term mean dimensionless baroclinity is close to 1, and does not have a large effect.

The tall profile model presented above is amenable for use with linearized flow models which account the effect of terrain and roughness variations on the mean flow, but more information is needed in order to obtain wind statistics. In order to predict the 2-parameter Weibull distribution of wind speeds—and the vertical variation of these two parameters—it is necessary to have the profile of the long-term variance (or another moment) of wind speed. Thus a model for the climatological wind variance profile is necessitated, including physically-based statistical dependences upon relevant variations in representative upper-ABL and surface quantities.

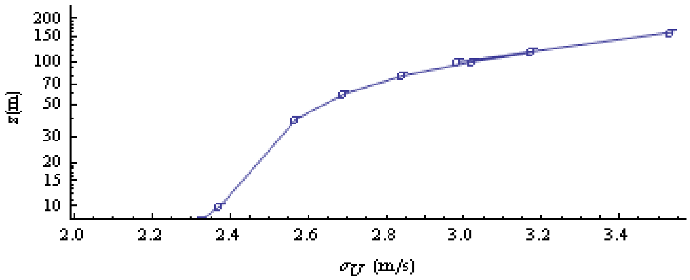

Figure 6: Long-term rms wind speed profile corresponding to Fig. 5.

An example of measured and modelled tall wind variance profiles is shown in Figure 6 (as long-term standard-deviation of 10-minute winds), and together with the long-term mean wind profile this leads to the Weibull shape parameter (k) as shown in Figure 7; this in turn allows estimation of profile of wind power density.

That is, observed and/or estimated low-order statistics of stability (surface heat and momentum flux), ABL depth, and baroclinity allow observation-based modelling of the profiles of long-term wind speed and wind variance, which together allow calculation of the vertical profile of Weibull parameters. This method is amenable to statistically adapted flow models which allow perturbations of the wind statistics due to roughness and terrain variations, and has been implemented in WAsP (following [7]).

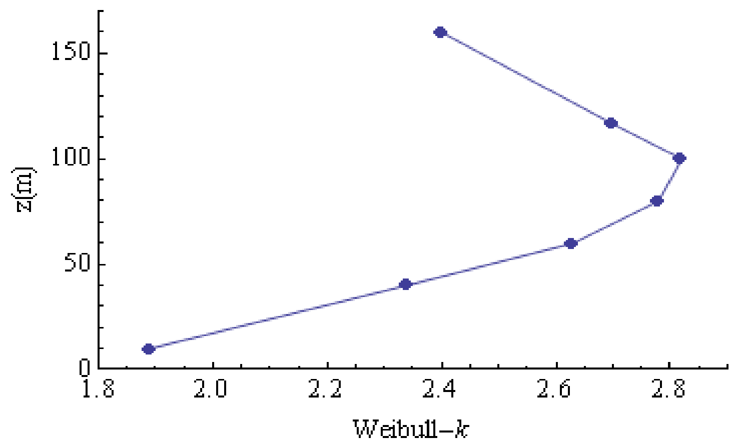

Figure 7: Long-term observed profile of Weibull-k (shape) parameter, corresponding to Figs. 5-6.

For tall profiles, the shortcomings of linearized microscale flow models—such as WAsP—is less of a problem than near the surface, particularly because we are considering heights over 100 m, above classically estimated mixing depths (~60-80 m) where flow recirculation is not an issue. There will be problems in areas where the heights are comparable to the terrain variation scales, and in complex terrain there can be issues with obtaining representative surface fluxes. The tall-profile theory works best with measured near-surface vertical fluxes (i.e. with a sonic anemometer), and work is now underway to exploit estimated distributions of boundary layer depth, since ABL depth is not often measured and cannot be reliably obtained from mesoscale models. Baroclinity tends to become a greater issue above 150 m, and use of mesoscale models is allowing estimation of its distribution for tall-wind parameterization.

Conclusions

Due to the complexity of multiple phenomena associated with the top of the atmospheric boundary layer (ABL) and large-scale mechanisms operating above, and the inability of both microscale CFD and mesoscale models to capture the relevant physics affecting the flow field near the ABL top, using these models alone without direct use of observations results in significant uncertainty and error in wind predictions above 80–100 m. Thus we have a developed a “tall profile” model which uses measured wind statistics—plus statistics representative of the non-surface phenomena that impact the flow field in the upper-ABL—to give wind statistical profiles which allow better calculation of wind power at heights more than ~100 m above surface level. The tall-profile formalism is made in conjunction with (implemented alongside) linearized flow models (WAsP) which calculate perturbed wind statistics based on measured winds and terrain descriptions.

Mesoscale models and their PBL schemes are currently being optimized for wind, but caution is presently advised for their use alone. The tall wind model can benefit from mesoscale studies which provide estimates of e.g. baroclinity, but we remind the reader that downscaling is needed in order to use mesoscale results in either RANS or linearized microscale models [8]. Microscale RANS models offer improvements over linearized models in complex terrain and some RANS include atmospheric stability to various extents, but they need to include ABL depth and/or more realistic forcing in order to produce usable tall wind statistics for many locations. There is a need for more long-term wind data above the atmospheric surface layer as well as near-surface fluxes, both for improvement and development of all three kinds of models (mesoscale, linearized 'tall' flow models, and CFD), as well as for model validation studies and direct use in tall turbine projects. The use of LIDAR greatly helps this cause, and long-term (multi-year) LIDAR measurements are now mounting. Research is underway to both couple meso- and microscale modelling as well as systematically connect results from each in a general way; in practice, mutual use of mesoscale and both kinds of microscale models is recommended for sites where doubts exist.

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