Abstract:
The new generation of turbines are reaching into heights where measurements rarely are performed. In this paper, we take a look at the vertical profiles along two high meteorology masts, the one at Risø with 125 m, and the one at Falkenberg, 99 m high. Special emphasis is given the stability situation, which is a parameter where WAsP, the standard package for wind resource estimation, can be adjusted for different wind shear situations.

The study starts with an introduction to WAsP and the way it treats the vertical extrapolation, under special consideration of the stability. The two parameters available for changing the stability treatment in WAsP are identified as RMS heat flux and offset heat flux. Measured heat fluxes from the masts were used to extract data sets with different stability. These data sets were then run through the Observed Wind Climate Wizard (part of the WAsP package), resulting in Weibull fits to the data. Using these observed wind climates, the quality of the cross-predictions is assessed, systematically varying the two heat flux parameters in WAsP.

Another emphasis is put on situations with abrupt changes in the wind profile. Such situations can occur when a stable boundary layer is lower than the mast, causing the wind regime at the upper measuring level of the mast to be decoupled from the regime near the ground.

Keywords: Profile, shear, WAsP, stability.

1 Background

Since the advent of the European Wind Atlas method and its incarnation in the WAsP program in 1989 [1], wind turbines have grown significantly. A standard wind turbine in 1989 was 225-300 kW with a hub height of ca 30 m a.g.l. During recent years turbines especially in low-wind regions like the German Binnenland kept growing towards the 100-m mark. The WAsP method is built on the assumption that the wind speed grows logarithmically with height (see chapter 2). However, this assumption is based on boundary layer theory, which is strictly valid only within the surface boundary layer and becomes dubious outside. Actual measurements in these heights are only available from few sources, since it is very expensive to run a meteorological mast of 100 metres or more for many years. One such analysis has been done by Focken [2], which led to the conclusion that a translation of the wind speeds from 10 or 40 m a.g.l. to 80 m works nicely, if the stability effects are treated according to Monin-Obukhov theory, while the theory broke down trying to forecast wind speeds in 140 m.

Nonetheless, WAsP has been used in many projects, including some with very high turbine towers. The problem is somewhat alleviated by the fact that higher masts are a commodity item now, so measuring at more than 10 m (say, over 40 m) is not as expensive as it used to be. Nevertheless, often the extrapolation from the standard WMO measuring height of 10 m a.g.l. is still used for the wind resource study.

Our first work on the topic was triggered by a completely different problem. For a project on the nightly sound immission from wind turbines, the Landesumweltamt Brandenburg needed an assessment of the treatment of stability in the standard package for wind resource estimation, WAsP. Risø did an assessment of the vertical profiles in WAsP and the treatment of stability therein, under special consideration of the nightly situation. Now, we have broadened the focus of the study and present the results here.

Four years worth of data from the meteorological mast at Risø, as well as one year of data from the Falkenberg site in Germany are used for the identification of the ideal WAsP parameter settings for stable conditions. To this aim, the measured heat fluxes from the masts were used to extract three data sets with successively higher stability in four different heights. These data sets were then run through the Observed Wind Climate Wizard (part of the WAsP package), resulting in Weibull fits to the data. Using these observed wind climates, a prediction of the highest wind climate using the lowest wind climate under stable conditions is undertaken and compared with the measured data set. To expand on this study, a systematic variation of the two heat flux parameters is done, finding the parameters yielding the lowest
overall errors for the predictions. In the last part, we do an analysis of how important this is at all. Here, we investigate the potential for the stable boundary layer to come in between the 10 m level and the hub height, together with the frequency of occurrence.

2 The stability parameters in WAsP

2.1 Boundary layer theory in WAsP

The relations describing the vertical wind profile in neutral conditions within the boundary layer are:

the logarithmic wind profile law

\[ u = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) \]  

(1)

the Geostrophic drag law

\[ G = \sqrt{\ln \left( \frac{u_*}{\sqrt{f}z_0} \right)^2 + B^2} \]  

(2)

and the simplified Geostrophic drag law

\[ u_* = \frac{0.5G}{\ln \left( \frac{G}{\sqrt{f}z_0} \right) - A} \]  

(3)

The notation is:

\( G \) Geostrophic wind [m/s]
\( u_* \) friction velocity [m/s]
\( z_0 \) surface roughness [m]
\( f \) Coriolis' parameter [1/s],
\( \kappa \) von Karman's constant,
\( A \) empirical constant, \( A = 1.8 \)
\( B \) empirical constant, \( B = 4.5 \)

Following the method outlined in the European Wind Atlas we determine the height of minimum response to stability effects

\[ \frac{z_m}{z_0} \approx \alpha \left( \frac{G}{\sqrt{f}z_0} \right)^{\beta} \]  

(4)

using the empirical constants \( \alpha = 0.002 \) and \( \beta = 0.9 \). At this height the wind-speed offset relative to neutral condition is estimated by

\[ \frac{\Delta u(z_m)}{u_0(z_m)} = \frac{\Delta u_*}{u_*} - \frac{\psi(\zeta_{off}) + \psi(0.6\zeta_{rms})}{\ln(z_m/z_0)} \]  

(5)

The first term on the right-hand side accounts for the stability effect on the friction velocity. This is estimated by

\[ \frac{\Delta u_*}{u_*} = \frac{c g}{|f|T \alpha \rho G^2} \Delta H_{off} \]  

(6)

where \( c \) is an empirical constant \( c = 2.5 \), \( g \) is gravitational acceleration [m/s²], \( T \) is absolute temperature [K], \( \rho \) is air density [kg/m³], \( c_p \) is air heat capacity [kJ/kgK], and \( H_{off} \) is the average surface heat flux [W/m²]. The second term on the right-hand side accounts for the stability effect on the vertical wind profile. This is expressed by an empirical stability correction function \( \psi(z_m/L) \) where \( L \) is the Obukhov stability parameter and \( z_m \) is the height of minimum stability variability. The purpose of the last term is to include a bias induced by an asymmetric response of the heat-flux variability. The 'form factor' 0.6 is empirical. The heat-flux statistics in Table 1 is suggested to be representative for Europe.

<table>
<thead>
<tr>
<th>Table 1: Mean and standard deviation of surface heat flux.</th>
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<tr>
<td>Over land</td>
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<tr>
<td>( H_{eff} = -40 ) W / m²</td>
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<tr>
<td>( \Delta H_{rms} = 100 ) W / m²</td>
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Next step in the procedure is to evaluate the stability correction at heights other than \( z_m \). This is done by

\[ \frac{u(z)}{u_0(z)} = 1 + \frac{\Delta u(z_m)}{u_0(z_m)} \left[ 1 - F(z) \right] + \frac{\Delta u_{off}}{u_0} \]  

(7)

for the average wind speed. The corrections are based on the following height dependence:

\[ F(z) = 1 - \frac{z \ln(z_m/z_0)}{z_m \ln(z/z_0)} \]  

(8)

These equations introduce stability-induced effects into the statistics for an ideal wind climate with neutral stability. The translation from one set of stability-perturbed wind statistics to another is based on ratios of these formulae derived with two sets stability conditions, observation heights and surface roughness.
2.2 The Risø mast data

The mast is situated at the Risø peninsula, Figure 1 (55.695° N, 12.089° E). At the western tip of the peninsula the coast forms a rather steep slope which rises to about 10 m above sea level. The western half of the peninsula is gently rolling land with the 117-m meteorological tower erected on a 6-m hill. East of the mast is a meadow, and to the south a shallow bay. Figure 2 shows a picture of the mast taken from a position indicated by the cross on Figure 1.

Data from the period 24 July 1998 to 31 December 2001 are used in this study. The analysis is based on half hourly averages and sorted with respect to the measured heat flux into three sub-sets:
1. all stable data corresponding to a negative heat flux (8635 data points)
2. data with a heat flux less than -10 W/m² (2993 data points) and
3. data with a heat flux less than -20 W/m² (848 data points).

Standard instrumentation of the Risø mast:
- Wind speed at 44.2, 76.6 and 125.2 m. (cup anemometers)
- Wind direction 76.5 and 125.2 m. (wind vanes)
- Temperature 2.5, 44.1 and 117.7 m.

Additional measurements performed since summer 1998:
- fluxes at 60 metres height (Kaijo Denki ultrasonic anemometer).

Figure 2: View of the 117 meters high meteorological mast at Risø and the surrounding area. The mast is on a 6-meter high hill. The picture is taken looking towards northwest.
higher, full generation of the turbine in stable conditions is a relatively rare event. Since according to equation (1) the wind speed increases with height, the percentage of wind speeds over 12 m/s in hub height is larger than shown here for 60 m a.g.l. The distribution of the daily variation for all measurements and for heat flux smaller than -10 and -20 W/m² respectively are shown in Figure 4. As is expected, most stable cases occur at night, the more stable ones even more so.

![Figure 4: Percentage of measurements as function of time of day for all stable cases (black line), heat flux less than -10 W/m² (red line) and heat flux less than -20 W/m² (blue line).](image)

2.3 The Falkenberg data

Considering the empirical nature of this investigation, it is very fortunate that the German Weather Service operate a site devoted for meteorological experiments centrally located in the flat area of the State Brandenburg, at Lindenberg. The measurements include long term climatological measurements of the main meteorological variables at the Lindenberg Meteorological Observatory and at the agricultural field site near Falkenberg (5 km south of the observatory, 52.1672°N, 14.1234°E).

The land-use of the Lindenberg area is dominated by forests (42 %) and agricultural fields (41 %), lakes (6.5 %), meadows (5 %), villages (3.5 %) and others (2 %). The area exhibits a moraine landscape with heights above sea level between 40 m (Spree river) and 120 m (north-eastern part), which is typical for large parts of the region south of the Baltic Sea between the Elbe river and Russia.

The main idea is to base the analysis on data from the Falkenberg site. This site is very well instrumented and all measurements of importance for this study are performed. A number of other parameters are measured as well at the Falkenberg site. The relevant parameters for the present study are performed at three measuring set-ups. They are:

- **12 meter mast**: wind speed at 0.25, 0.5, 1, 2, 4, 6, 8, 10 and 12 meters wind direction at 12.5 metre Temperature 0.5, 1, 2, 4 and 10 metres
- **99 meter mast**: wind speed at 10, 20, 40, 60, 80 and 98.5 meters wind direction at 40 and 98.5 metres Temperature 10, 20, 40, 60, 80, 98.5 metres

Furthermore the turbulent fluxes of momentum and sensible heat is measured with an ultrasonic anemometer at a height of 2.4 metre.

We were using wind speed and direction data, plus heat flux measurements from the sonic in 2.5 m a.g.l., from all of 2001.

Heat flux classes:
- Unstable: H > 25 W/m²
- Neutral: -5 < H < 25 W/m²
- Stable: -20 < H < -10 W/m² (for winds with even stronger negative heat fluxes, not enough well-distributed data was available).

![Figure 5: The meteorology mast at Falkenberg/North-Eastern Germany. The immediate surroundings are flat and grassland. In the background the forest can be seen. This combination of forest and agricultural land is very typical for the region.](image)
3 Results

The latest version of WASP (8.0 and upwards) can be run with varying parameters directly from MS Excel (see screenshot in Figure 6). This scripting was used to crosspredict the wind speeds from the various measured heights, while systematically varying the offset and RMS heat flux. This is to say, the 98-m wind was forecasted using the 10-m and 40-m wind speeds, systematically varying the heat flux parameters. Thereafter, this is done for the other combinations of heights as well. As error criterion, the mean of the squared deviations of all predictions from the measured power density was used:

\[
Error = \sqrt{\sum \left(1 - \frac{PD_{pred}}{PD_{meas}}\right)^2}
\]  

(Eq 9)

In Figure 7-9, the prediction error measure (Eq 9) is shown versus the offset (front axis) and RMS (side axis) heat fluxes, varied in WASP. The parameter variations shown here are for Falkenberg.

The main variation in the result comes from the offset heat flux. The variation of the RMS heat flux has only little influence. The default offset heat flux on land in WASP is -40 W/m², which is considered slightly stable, and therewith biased towards negative heat fluxes. It does not represent the measured heat flux accurately. Rather, for measured stable cases, the parameter has to be set even further negative. The results here indicate values between -60 W/m² for the Lindenberg mast and -85 W/m² for the Risø mast. The best offset heat flux for neutral cases was found to be -30 W/m², while all unstable cases showed good results using an offset heat flux of 0 W/m².
Two main results can be seen from these tables:

- the $\Delta H_{\text{rms}}$ should be lower than the default of 100 W/m², and
- the optimal $\Delta H_{\text{eff}}$ decreases with decreasing heat flux.

The best performing $\Delta H_{\text{rms}}$ for strictly stable cases was found to be in the order of 10 W/m². This is obvious, since the variation in stability of the initial data set is also strongly reduced.

The reduction of $\Delta H_{\text{eff}}$ with reduced measured heat flux also sounds obvious, but the magnitude is not. WASP as such calculates slightly stable, using $\Delta H_{\text{eff}}$ equals -40 W/m² as default. Therefore, to achieve strongly stable parameterisation of the wind profile, the value has to be lower than the default.

Our findings are that for data cut off at -20 W/m² measured heat flux and lower, the $\Delta H_{\text{eff}}$ in WASP has to be set in the vicinity of -100 W/m².

4 The Applicability of the Corrections

The WASP model should not be applied in situations with an abrupt change in the wind profile. Such situations occur when the boundary layer is lower than the mast, such that the wind regime at the lower level is decoupled from the upper level. This rarely happens during daytime where the convective boundary layer typically reaches 1 km or more, but the situation is likely to occur in the night-time, stable atmosphere, because the height of the stable boundary layer, $h_{\text{stb}}$, is much lower than its daytime counterpart, and can be as low as a few tens of metres. This problem naturally occurs more frequently when extrapolating from lower measuring heights, such as the standard height for meteorological observations of 10 m a.g.l.

We investigated the frequency of occurrence and the effect on the wind when the lower level wind régime can be considered as decoupled from the wind regime at the upper level, rendering the WASP approach inappropriate. For the investigation we used measurements from the meteorological mast at the Falkenberg site for the year 2001. The height of the stable boundary layer is not a part of the data-set from Falkenberg, it therefore was modelled. There exists a multitude of models for the height of the stable boundary layer, with associated multitude of empirical constants. Here we have chosen a widely used, generally accepted and physically transparent form [3]:

$$h_{\text{stb}} = 0.35 \frac{u_* L}{|f|}$$ (10)

where $u_*$ is the friction velocity, $L$ the Obukhov length and $f$ the Coriolis parameter.

Actually, this relationship models the boundary layer and not the surface layer height, which is where, strictly speaking, the logarithmic wind speed profile is valid. However, we deal here with the more serious case of complete decoupling between the boundary layer and the upper air. Here, we do not deal with the validity of the logarithmic approximation within the boundary layer itself.

Figure 10 shows the directional shear between 10 and 98 metres at the meteorological mast at the Falkenberg site during nighttime as function of $h_{\text{stb}}$. It can bee seen that for $h_{\text{stb}} > 100$ metres, signifying that both the 98 and 10 metres levels are imbedded into the stable boundary layer, the directional shear is small, only about 10 to 20 degrees. For $h_{\text{stb}} < 100$ metres the directional shear increases sharply, suggesting that the wind regimes at 10 and 98 metres are decoupled.

![Figure 10: The absolute value of the directional shear between 10 and 98 metres height at Falkenberg as function of the stable (nighttime) boundary layer height. The bars indicate two standard deviations of the measurements. The line is a power fit to all measurements.](image-url)
Figure 11: Normalised wind speed difference between 10 and 98 metres height at Falkenberg as function of the stable (nighttime) boundary layer height. The bars indicate two standard deviations of the measurements. The line is a power fit to all measurements.

Figure 11 illustrates in a similar way the effect on the wind speed. For neutral conditions the non-dimensional wind speed difference \((u_{98}-u_{10})/u_{10} \approx 0.5\) according to the neutral wind profile. Again it can be seen that when the wind regimes at 10 and 98 metres can be considered to be decoupled, \(h_{bl} < 100\) metres, there is a sharp increase in the normalized wind shear. The effect is absent for \(h_{bl} > 100\) metres for the reasons given above.

This implies that wind turbines can have a considerable energy potential even when the wind speed near the ground is vanishing, but it also implies that under such conditions the blades will experience considerable shear in both wind speed and direction with negative consequences for the fatigue of the blades.

For practical applications it is of interest to know when the stable boundary layer is lower than a given height. In the absence of information on the Obukhov length, which is unavailable in most practical applications, a simplified parameterisation of the boundary layer height in terms of the wind speed at 10 metres has been suggested [4]:

\[
h_{bl,\text{simp}} = 25u_{10}^{3/2} \tag{11}
\]

where the empirical constant has units of \(m^{1/2}s^{3/2}\) and the wind speed \(m/s\). The fact that the constant is not dimensionless underscores the physical incompleteness of this formulation.

The relationship is illustrated in Figure 12. It can be seen that a height of the stable boundary layer of 50 metres corresponds to \(u_{10}=1.6\) m/s and a height of 100 metres to 2.5 m/s. This means that even with the high wind speed shear factor of 2 from Figure 11, the wind in hub height is not much more than 5 m/s. While this means that WAsP underpredicts for large hub heights, the underprediction is not very large, and the WAsP estimates are conservative.

The accumulated frequency of occurrence is given in Figure 13. The dashed line is for nighttime, stable conditions only, and the full line reflects all measurements. It can be seen that a stable boundary layer less than 50 metres occurs 7 per cent of the time during night and 4 per cent for all measurements. The corresponding numbers for 100 metres are 24 percent and 14 per cent respectively. This also means that the frequency of occurrence of WAsP errors in the upscaling is low.
5 Outlook and Conclusions

The WAsP 8 scripting facility can be used for sensitivity analyses along the lines shown here. This type of analysis can also be used to improve the quality of the resource estimate for large height differences between measured and predicted wind climate or for cases in climates significantly different from northern Europe. However, the technique of splitting up the data according to stability is not recommended for daily use. In our case, the Weibull approximation for very stable cases was no longer fulfilled.

WAsP is based on the assumption of a logarithmic wind profile all the way up to hub height. If that assumption is broken due to stability effects and a very large vertical distance to extrapolate, WAsP errs conservatively, slightly underpredicting the resource for large hub heights. Our advice is to measure for at least one year with a meteorological mast going all the way to the expected hub height.

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References