Influence of Thermal Stratification on Wind Profiles for Heights up to 140 m

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The vertical wind speed profile has to be know for many wind power applications. Although the large effect of the thermal stratification is well known normaly the neutral logarithmic wind profile is used, which leads to large errors in the determination of the needed wind speed. In this work a parameterisation of DeBruin for the thermal stratification is testet with measured data from the 200 m high met mast in Cabouw, Netherlands. This parameterisation is quite generel as it uses wind speeds at two heights (one can be z_0 with u=0) and two temperatures for the calculation of the Monin-Obukhov-Length. It is robust to the determination of the roughness length z_0 and tolerant for unsteady situations. It can be shown that the calculations of higher levels (up to 80 m) is much more accurate by applying this stability correction. This correction is integrated in the wind power prediction system *PREVIENTO*. Even here where the large uncertainty are caused by the numerical weather prediction the consideration of the stability effects leads to a significant improvement of the wind power prediction.

1 Introduction

In wind power applications the problem often occurs that wind speeds are not measured or predicted in the hubheight of the wind turbine. For the vertical transformation of the wind speed the wind speed profile has to be known. State of the Art is to take a neutral logarithmic profile, where the Reynolds stress described by the friction velocity is the only dominant effect on the profile. This profile is used for wind power assessment (in the standard tool WAsP [1]) to transform statictics of measured wind speeds in lower levels to hubheight. But this profile is used also for wind power prediction where the output of the numerical weather prediction (with very coarse vertical resolution) is transformed to the wind speed in hubheight for each specific situation of the boundary layer (so no statistics). In all these calculations it is neglected that the thermal stratification of the boundary layer has also an important influence on the vertical wind speed profile. Only Landberg did some investigations to include a stability corrected geostrophic drag law in a wind power prediction system without success [2].

Figure 1: 200 meter high met mast in Cabouw, Netherland. The measurements are operated by the Royal Netherlands Meteorological Institute (KNMI)

2 Met mast Cabouw

For the investigations in this work data from the metmast in Cabouw, Netherlands are used. The met mast is operated by the Royal Netherlands Meteorological Institute (KNMI) and is shown in figure 1. Wind speed, wind direction and temperature are availiable in 10, 20, 40, 80, 140, 200 m height. The temperature is also availiable in 2 m. The measurement period is from 1993 to 1996 and from 2000 to 2002. In each height are three booms. For this work only winds from 165° to 195° are used due to very homogeneous roughness in this sector. In this sector Wessels [3] located also the lowest flow distortion from the mast (less than 2%.).

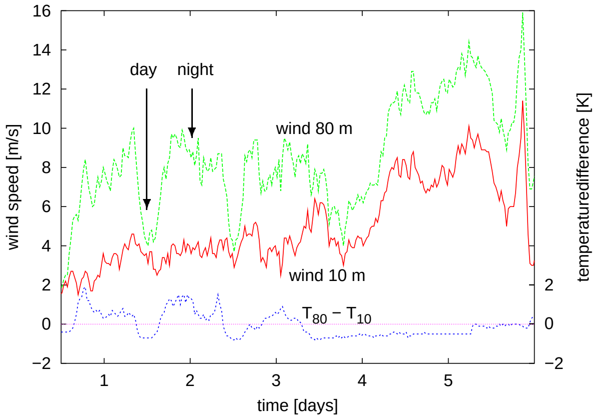

Figure 2: Example of an DDDzeitliche development of the wind speed in 10 and 80 m height from 1. to 5. of Janury 1993 in Cabouw, Netherlands. The difference of the wind speeds dddschwankt strongly from 0.5 to 5 m/s. The wind speed difference correlates with the difference of the potential temperatures in 10 and 80 m height.

3 Influence of thermal stratification on the vertical wind profile

To get an impression how the wind speeds in the surface layer could behave the wind speeds in 10 and 80 m for the first five days of 1993 in Cabouw are shown in figure 2. Even if the wind speed in 10 m is only increasing little over the first three days the wind speed in 80 m shows large variations. This change of wind speed is highly correlated to the temperature difference which is an indicator of the thermal stratification of the surface layer. In this extreme situation the wind speed difference ranges from 0.5 to 5 m/s.

This differences can be seen also in the vertical profile. Figure 3 shows two examples of the profiles on the 4th of January 1993. For higher levels the difference of the wind speeds increases.

This has also an influence on the diurnal mean wind speed in different heights. It is well known that in 10 m height there is a maximum at noon (figure 4). The thermal stratification leads to a reversed diurnal variation with a clear maximum at night. This effect is significant regarding the hubheights of today's wind turbines.

The wind speed profile of the surface layer is derived under the assumption that shear forces described by the friction velocity are the only important forces and are constant. It results in a logarithmic profile. This profile fits quite well to real measurements for neutral thermal stratification. For situations which aren't neutral the Monin-Obukhov-Theory leads to a correction using the stability funktion ψ.

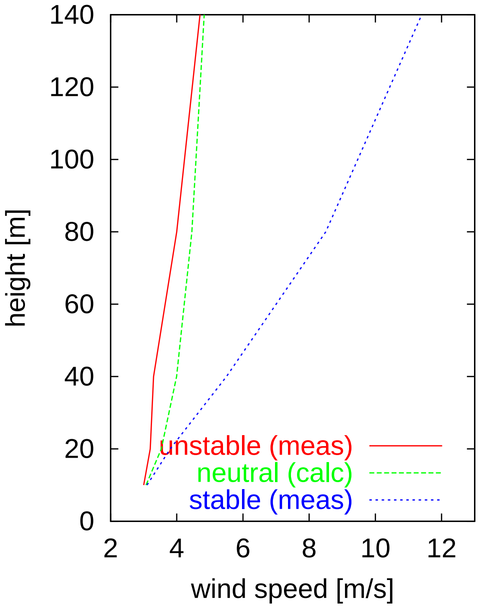

Figure 3: Measured wind speed profiles at 1:45 (stable) and 18:45 (unstable) of the 4 January 1993 in Cabouw. The profiles are mean values over half an hour. For comparison a calculated neutral profil is ploted.

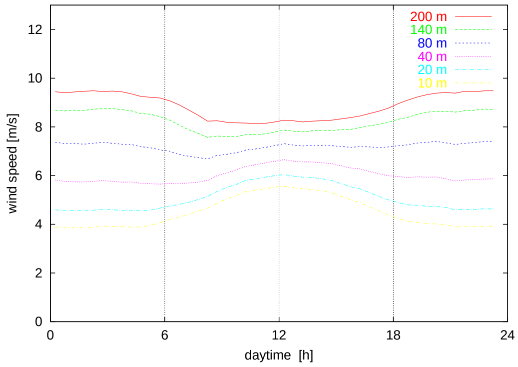

Figure 4: Mean measured wind speed profiles for different heights at the site of Cabouw.

$$u(z) = \frac{u_*}{\kappa}\left(ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right) \qquad (1)$$

where u_* = friction velocity, κ = von Kármán constant, z_0 = roughness length, ψ = stability funktion, L = Monin-Obukov-Length.

3.1 Parameterisation of thermal stratification

The Monin-Obukhov-Length L is the indicator of the stability of the surface layer. For wind power utilisation an parameterisation of the Monin-Obukhov-Length is needed which is fulfills following demands:

- often only one wind speed is avialiable so it should be possible to determine the profile by only one wind speed

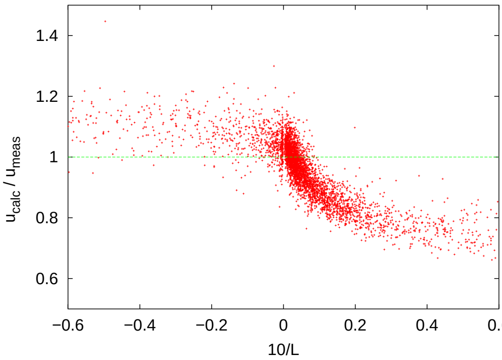

Figure 5: Ratio of calculated (from 10 m measurements with neutral wind speed profile) and measured wind speed in 40 m over the stability dddMaß 10/L.

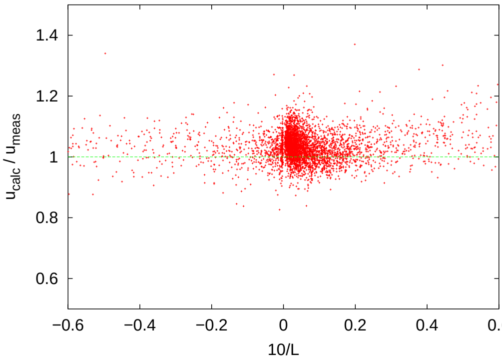

Figure 6: equal plot as figure 5 with stability corrected wind speed profile.

- the parameterisation should be done by measured entities, e.g. no heat flux should be taken because it is rarely available
- the parameterisation should be tolerant for many situation of the surface layer as unsteady cases of the flow
- the parameterisation should be robust to the roughness length due to its subjective determination
- due to operational use it should always have a solution.

Therefore, an analytical parameterisation of DeBruin [4] is selected for the Monin-Obukhov-Length L. L is here calculated through two potential temperatures Θ_1, Θ_2 and two wind speeds u_1, u_2. It is quite universal as the heights of the wind speeds and temperatures may differ: $h_{u1} \neq h_{\Theta 1}$ and $h_{u2} \neq h_{\Theta 2}$. If only one wind speed is availiable it is possible to choose $h_{u1} = z_0$ so that $u_1 = 0$. So it is possible to determine the Monin-Obukhov-Length by one wind speed and two temperatures. For stable situations the stability funktion of Beljaars and Holtslag [5] and for unstable situations the stability funktion of Dyer [6] is used.

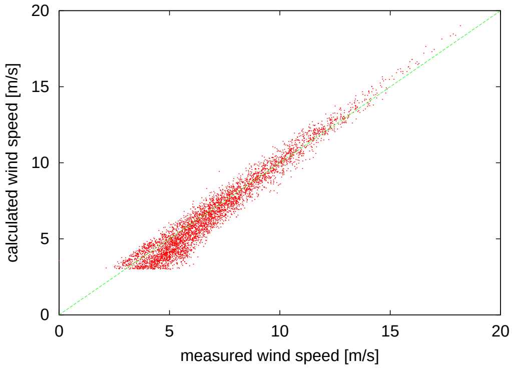

Figure 7: Calculated (from 10 m measurements with neutral wind speed profile) over measured wind speed in 40 m height.

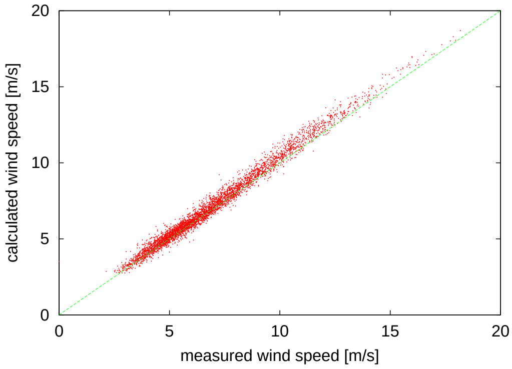

Figure 8: equal plot as figure 7 with stability corrected wind speed profile.

4 Verification using measurements in Cabouw

To verify the parameterisation we will investigate the mean profiles for different thermal stratifications. For the application it is important how high the accuracy for a long time series will be. Therefore we take the measurements in lower levels, apply the thermal corrected wind profil and calculate the wind speed in higher levels. This calculated wind speed time series is compared with the real measured wind speed time series. In the first calculations we take the measured wind speed in 10 m height to calculate the wind speed in 40 m. In figure 5 the ratio of calculated (here with neutral wind profile) and measured windspeed in 40 m height is shown over 10/L. As assumed (see figure 3) the wind speed is overestimated for unstable situations (10/L $<$ 0) and strongly understimated for stable situations (10/L $>$ 0) by application of the neutral profile. If we apply the thermal corrected wind speed profile with measured temperatures in 2 and 40 m for the parameterisation of the stability the scatter looks much better (figure 6). The correction of the wind speed profile works for unstable (z/L $<$ 0) as well as the more often stable (z/L $>$ 0) situations. For very stable situations the corrections tend towards an slightly overestimation. In Figure 7 and 8 the wind

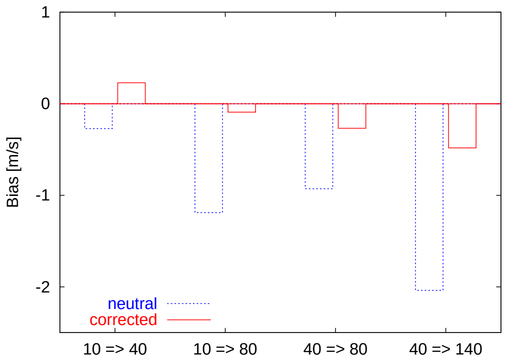

Figure 9: Comparison of calculated wind speeds with neutral or stability corrected profile in different heights. 10 => 80 means: the 80 m wind speed is calculated from the 10 m wind speed. The bias shows its mean deviation from the measurements in 80 m height.

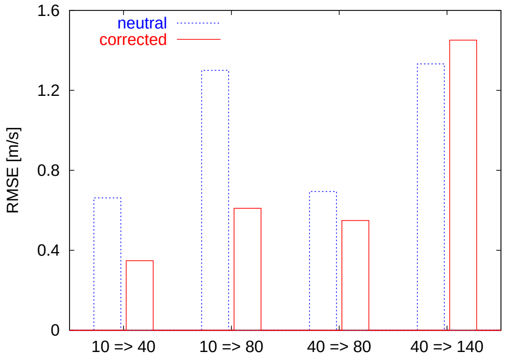

Figure 10: equal to figure 9 but the RMSE.

speed dependency of the correction can be seen by plotting the calculated wind speed over the measured wind speed. The reason for overestimation for high wind speeds is not caused by the roughness length. There is no change for even lower roughness length.

The statistical evaluation is done using the mean deviation (bias) and the root mean square error (RMSE).

$$bias = \overline{u_{calc}} - \overline{u_{meas}} \tag{2}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[(u_{calc,i} - \overline{u_{calc}}) - (u_{meas,i} - \overline{u_{meas}})]} \tag{3}$$

This evalutions is done for some other availiable heights in Cabouw. That means to extrapolate the measured wind speed in 10 m also to 80 m, and use the measured wind speed in 40 m height to calculate the wind speed in 80 and 140 m. For all calculations the potential temperature in 2 and 40 m height is used to parameterise the stability. The bias is reduced extremly for all four calculations by using the corrected wind speed profile (figure 9). The RMSE is reduced by around 50% for calculating from 10 m to 40 m or 80 m (figure 10). The RMSE is decreasing only slightly by applying the corrected profile and is in the same magnitude as the calculation from 10 m to 80 m. This is expected due to the relatively high gradients of the wind speed profile in low heights. Surprisingly the RMSE for the calculation from 10 m as from 40 m to 80 m is of the same magnitude. That means that the wind speed profile up to 80 m is described with the same accuracy by to wind speeds in 10 m or 40 m height. The RMSE increases by applying the stability corrected profile to calculate the wind speed in 140 m height. This is expected simply because even the neutral logarithmic profile is not valid anymore. More details are described in [7].

5 Application to wind power prediction

For wind power prediction the wind speed at hub height for each specific atmospheric situation is needed. In this work the stability is included in the short term prediction system *PREVIENTO*. Here the wind speed forecast of the *Lokalmodell* run by the *German Weather Service* is used to predict the power output of a wind farm. The forecast wind speed is refined to the specific conditions at the site taking the roughness and orography into acount. Knowing the wind speed in hubheight the power output of a wind farm can be calculated under consideration of the type depending power curve of the wind turbines and wind farm effects. A more detailed description of the wind power prediction system *PREVIENTO* can be found in [8]. For the stability correction another uncertainty besides the paramerterisation of the stability occurs: the thermal stratification has to be known in advance. Therefore the temperature forecast of the Lokalmodell in two levels (2 m and 33 m) is used. Details on the accuracy of the temperature difference forecast can be found in [7].

In wind power prediction the main error is caused by the wind power prediction of the numerical weather prediction system. There are also many other sources for errors so the question is here if the stability correction of the wind speed profile is remarkable. In this example the forecast is made for a wind farm of 6 turbines type An Bonus 1 MW with 70 m hubheight. Figure 11 shows the ratio of predicted and measured power output over z/L by using a neutral wind speed profile. Due to the large errors in the forecast this scatter is much bigger than in figure 5. The scatter for unstable situations is so large that no overestimation can be seen visually. But a underestimation for stable situtation occurs very clearly. By applying the stability corrected profile the scatter centers more around the optimal forecast (figure 12.

Stable situations occurs mostly at night while unstable

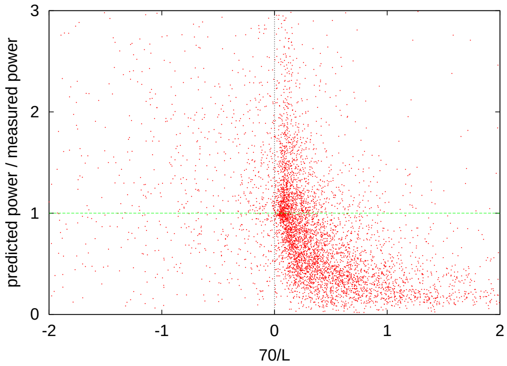

Figure 11: Ratio of predicted power output and measured power output of the wind farm Neuenkirchen over the stability DDDMaß 70/L using the neutral wind speed profile.

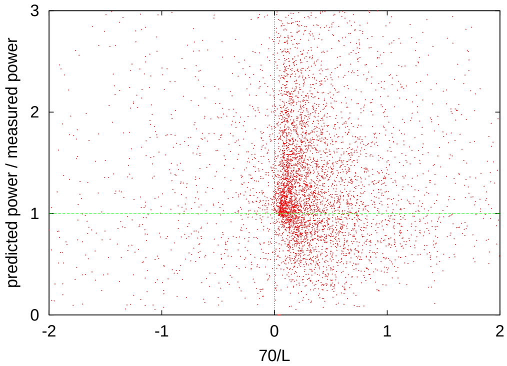

Figure 12: equal to figure 11 but using the stability corrected wind speed profile.

thermal stratification can be found mostly at daytime. So the underestimation of the wind power output for stable situations can be seen in the diurnal variation of the bias (figure 13), where the smooth deviation follows the position of the sun. The correction leads to a constant bias.

6 Resume

The thermal stratification has an enourmous influence on the vertical wind speed profile. Therefore, a correction of the logarithmic profile is necessary, but is not done yet for wind potential assessment as for wind power prediction. An analytical parameterisation of the Monin-Obukhov-Length due to temperaturedifferences is applied for this correction. It can be shown for measurements in Cabouw that the bias and the RMSE for calculating wind speed in higher level with lower wind speed measurements decrease by around 50% for levels up to 80 m. Surprisingly, the wind speed profile is described with same accuracy by the wind speed of 10 m or 40 m. Above these heights (140 m) the logarithmic profile fails so a new theory has to be applied here which is not developed right now.

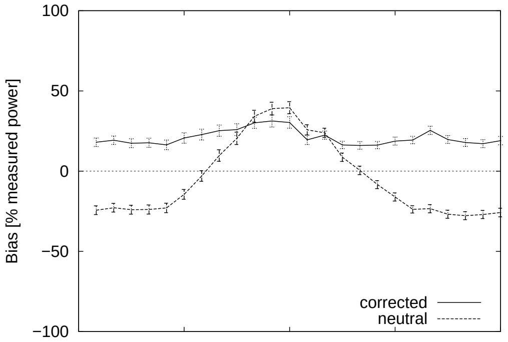

Figure 13: Diurnal bias of the wind power prediction for the wind farm Neuenkirchen using the neutral or stability corrected profile.

The integration of the stability corrected profile in the wind power prediction system *PREVIENTO* leads to a significant improvement of the forecast accuracy, even the high uncertainty results from the wind speed forecast of the numerical weather prediction.

7 Acknowledgements

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