A new Turbulence Model for the Stable Boundary Layer with Application to CFD in Wind Resource Assessment

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Abstract: In wind resource assessment, the impact of the atmospheric thermal stability attracts more and more attention. The first reason is the increase of wind turbines height. The second reason is that the practice of WRA engineering is evolving towards a regular use of time series extrapolations (measurements or mesoscale data) or at least more detailed statistical analysis. Using time series instead of global statistics leads to considering more stable situations.

In CFD models, the turbulent fluxes are linked to the gradients of the mean variables via the concept of turbulent viscosity, considered as the product of a turbulent wind speed scale, and a turbulent length scale. Up to now, this approach failed to reproduce strong stability cases because of the underlying hypothesis of the Monin-Obukhov Similarity Theory (MOST). We propose a new multi-layer approach for the turbulent viscosity modeling by taking benefit of the k-L model which offers a very good adaptation to real atmospheric flows. This 3-L (three layers) model is implemented in the CFD software Meteodyn WT. The model calibration has been made with high quality measurements at the Cabauw tower (the Netherlands), located in a flat and low roughness terrain. The validation of the 3-L model has been made with data obtained at Rödeser Berg (Germany) on a hilly forested site. It is shown that the implementation of the 3-L model in a CFD software (here Meteodyn WT) allows to reproduce mean wind speed and TKE profiles even in cases where the Stable Boundary layer lays below the height of 200 m or under (until 75 m).

Key words: wind resource assessment; WRA; atmospheric boundary-layer; thermal stratification; CFD

1. INTRODUCTION

The impact of atmospheric stratification on the wind profile attracts more and more attention in wind resource assessments, especially for the extrapolation of time series wind speed measurements (measurements or mesoscale data) to large hub heights.

The daily and seasonal cycles of the surface heating and cooling (the thermal stable conditions) cause a wide variation of wind shear (as shown by measurements at Cabauw tower (www.cesar-database.nl) [1] in Netherlands). The daily variation of wind shear shows a minimum in day time and a maximum at night. The time-averaged wind profiles, widely used to project the wind speed at the turbine hub height will introduce errors for scaling a time series of wind speed profile at hub heights and Energy Production estimate.

In the classic Monin-Obukhov Similarity Theory (MOST), which is applied for the thermal stable condition, the turbulent fluxes are linked to the gradients of the mean variables via the concept of turbulent viscosity which can be modeled as the product of a wind speed scale, generally the square root of the turbulent kinetic energy (TKE), and a turbulent length scale LT. The TKE is computed via the transport equation, including a dissipation term which depends on LT. A unique average thermal stability is generally considered over a site. This average stability is deduced from the average wind and temperature profiles, and it is generally slightly stable. Therefore it is appropriate only within the limit of a critical Richardson number.

We propose a new turbulence model so that strong stability cases can be considered. In this model, three layers are considered over the dynamic layer:

- The MOST layer where the Gradient Richardson number is lower than about 0.1 [2]: Yamada and Arritt's model [3] is used with a modification in the mixing length formulation in order to take into account a limiting buoyancy length scale. In the classical MOST layer, a constant turbulence length Lt which only depends on the stability is applied.
- A transitional layer, where the fluxes are either modeled by a "z-less" scaling or a local MOST theory where the fluxes decrease with height up to a critical Richardson number.
- The outer layer, where the turbulent fluxes depend on large scale turbulence generated at the meso-scale level [4].

This three layer (named 3-L model) model is fitted through the following parameters: the Obukhov length L inside the MOST layer; the height HMOST of the MOST layer, defined through the ratio HMOST/L; the height Hout of the outer layer basis, defined through the ratio Hout/L; the inferior limit of the turbulent length scale inside the SBL l0; the stability coefficient Sout inside the outer layer Sout in Yamada and Arritt model.

This model is implemented in Meteodyn WT. And the calibration has been done with measurements at the Cabauw tower (the Netherlands), located in a flat and low roughness terrain. The validation of the model has been made with data obtained at Rödeser Berg (Germany) on a hilly forested site.

2. CABILRATION ON CABAUW DATA

The measurements at Cabauw include air temperatures and wind speeds at various heights between 10 m and 200 m [5, 6]. We have selected the wind direction sector 255-285 deg, in which the mean wind speed and the turbulent intensity profiles correspond to a homogeneous terrain with a roughness of 4 cm. After removing very low speed wind situations, we get 19,000 10-min runs during 4 years (2009-2012). These data have been sorted according to thermal stabilities. The exact estimation of the Gradient Richardson number at a given height is not straightforward for the reason that it would require the knowledge of the vertical profiles shape. Then, we considered the differences of temperature and wind speed between the heights z1=10 m and z2=80 m, leading to a "Stability Index" (SI) which looks like an approximation of the gradient Richardson number:

$$SI = \frac{g}{\theta_1} \frac{(\theta(z_2) - \theta(z_1))/(z_2 - z_1)}{\left[(V(z_2) - V(z_1))/(z_2 - z_1)\right]^2}$$

where θ is the potential temperature and g is the gravity. In each class of SI, vertical averaged profiles of measured mean wind speed and turbulent kinetic energies (TKE) have been plotted. Table 1 gives characteristics (the frequency of occurrence of the SI class, the proportion of wind power density inside each class, the average mean wind speed between 80 m and 140 m, the averaged normalized wind speed at 80 m, 140 m and 200 m) of each class. If we look at figure 1, we observe that up to the class S07 the wind gradients increase with the stability growth what can be expected. From class S08 the gradients are decreasing as the stability increases. We can suppose that this behavior is linked to the height of the Stable Boundary Layer which seems to be inferior to 200 m when SI > 0.20, inferior to 140 m, when SI > 0.30, and inferior to 80 m when SI > 0.40.

	S03	S04	S05	S06	S07	S08	S09	S10	S11	S12
SI	0.00-0.01	0.01-0.05	0.05-0.10	0.10-0.15	0.15-0.20	0.20-0.25	0.25-0.30	0.30-0.40	0.40-0.50	0.50-0.70
frequency	7.3%	9.4%	14.4%	11.2%	9.0%	6.9%	4.8%	6.4%	3.4%	3.1%
energy fraction	9.1%	24.1%	21.4%	9.6%	6.0%	4.0%	2.5%	3.0%	1.4%	1.0%
(V80+V140)/2	8.1	11.3	9.5	8.0	7.4	7.1	6.8	6.5	6.2	5.8
V80/V40	1.12	1.17	1.23	1.27	1.29	1.30	1.32	1.32	1.28	1.25
V140/V40	1.22	1.31	1.42	1.51	1.54	1.54	1.54	1.52	1.47	1.41
V200/V40	1.30	1.42	1.58	1.67	1.69	1.66	1.66	1.64	1.57	1.52

Table 1: Characteristics of the SI classes at Cabauw (stable configuration only)

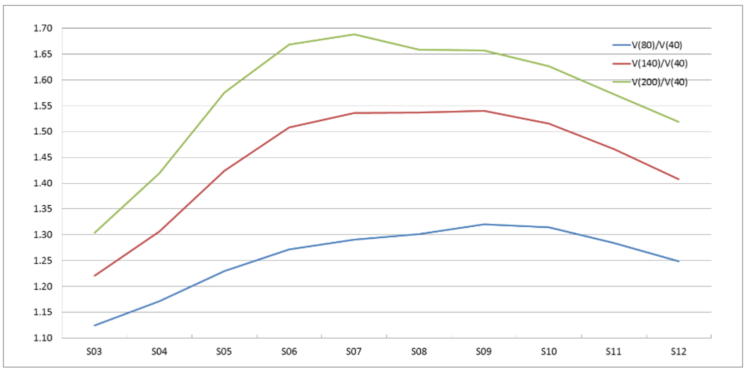

Fig 1: Averaged normalized wind speed gradients according to SI classes

The inlet wind speeds profiles follows the log-linear law (defined by L) in the MOST layer and linearly increases in the local-MOST and outer layers. In the dynamic layer, the inlet TKE profiles follows a linear relation, based on a constant neutral mixing length. We specified a TKE in the outer layer and then give a linear decreasing between them in the transitional layer.

The parameters of the 3-L model (Obukhov length L, height HMOST of the MOST layer, height Hout of the outer layer, inferior limit of the turbulent length scale l0 and the stability coefficients Sout inside the outer layer) are fitting by comparisons of Meteodyn WT simulations and measurements for the different stability classes 4, 7 to 12. Here, the stability coefficients Sout inside the outer layer is independent on the stability.

Figures 2 and 3 show the comparisons between calculated and measured profiles of mean wind speed and TKE. In the figures, the classification WT04 until WT12 are Meteodyn WT stability classification fitted with the stability indices in table 1 as below:

- Class 4 (WT04) , fitted with the S03 bin
- Class 7 (WT07), fitted with the S04 bin
- Class 8 (WT08), fitted with the S05 bin
- Class 9 (WT09), fitted with the S06 bin
- Class 10 (WT10), fitted with the average of S07, S08, S09 bins
- Class 11 (WT11), fitted with the average of S10 and S11 bins
- Class 12 (WT12), fitted with the S12 bin

In these figures, the simulations agree very well with observed profiles of normalized mean wind speed and the Turbulent Kinetic Energy. From WT04 to WT10, the stronger the thermal stability condition, the greater the wind shears. While for the very strong stable condition (from WT11 to WT12), the wind shear become weaker. Very different from the neutral condition, TKE is not constant anymore. It decreases with height due to the buoyancy force. And in the strong stable condition, we have less TKE in both measurements and simulations.

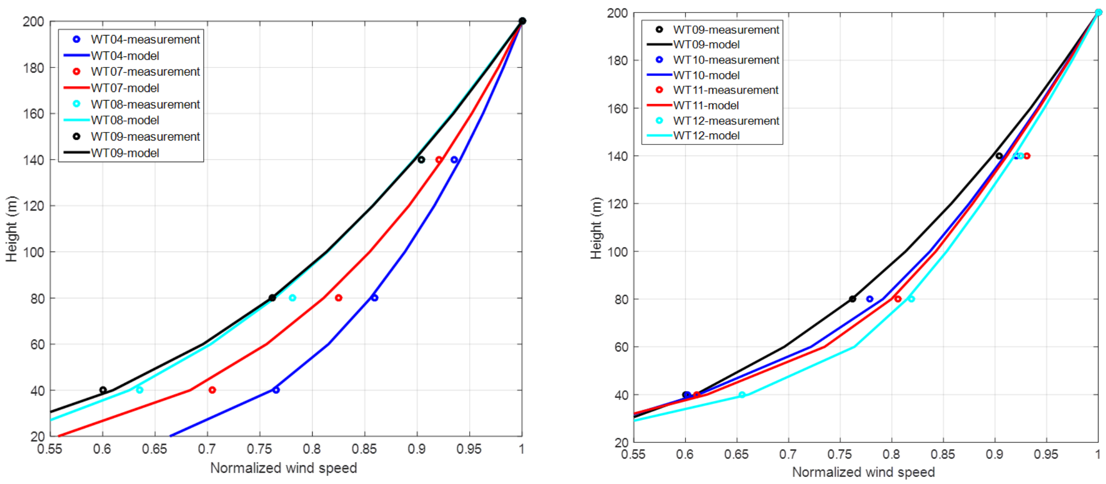

Fig 2: Normalized profiles of mean wind speed (measurements and computations)

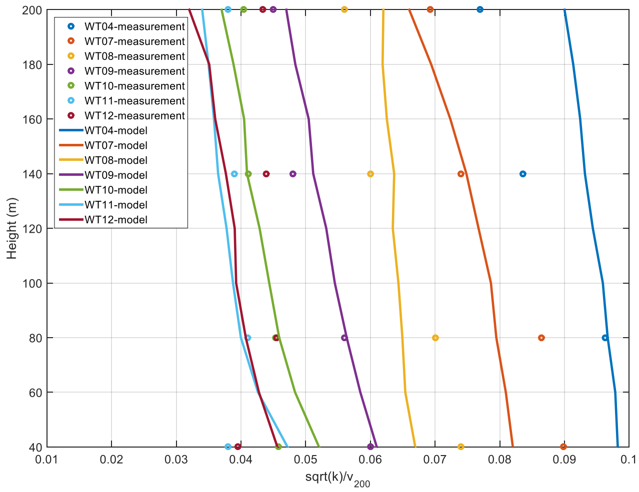

Fig 3: Normalized profiles of the TKE square root (measurements and computations)

Table 2 and table 3 show the relative error on the gradient value and the turbulent standard deviation. We see that the maximal error of normalized velocity is less than 4% and about 24% for the root square of the turbulent kinetic energy.

	error on V/V200 (%)						
Stability Class	WT04	WT07	WT08	WT09	WT10	WT11	WT12
40 m	0.5	4.2	1.5	1.6	1.7	1.6	1.0
80 m	0.5	3.8	2.2	0.1	1.6	0.8	0.5
140 m	0.6	1.0	0.8	0.7	1.2	2.1	0.7

Table 2: Errors (%) of normalized velocity as a function of height

	error on sqrt(k) (%)						
Stability Class	WT04	WT07	WT08	WT09	WT10	WT11	WT12
40 m	2.1	15.0	9.6	-1.6	-13.6	-24.2	-15.5
80 m	1.6	12.4	6.6	-4.4	-6.7	-4.0	6.0
140 m	15.6	0.7	-8.2	-17.4	-11.7	-2.5	7.2
200 m	24.7	7.7	-14.9	-21.1	-9.8	-2.0	9.6

Table 3: Errors (%) of normalized profiles of the TKE square root as a function of height

3. VERIFICATION ON RÔDESER BERG DATA

Rödeser Berg is a hilly and forested site in Germany [7,8]. A dense forest lies in the South-West and South sectors, while the roughness is lower in the East sector. We consider the mean wind speed and direction and standard deviation measured every 10 min at 6 levels: 40 m, 80 m, 120 m, 160 m and 200 m, and also the Obukhov length, measured every 30 min with a 3D ultrasonic anemometer at 40 m height. The data covers the whole year 2013. We selected the 3 main direction sectors with a width of 30 deg: East sector (85-105 deg), SSE sector (155–185 deg), SSW sector (185-215 deg). The data have been selected according to the following criteria:

- mean wind speed, averaged over the heights 40 m to 200 m, greater than 3 m/s.
- positive Obukhov length scale , and greater than 20 m and less than 2500 m.

In case of Eastern winds, as shown in figure 4, the wind speed gradients increase according to the thermal stability (L decrease) as computed in Meteodyn WT. From the great L to the small L, the wind shear becomes greater. But the measured TKE are less dependent on stability than expected in the computations (max gap is less than 20%).

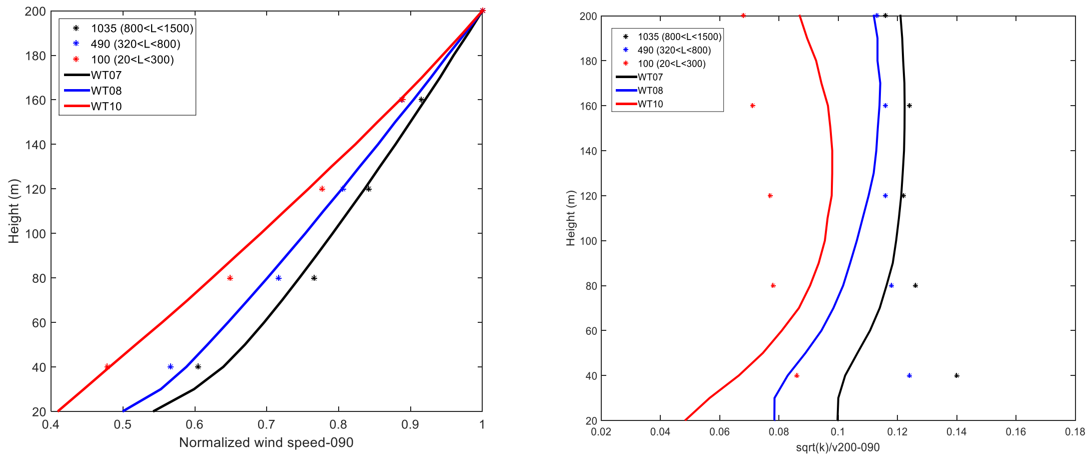

Fig 4: Comparison with Rödeser Berg (East direction): Normalized V profile (left) and TKE square root (right)

When the wind comes from South and South-West directions (Fig. 5 and 6), the surface friction generated by the tree weakens the thermal effect for the wind speed gradient, but the TKE is still strongly affected by stability. This phenomenon is well reproduced by the 3-L model.

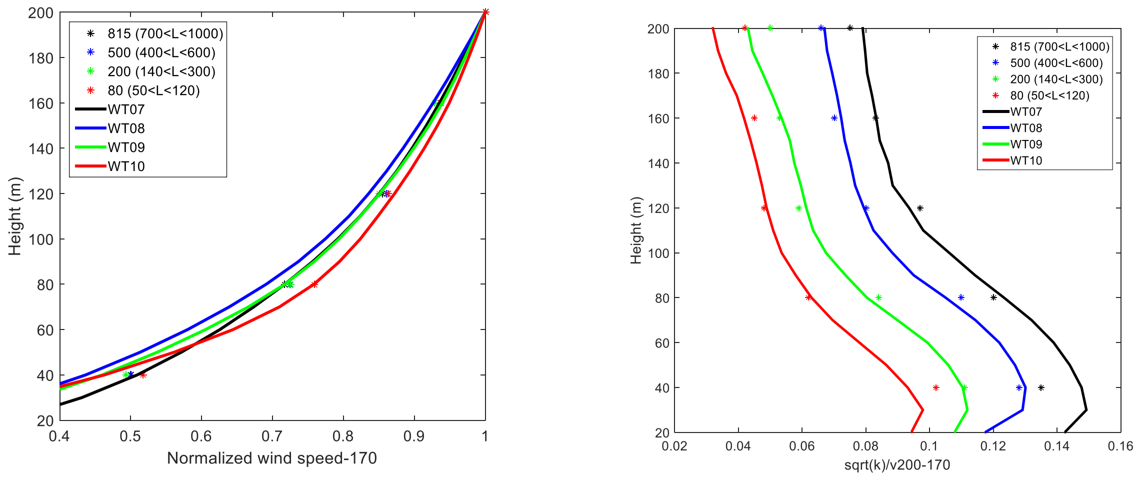

Fig 5: Comparison with Rödeser Berg (SW direction): Normalized V profile (left) and TKE square root (right)

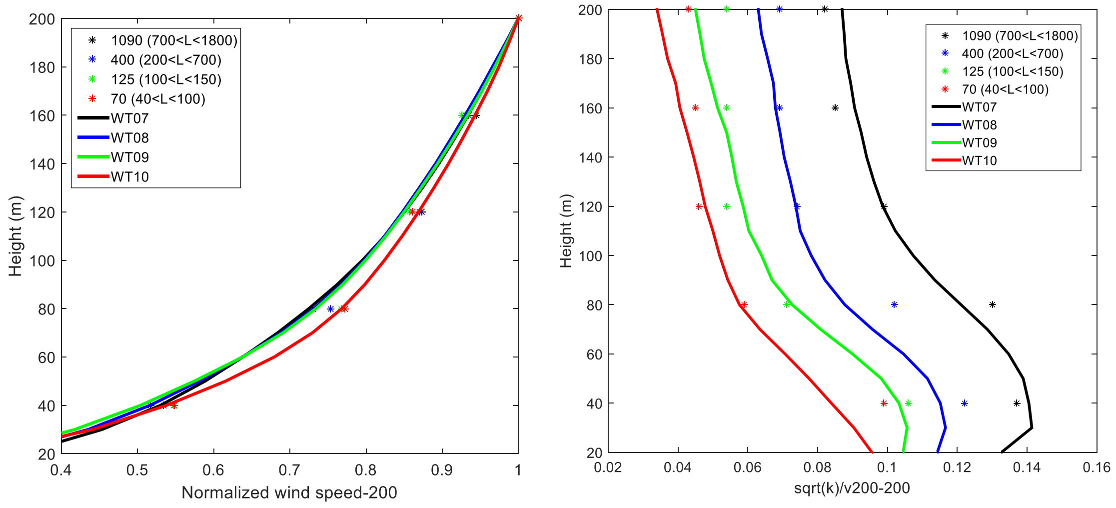

Fig 6: Comparison with Rödeser Berg (South direction): Normalized V profile (left) and TKE square root (right)

Table 4 recapitulates the relative error on the gradient value and the turbulent standard deviation. If we consider heights of 80 m and 120 m, corresponding to common hub heights, we see that the error is always inferior to 5% for the gradients, and inferior to 15% for the root square of the turbulent kinetic energy.

The main discrepancies stand at 40 m height for the wind gradient (up to 12% error). Considering the turbulence, the stable cases for the East wind sector give high errors (up to 37% error), but it must be relativized by the fact that the turbulence is very low for this direction and this stability class , then the error on the gust values (mean value plus 3 standard deviation) remains acceptable.

	L range	error on V/V200 (%)				error on sqrt(k) (%)				
		40	80	120	160	40	80	120	160	200
90 deg	20-300	1	4	2	0	23	15	27	37	28
	320-800	4	2	0	2	33	14	5	2	1
	800-1500	6	3	1	1	27	8	1	2	4
170 deg	50-120	10	0	1	1	9	2	2	7	24
	140-300	7	1	0	1	1	4	4	1	14
	400-600	12	5	3	1	2	5	1	3	2
	700-1000	2	0	0	0	9	3	3	0	5
200 deg	40-100	2	1	1	1	15	2	4	10	21
	100-150	8	4	1	1	3	2	9	5	17
	200-700	3	3	3	1	6	14	0	2	9
	700-2500	3	1	3	1	2	7	0	7	6

Table 4: Errors (%) as a function of height, Obukhov length, wind direction

4. CONCLUSION

The data from Cabauw have allowed the elaboration of 3-L model for the turbulent viscosity in case of Stable atmospheric stratification. This model aims at calculating wind flows between 40 m and 200 m height. Then 3-L model has been validated thanks to 1 year data at Rödeser Berg site, for the new stability class WT 07 to WT 10. This site is a hilly and forested site very different from the flat and low roughness terrain of Cabauw. In Rödeser Berg, no situation was fitting with models WT11 and WT12.

At Rödeser Berg, the influence of the thermal stability on vertical profiles is very different from Cabauw. The model has reproduced this specific behaviour (vertical wind profiles not sensitive to thermal stability when the winds come from the South, and more sensitive for Eastern winds), while turbulence profiles remain very sensitive to the thermal stability. It is supposed that the difference between Southern and Eastern winds behaviour is due to the large forests in the South and the difference in orography.

At 80 m and 120 m height, the model is able to reproduce the wind gradient with an error of less than 5%, for the turbulent fluctuations, the error on the wind speed standard deviation is less than 10% in 18 cases, between 10% and 15% in 3 cases, and equal to 27% in one case.

It has been demonstrated that applying a k-L multi-layer model for large heights or strong stability is a promising way to reproduce observed behavior of the Stable Boundary Layer (SBL), especially when the height of the SBL becomes inferior to the wind turbine hub heights, allowing a step forward for a better consideration of the atmospheric stability in wind resource assessment. This model will be implemented in a next version of Meteodyn WT.

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